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Direct User-Charging of Commercial Vehicles for Infrastructure Cost Recovery

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Direct User-Charging of Commercial Vehicles for Infrastructure Cost Recovery

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Dissertation

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Direct User-Charging of Commercial Vehicles for Infrastructure Cost Recovery

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The purpose of this research is to provide a theoretical framework for future commercial vehicle user-charging using real-time vehicle weight and configuration information collected using weigh-in-motion (WIM) systems. This work provides an extensive review of both mechanisms and technologies employed for commercial and passenger vehicle user-charging worldwide. Existing commercial vehicle-user charging structures use only broad vehicle classifications to distinguish between vehicles for the pricing of user-fees. The methodology proposed in this study employs highway cost allocation methods for development of an "Axle-Load" toll structure. A theoretical case study, based on information from Texas State Highway 130, is performed to explore the equity improvements that could be achieved through implementation of this proposed structure. Some sensitivity analysis is also performed to examine the potential revenue impacts due to uncertainties in different data inputs under existing and proposed structures.

TABLE OF CONTENTS

Chapter 1: Introduction 1

Chapter 2: Current Mechanisms for Highway Funding in the US 5

2.1 User Fees 5

2.1.1 Federal User Fees 5

2.1.2 State User Fees 6

2.1.3 Toll Road User Fees 11

2.2 User Fee Revenues 14

2.2.1 Federal User Fee Revenues 15

2.2.2 State User Fee Revenues 22

2.3 User Fee Equity 24

2.3.1 Federal User Fee Equity 24

2.3.2 State User Fee Equity 28

2.3.3 Toll Road Equity 29

Chapter 3: Future Mechanisms for Highway Funding 34

3.1 User Fee Alternatives 34

3.2 Road Pricing Motivations 41

3.3 Road Pricing Technologies and Applications 44

3.3.1 Electronic Toll Collection 46

3.3.2 Facility Congestion Tolls 48

3.3.3 Cordon and Area Congestion Pricing 58

3.3.4 Distance-Based Charges 62

3.3.5 Emissions Based Charges 67

3.3.6 Truck-Related Road Pricing Impacts 70

3.4 Future Road Pricing Alternatives 73

Chapter 4: Weigh-in-Motion Systems and Technologies 81

4.1 WIM Technologies 81

4.2 WIM Applications 86

4.2.1 Planning 86

4.2.2 Weigh Enforcement 87

4.2.3 WIM for Highway Cost Allocation 90

Chapter 5: Highway Cost Allocation Studies 94

5.1 General Cost Allocation Methods 94

5.2 Quantifying Infrastructure Costs 98

5.2.1 Pavement Consumption 98

5.2.2 Bridge Consumption 102

Chapter 6: Methodology for Toll Rate Determination and Analysis 107

6.2. Determination of Toll Structure..... 107

6.3 Axle-Load Toll Rate Estimation 117

6.3.1 Common Base Toll Estimation 119

6.3.2 Pavement Construction Toll Share 120

6.3.3 Pavement Maintenance Toll Share..... 124

6.3.4 Bridge Construction Toll Share 125

6.3.5 Bridge Maintenance Toll Share..... 128

6.3.6 Final Axle-Load Toll 129

6.4 Number-of-Axle Toll Rate Estimation 130

6.5. Cost Responsibility Estimation..... 131

6.5.1 Pavement Construction Cost Responsibility Estimation..... 133

6.5.2 Pavement Maintenance Cost Responsibility Estimation 135

6.5.3 Bridge Construction Responsibility Estimation..... 135

6.5.4 Bridge Maintenance Responsibility Estimation 136

6.5.5 Final Vehicle Cost Responsibility..... 136

6.6 Toll Rate Equity Analysis 137

Chapter 7: Case Study 141

7.1 Proposed Technology System for Tolling 141

7.2 Traffic Volume Estimation 141

7.2 Cost Estimation 148

7.2.1 Bridge Cost Estimation 149

7.2.2 Pavement Cost Estimation 150

7.2.3 Other Construction Costs 151

7.2.4 Operations and Maintenance Cost Estimation 153

7.2.5 Debt Service Cost Estimation 155

7.3 Load-Related Class Determination 156

7.4 Axle-Load Toll Rate Determination 157

7.4.1 Common Toll Share Determination 158

7.4.2 Pavement Construction Toll Share Determination 160

7.4.3 Pavement Maintenance Toll Share Determination 164

7.4.4 Bridge Construction Toll Share Determination 165

7.4.4 Final Axle-Load Toll Rate 174

7.5 Number-of-Axle Toll Rate 175

7.6 Cost Responsibility Estimation 176

7.6.1 Pavement Construction Cost Responsibility Determination 177

7.6.1 Pavement Construction Cost Responsibility Determination 178

7.6.1 Bridge Construction Cost Responsibility Determination 178

7.6.1 Final Cost Responsibility 179

7.7 Toll Equity Analysis..... 179

7.8 Sensitivity Analysis 183

7.8.1 Truck Share Sensitivity 184

7.8.2 Truck Profile Sensitivity..... 185

7.8.3 WIM Error Sensitivity 187

Chapter 8: Conclusions and Future Research 190

8.1 General Findings 190

8.2 Improved Cost Estimation..... 192

8.3 Improved Methods of Cost Allocation..... 193

8.3.1 Pavement Cost Allocation 193

8.3.2 Bridge Cost Allocation 195

8.3.3 Common and Base Infrastructure Cost Allocation 196

8.4 Addition of Larger Vehicle Classes 197

8.5 Dynamic Load Measurement 198

8.6 Toll Elasticities..... 200

8.7 Integration of Congestion and Emissions Costs 202

8.8 Quantification of WIM Error 202

8.9 Data Uncertainty 204

8.10 Final Conclusions 204

Appendix A: Program for Live-Load Moment Calculation 206

References 302

VITA 316

TABLE OF FIGURES

Figure 1. US State Weight-Distance Taxes 11

Figure 2. Basic Rate Structures for US Toll Roads 13

Figure 3. Estimated Toll Rates per Mile for Selected US Toll Roads 14

Figure 4. Purchasing Power of Fuel Taxes, 1956-2009 19

Figure 5. Impact of Selected World Events on Crude Oil Prices (Source EIA) 20

Figure 6. Euro Emissions Criteria for Road Pricing 70

Figure 7. WIM Data Processing 110

Figure 8. Mixed Lognormal PDFs for Single, Tandem, and Tridem Axles 117

Figure 9. Cost Allocation Method for Toll Rate Determination 118

Figure 10. Iterative Pavement Design Process 121

Figure 11. Pavement Construction Cost Responsibility Example 123

Figure 12. Cost Allocation Method for Estimating Cost Responsibilities 132

Figure 13. Case Study Pavement Design Cross-Section 151

Figure 14. Program for Calculating Maximum Live-Load Moment..... 169

Figure 15. Distribution of R for 2 Axle Single Unit Trucks 181

Figure 16. Distribution of R for 5 Axle Semi-Trailer Trucks..... 183

Figure 17. Axle-Load Toll Rates by Class 191

TABLE OF TABLES

Table 1. Federal Highway User Fees, 2005 6

Table 2. Texas State Highway User Fees, 2005..... 8

Table 3. TxDOT General Oversize/Overweight Vehicle Permits, 2005 9

Table 4. Revenues Used for Highways, All Levels of Government, 2005 15

Table 5. Federal Fuel Tax Revenue Distribution 16

Table 6. Federal Fuel Tax Rates, 1956-1997 18

Table 7. Revenue Sources, Texas State Highway Fund, FY2007 23

Table 8. Equity Ratios and Associated Over/Under-Payment Estimates for Selected Truck Classes, 1997 Federal HCA Study 26

Table 9. Equity Ratios by Class and Weight for Selected Truck Classes, 1997 Federal HCA Study 27

Table 10. Equity Ratios for Selected Truck Classes, Texas HCA Study 29

Table 11. Road Pricing Policy Goals 42

Table 12. Truck-Related Road Pricing Policy Goals 43

Table 13. Truck-Related Road Pricing Variables 44

Table 14. VPPP Projects Funded to Date by State and Project Type 45

Table 15. WIM System Cost Comparison 83

Table 16. Cost Categories and Allocation Variables, 1997 Federal HCA Study 96

Table 17. AASHTO Bridge Design Vehicles 103

Table 18. Estimated Parameters for the Mixed Lognormal Distribution 116

Table 19. Matrix Analysis: Vehicle Moment Class vs. Axle Load Class 127

Table 20. Estimated Truck and Passenger Car Volumes, Case Study Facility 143

Table 21. Case Study Truck Profile 145

Table 22. Vehicle and Axle Load Type Estimates, Design Life 146

Table 23. Vehicle and Axle Load Type Estimates, 2008-2015 146

Table 24. Vehicle and Axle Load Type Estimates, 2016 to 2025 147

Table 25. Vehicle and Axle Load Type Estimates, 2026 to 2035 147

Table 26. Vehicle and Axle Load Type Estimates, 2036 to 2037 148

Table 27. Case Study Bridge Statistics 150

Table 28. Case Study Pavement Construction Costs 151

Table 29. Final Construction Cost Estimates 153

Table 30. Final Maintenance Cost Estimates 155

Table 31. Final Load Classes 157

Table 32. Total Common Costs 159

Table 33. Base Common Toll Shares 160

Table 34. Total Pavement Construction Costs 160

Table 35. TxDOT Rigid Pavement Design Input Values 161

Table 36. Pavement Base Toll Share 162

Table 37. Increment Costs for Pavement Construction 162

Table 38. Pavement Construction Toll Shares 163

Table 39. Total Load-Related Pavement Maintenance Costs 164

Table 40. Pavement Maintenance Toll Shares 165

Table 41. Total Bridge Construction Costs 166

Table 42. Relative Costs for Design Bridge Types 166

Table 43. Bridge Type Increment Costs 167

Table 44. Bridge Base Toll Share 168

Table 45. Design Vehicle Live Load Moments 170

Table 46. Bridge Type Design Moment Classification Criteria 171

Table 47. Design Vehicle Moment Class vs. Axle-Load Class Matrix 171

Table 48. Increment Costs for Bridge Construction 172

Table 49. Bridge Construction Toll Shares 174

Table 50. Final Base Toll Rate 174

Table 51. Final Toll Rate per Load 175

Table 52. Time Period Toll Multipliers 175

Table 53. Final Number-of-Axle Toll Rates 176

Table 54. Incremental Pavement Cost Responsibilities 177

Table 55. Incremental Bridge Cost Responsibilities 178

Table 56. Mean Responsibility Ratios 180

Table 57. Toll Rate Dispersion Measures 182

Table 58. Toll Rate Summary 184

Table 59. Truck Share Revenue Sensitivities 185

Table 60. Average Vehicle Type Toll Rates 185

Table 61. Truck Profile Revenue Sensitivites 186

Table 62. WIM Error Sensitivities 188

Table 63. Vehicle Type Toll Rates and Configurations 192

Table 64. Vehicle Class Extreme Tolls 200

CHAPTER 1: INTRODUCTION

In recent years, it has become clear that America's system of road user charging is "broken." At both the federal and state levels, highway system needs are far outpacing available funds for construction, maintenance and operations. While fuel and construction materials have increased in price, the nation's primary source of transportation revenue, the federal fuel tax, has lost value per mile. Excessive demand on insufficient capacity in the nation's urban areas has created gridlock that costs the nation billions of dollars in lost productivity and fuel, and leads to increased harmful vehicle emissions.

Recent research and legislation in the US and abroad indicate a future fundamental shift in the way that roads will be priced. It is likely that fuel taxes, and the other indirect user fees currently employed to recover costs from commercial vehicles, such as oversize and overweight permits and equipment sales taxes, will be replaced or supplemented with a more direct form of user charging – likely a distance-based fee per mile. Three primary system costs will need to be considered in development of these future fees; vehicles will pay more or less depending on their contributions to congestion, their vehicle emissions, and their consumption of highway infrastructure.

The final report of the National Surface Transportation Policy and Revenue Study Commission concluded that for commercial vehicles, this future form of user-charging should "charge trucks based on infrastructure wear and tear".[1] The report also

concluded that with changes in total user fees, freight-specific charges should be adjusted to maintain the "current allocation of highway cost responsibility." However, these two goals are not necessarily compatible. Highway Costs Allocation (HCA) studies performed at both state and federal levels have found that currently, truck user fees do not equitably recover costs from all system users. Looking forward, it is unclear how future mechanisms for truck highway user charging will achieve the necessary gains in equity to ensure sustainable funding for the nation's highway network.

Advanced technologies offer an opportunity to better measure the real impact of individual vehicles. Throughout the world, new technologies are being implemented for real-time road pricing. However, so far, these projects have primarily focused on better recovering congestion costs; those traveling during peak periods or on congested facilities pay a higher fee for the marginal social cost they are imposing on system users. Mechanisms employed for this purpose include area- and cordon-based congestion charges. Managed lanes projects also try to better match user fees with congestion costs; users who choose to pay to use a managed lane must pay a fee for a higher level service. Otherwise, they would have "paid" the fee in lost time and fuel while idling in congestion. This relationship is particularly evident on dynamically priced facilities, where real-time traffic data is used for toll rate variation.

The only advanced mechanism that has been developed to significantly improve recovery of infrastructure consumption costs from trucks is the distance-based truck mile tax. In the US, four states charge a fee per mile for trucks traveling within state

borders; however, for collection of these fees mileage must be self-reported. Recent European applications have employed a variety of technologies, including automatic vehicle identification systems, vehicle monitoring systems, and on-board measurement, for automatic collection of information on vehicle miles traveled, as well as for automatic collection of related user fees. Better measurement of distance traveled will provide some equity improvement, as vehicles traveling more often and over longer distances will pay a higher share of costs.

However, distance is not the only variable that should be measured in estimation of "wear and tear." All trucks do not consume infrastructure at the same rate; vehicles with varying weight and axle configurations will impact pavements and bridges very differently, even when traveling equivalent distances. Distance-based fees, like more traditional forms of truck user charging, distinguish between different classes of trucks based on either gross vehicle weight or vehicle number-of-axles. Neither or these variables alone is a very good indicator of infrastructure consumption. Advanced technologies may also offer a solution here. Weigh-in-motion (WIM) systems, already employed throughout the world for collection of data for planning and for motor vehicle size and weight enforcement, could be employed to capture real-time axle weight and configuration information from individual trucks.

This research explores the possibility for using WIM systems for real-time toll collection. A methodology is proposed to use HCA methods for estimation of a more equitable fee structure that would recover costs from users based on individual axle

weights rather than on vehicle number of axles. WIM systems could then be employed for real-time axle-load classification within the proposed structure. The broader purpose of this research is to begin to answer the question – what future method of truck user charging can be employed to equitably recover infrastructure costs from individual vehicles based on real-time operations?

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[1] *Transportation for Tomorrow: Report of the National Surface Transportation Policy and Revenue Study Commission. National Surface Transportation Policy and Revenue Study Commission, Washington, D.C., January 2008.*

CHAPTER 2: CURRENT MECHANISMS FOR HIGHWAY FUNDING IN THE US

2.1 USER FEES

The first step in identifying an improved method for commercial vehicle highway user-charging in the US is to examine the current system of charges employed at both state and federal levels, as well as on individual highway facilities. Through this examination, the current rate variables used to distinguish between classes within existing charging structures can be identified. Additionally, these methods of charging can be evaluated to determine the weaknesses that prevent existing user fees from providing adequate revenue for system operations. This chapter provides an overview of the current methods employed by federal and state government entities, as well as public and private toll road operators, to recover costs from truck users.

2.1.1 Federal User Fees

The highway system in the United States is primarily funded at both federal and state levels through a series of indirect user fees. The main federal source of highway user revenue is the fuel tax, which imposes a cent per gallon fee on different fuel types. The rates of this tax for gasoline, diesel, and alternative types of fuel are shown in Table 1.[2] In addition to federal fuel taxes, other federal highway user fees for commercial vehicles include sales taxes on certain tires, trucks, tractors, and trailers, and a heavy vehicle use tax annually charged to large trucks based on registered gross vehicle weight

(GVW). Detailed information on the rates and requirements governing these fees are also provided in Table 1.

Table 1. Federal Highway User Fees, 2005
(Source: Table FE-21B, Highway Statistics 2005)

Fee	Rate
Fuel Taxes	**cents/gallon**
Gasoline	18.4
Gasohol	18.4
Diesel and Kerosene	24.4
Liquefied Petroleum Gas	13.6
Liquefied Natural Gas	11.9
Other Special Fuels	18.4
Neat Alcohol	9.25
Compressed Natural Gas	4.3
Other Taxes	
Tires	Tax is imposed on tires sold by manufacturers, producers, or importers at the rate of $.0945 ($.04725 in the case of a bias ply or super single tire) for each 10 pounds of the maximum rated load capacity over 3,500 pounds.
Truck and trailer sales	12 percent of retailer's sales price for tractors and trucks over 33,000 pounds gross vehicle weight (GVW) and trailers over 26,000 pounds GVW. The tax applies to parts and accessories sold in connection with the vehicle sale.
Heavy vehicle use tax	Trucks 55,000-75,000 pounds GVW: $100 plus $22 for each 1,000 pounds (or fraction thereof) in excess of 55,000 pounds. Trucks over 75,000 pounds GVW: $550

2.1.2 State User Fees

At the state level, the primary source of user revenue is the state fuel tax. All 50 U.S. states and the District of Columbia charge a volume-based state fuel tax, although heavy trucks paying the weight-mile tax (WMT) in Oregon do not pay state tax on diesel fuel.

For diesel fuel, state tax rates vary from a high of 38.1 cents per gallon in Pennsylvania to 7.5 cents per gallon in Georgia, with a national average cost of 21.8 cents per gallon.[3] The Texas fuel tax rates of 20 cents per gallon on both gasoline and diesel are very close to this average. Fifteen states tax diesel fuel at a higher rate than gasoline, while 26 states and the District of Columbia tax diesel and gasoline at the same rate. The remaining 9 states tax gasoline at a higher rate than diesel. Some states also charge an additional sales tax on fuel. In some states, local municipalities can levy their own local fuel taxes.[4] At the state level, highway user fees are also collected through licensing fees, vehicle registration fees, heavy vehicle permits, sales tax on motor fuel, and toll road operations. In Texas, user fees for commercial vehicles on non-tolled facilities include vehicle registration fees, sales tax on motor oil, and a series of overweight and over-dimensional permits (Table 2).[5]

Table 2. Texas State Highway User Fees, 2005
(Sources: Highway Statistics 2005, Texas Highway Cost Allocation Study)

Fee	Rate
Fuel Taxes	**cents/gallon**
Gasoline	20
Gasohol	20
Diesel	20
Liquefied Petroleum Gas	15
Other Fees	
Registration	Combination Trucks: $148 - $840 (varies by weight). Semi-trailer: $15. Full trailers assessed according to weight: approximately $225.*
Motor Oil Sales Tax	Texas State Sales tax of 6.25 percent collected on motor oil purchases. Additional city or county taxes up to total state and local tax of 8.25 percent may be collected.
Overweight/Over-Dimension Permits	See Table 3 for permit types and costs.
* Estimated in Texas Highway Cost Allocation Study.	

Overweight and over-dimensional vehicle permits may be issued for single trips, for short time periods (30-90 days), or annually. Permits may also be issued for both divisible and non-divisible loads. The complete list of available permits for the state of Texas is provided in Table 3.[6] As many of these permits are offered at a fixed cost and apply over lengthy time periods, the actual distances traveled and operating weights of vehicles traveling under the same permit types likely vary considerably.

Table 3. TxDOT General Oversize/Overweight Vehicle Permits, 2005
(Source: TxDOT)

Permit Type	Requirement	Cost ($)	Valid
General Single Trip Permit	Vehicle or load exceeds legal size and weight limits	30*	One origin to destination trip
General Single Trip Mileage Permit	Vehicle or load exceeds legal size and weight limits	31 (minimum)	Max 7 days. Vehicle may return to origin on same permit.
30 Day Overwidth/ Overlength Permit	Oversize load traveling on state-maintained roads	60	30 days from begin date
60 Day Overwidth/ Overlength Permit	Oversize load traveling on state-maintained roads	90	60 days from begin date
90 Day Overwidth/ Overlength Permit	Oversize load traveling on state-maintained roads	120	90 days from begin date
Vehicle Specific Annual Envelope Permit	Oversize load (with specific dimensions) traveling on state-maintained roads. Only valid for commodities unable to be reasonably dismantled	2,000	1 year
Company Specific Annual Envelope Permit	Oversize load (with specific dimensions) traveling on state-maintained roads. Only valid for commodities unable to be reasonably dismantled	2,000	1 year
Annual Over Axle/Over Gross Weight Tolerance Permits	Vehicle weight exceeds allowable axle weight by less than 12% for agricultural commodities or 10% for non-agricultural commodities	205 - 2,080 (varies by # of counties)	1 year
Super Heavy Vehicle/Load Single Trip Permit	Vehicle weight exceeds 254,300 lbs gross weight, exceeds maximum weight on any axle or axle group, or exceeds 200,000 lbs with less than 95 feet axle spacing	155 + vehicle supervision fee	One origin to destination trip
WASHTO Permit	Optional for multi-state travel of oversize/overweight vehicles	Varies by route	One origin to destination trip (max 5 days)

* Vehicles over 80,000 lbs must pay additional road maintenance fees

Four U.S. states, Kentucky, New Mexico, New York, and Oregon, currently charge a distance-based tax on heavy vehicles (Figure 1). Truck operators are required to self report total mileage traveled in the state and pay a fee per mile. In Kentucky, this

charge is simply a flat rate per mile for all trucks over 60 kilopounds (kips).[7] In New Mexico the rate is graduated based on maximum registered gross vehicle weights; the fee per mile increases for each 2000 pound weight class up to the federal weight limit of 80 kips, after which it is constant.[8] In New York, the fee is also graduated by GVW, although the rate increases up to 105.5 kips, the maximum weight of a permitted vehicle.[9] New York is the only state that distinguishes empty truck trips from loaded truck trips, so trips made when the truck is empty and lighter pay a lower fee. Oregon is the only state that distinguishes between vehicles by number-of-axles.[10] For trucks greater than 80,000 pounds the distance based fee per mile actually decreases for each additional axle.

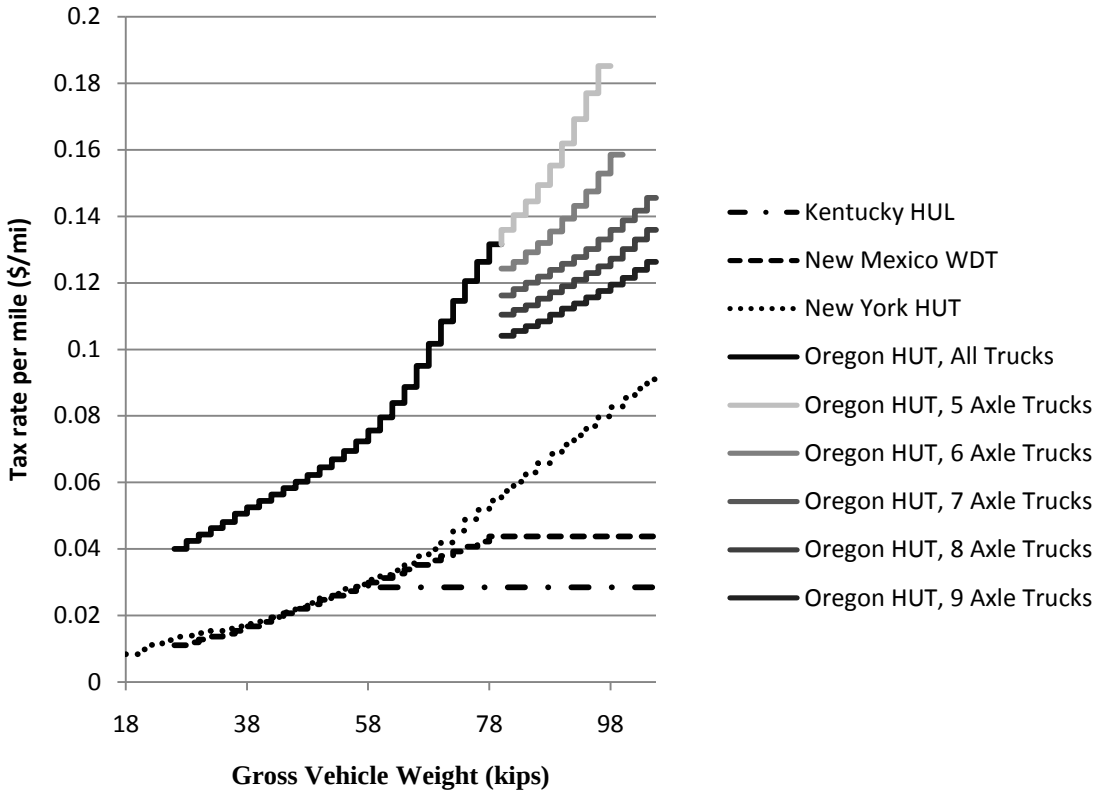
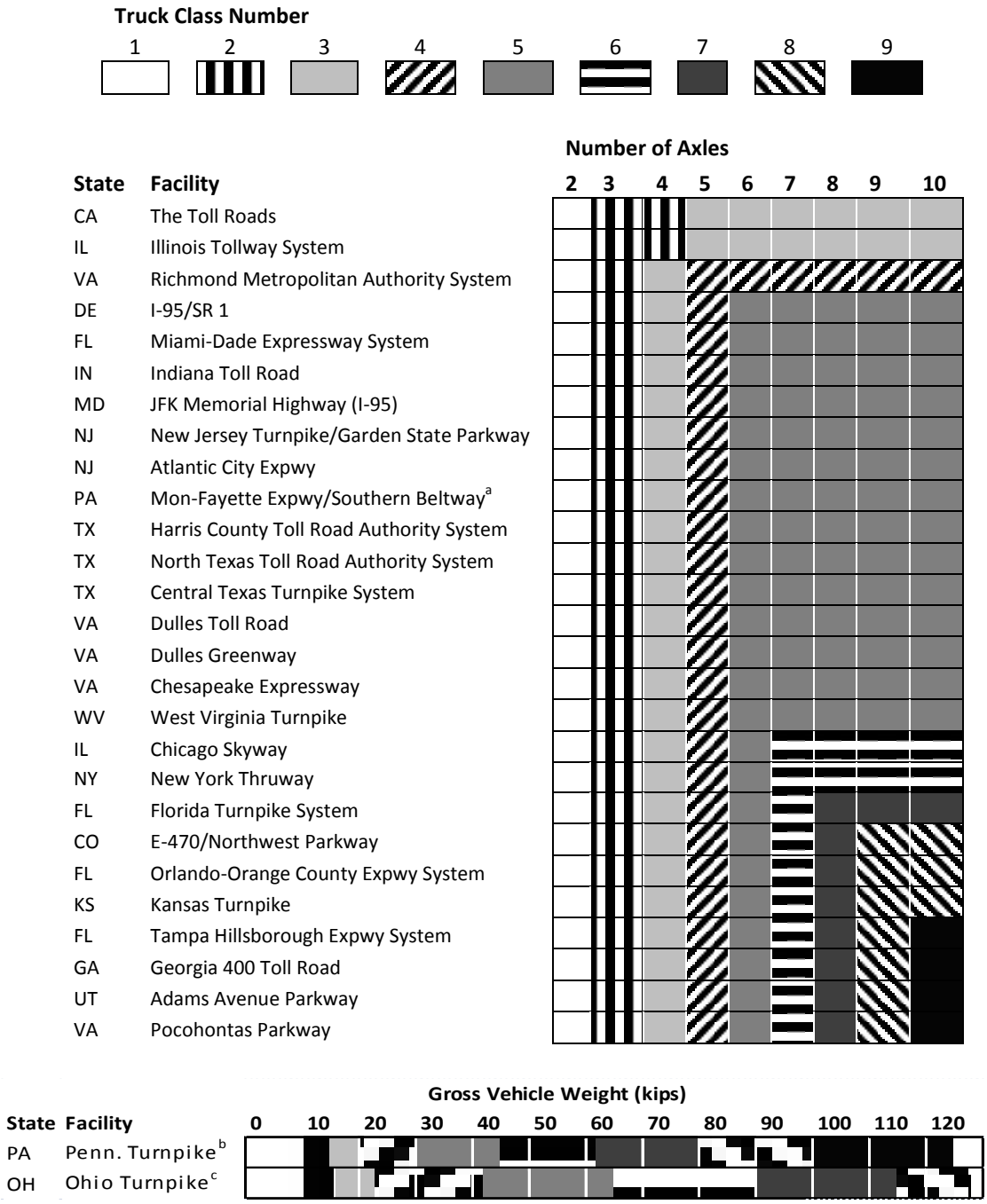


Figure 1. US State Weight-Distance Taxes

2.1.3 Toll Road User Fees

Toll road and bridge facilities are currently operational in 31 states.[11] Although the role of the private sector in providing transportation facilities in the U.S. is increasing, the majority of tolled facilities are operated by public entities. A few states receive a considerable portion of their total state user revenues from toll roads and bridges. The states of Florida and New Jersey both receive more than 15 percent of their transportation user revenues from tolling, and Illinois, Pennsylvania, and Texas collect between 5 and 10 percent of user revenues through direct tolling.[12]

Toll roads and bridges usually define separate rates for different types of vehicles. In the U.S., most toll roads establish user rates for trucks based on vehicle number-of-axles, with vehicles paying a higher toll for each additional axle, regardless of vehicle weight (Figure 2).[13] As the figure shows, number-of-axle based toll rate structures vary from as few as three classes to systems where each additional axle is tolled. Figure 3 demonstrates the estimated toll rates per mile for selected US toll roads. It is clear that there is significant variability in the rates per mile paid on these facilities. Those facilities operated by private operators in congested regions, including the Pocahontas Parkway, 73 Toll Roads, and Chicago Skyway, charge higher tolls across all classes. A few toll facilities, including the Ohio and Pennsylvania Turnpikes, establish toll rates for heavy vehicles based on gross vehicle weight (GVW) (Figure 2). On these facilities, heavier vehicles pay a higher rate per mile, regardless of axle configuration.



a The Mon-Fayette Expressway and Southern Beltway are part of the Pennsylvania Turnpike System, however they use a different toll rate structure than other components

b Includes all components of the Pennsylvania Turnpike System except the Mon-Fayette Expressway, the Southern Beltway, and Turnpike 66.

c Classes 7 and 8 are LCV only and require a special permit

Figure 2. Basic Rate Structures for US Toll Roads

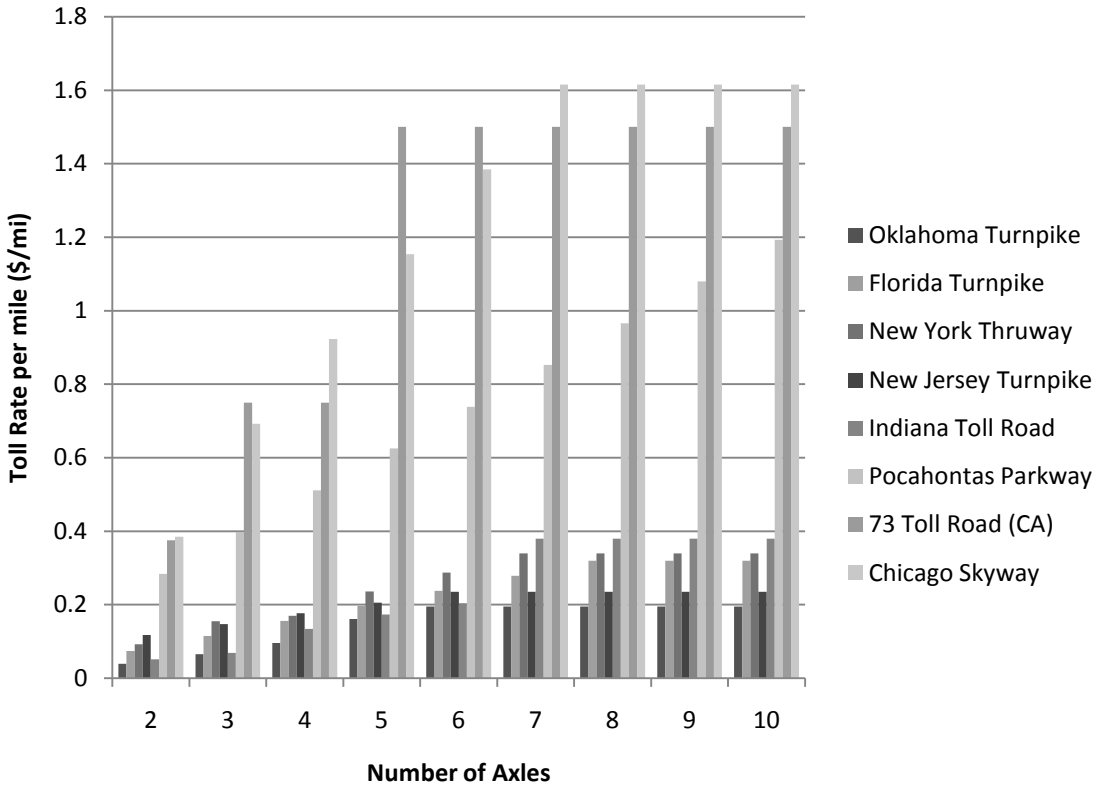


Figure 3. Estimated Toll Rates per Mile for Selected US Toll Roads

2.2 USER FEE REVENUES

In 2005, total highway user fee receipts for all levels of government in the U.S. totaled $114.6 billion.[14] After redistribution of funds for collection expenses, mass transit, and other non-highway purposes, total revenues available for highway purposes totaled $90.3 billion. About 91 percent of these revenues were collected through motor fuel and vehicle taxes (Table 4). Overall, direct tolling revenues contributed about 9 percent of highway user fees. All of these toll revenues were collected at the state level and by local governments. Toll revenues contribute about half of all user-fees collected

at the local level, which likely reflects the difficulty of levying user taxes or requiring vehicles to purchase permits for use of local facilities. The $90.3 billion in user-fees collected by all levels of government totaled about 59 percent of total highway disbursements for 2005. Additional sources of income providing highway revenue included non-highway state and local taxes such as property taxes, appropriations from general funds, investment income, and bond proceeds.

Table 4. Revenues Used for Highways, All Levels of Government, 2005
(Source: Table FE-21B, Highway Statistics 2005)

Source	Percent of Total Highway User Revenues			
	Federal	State	Local	Total
Motor-Fuel and Vehicle Taxes	35	54	2	91
Tolls	0	7	2	9
Total	35	61	4	100

2.2.1 Federal User Fee Revenues

At the federal level, the vast majority of user fees are deposited to the Highway Trust Fund, which was established through the Highway Revenue Act of 1956 as the nation's dedicated source of highway funding.[15] In their report *The Fuel Tax and Alternatives for Transportation Funding*, the Transportation Research Board (TRB) Committee for the Study of the Long-Term Viability of Fuel Taxes for Transportation Finance described the Highway Trust Fund as a "bookkeeping device to make apparent the relation of user fee collections to spending."[16] Receipts from the federal fuel taxes are divided between the Highway Account and the Mass Transit Account of the Highway Trust Fund (HTF), and the Leaking Underground Storage Tank Trust Fund. The percentage of tax distributed to each fund varies based on fuel type (Table 5).[17] In

2005, Highway Trust Fund Receipts from user fees totaled about $39.5 billion, of which $32 billion was deposited to the Highway Account and $7.5 billion to the Mass Transit Account.[18] Total Highway Account expenditures in 2005 totaled $33.1 billion. $31.5 billion was distributed to states as federal aid to the National Highway System; the remainder was distributed directly to U.S. Department of Transportation (DOT) and other federal agencies.

Table 5. Federal Fuel Tax Revenue Distribution
(Source: Table FE-21B, Highway Statistics 2005)

Fee	Highway Trust Fund		Leaking Underground Storage Tank T.F.
	Highway Account	Mass Transit Account	
Fuel Type	**cents/gallon**		
Gasoline	15.44	2.86	0.1
Gasohol	15.44	2.86	0.1
Diesel and Kerosene	21.44	2.86	0.1
Liquefied Petroleum Gas	11.47	2.13	0.0
Liquefied Natural Gas	10.04	1.86	0.0
Other Special Fuels	15.44	2.86	0.1
Neat Alcohol	7.72	1.43	0.1
Compressed Natural Gas	3.44	0.86	0.0

The most recent transportation funding bill passed in congress, the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU), signed on August 10, 2005, guaranteed $224.6 B in highway funding for FY 2004 to 2009. The bill defined annual guaranteed funding limits for each year, starting at $34.4 billion in 2004, and including 4.4 percent annual increases in spending.[19] However, due to inflation and related increases in costs of construction, real annual growth is only about 1.8 percent. Overall, SAFETEA-LU fell more than $88 billion short of U.S.DOT

estimates to simply maintain and operate the existing system. As the 2005 figures above demonstrate, Highway Account disbursements are exceeding receipts; as a result, the balance in the Highway Trust Fund has been steadily declining in recent years. The U.S. Department of Treasury and the Congressional Budget Office projected that the Highway Account will reach a balance of negative $4 to $5 billion by the end of fiscal year 2009.[20] Although this negative balance may not have an immediate impact on highway funding since the HTF can borrow from the General Fund to meet expenses in the short term, a precedent of borrowing general revenues may negatively impact future legislation.[21]

It is clear from the declining health of the Highway Trust Fund that the existing system of user-charging through indirect fees is not achieving adequate revenue for the continued operation and maintenance of the nation's highway network. Many user fees, including the federal fuel tax, have not been indexed for inflation; as a result, fees charged at the same rate have lost value per mile.[22] Table 6 shows the progression of federal gasoline and diesel tax rates since the Interstate Highway Act of 1956.[23] Figure 4 demonstrates the purchasing power of these rates as an equivalent share of a 2009 dollar; these values were estimated using the Consumer Price Index issued by the Bureau of Labor Statistics.[24] Since 1997, when the 4.3 cents of the tax previously deposited to the General Fund was dedicated to the HTF, the fuel tax rate has remained constant, while the purchasing power of the dollar has decreased by nearly 25 percent. As can be seen from the graph, the purchasing power of diesel tax revenue reached its

peak in 1993, and has been steadily declining since as a result of inflation (although the economic downturn has slightly reversed the impact of inflation for 2009). Even if vehicle fuel efficiency remained constant, the amount of construction and maintenance that can be funded through fuel tax revenues has decreased.

Table 6. Federal Fuel Tax Rates, 1956-1997
(Source: Table FE-101A, Highway Statistics 2007)

Year	Fuel Tax Rate ($)	
	Gasoline	Diesel
1956	0.030	0.030
1959	0.040	0.040
1983	0.090	0.090
1984	0.090	0.150
1987	0.091	0.151
1990	0.141	0.201
1993	0.184	0.244
1994	0.184	0.244
1995	0.184	0.244
1996	0.183	0.243
1997	0.184	0.244

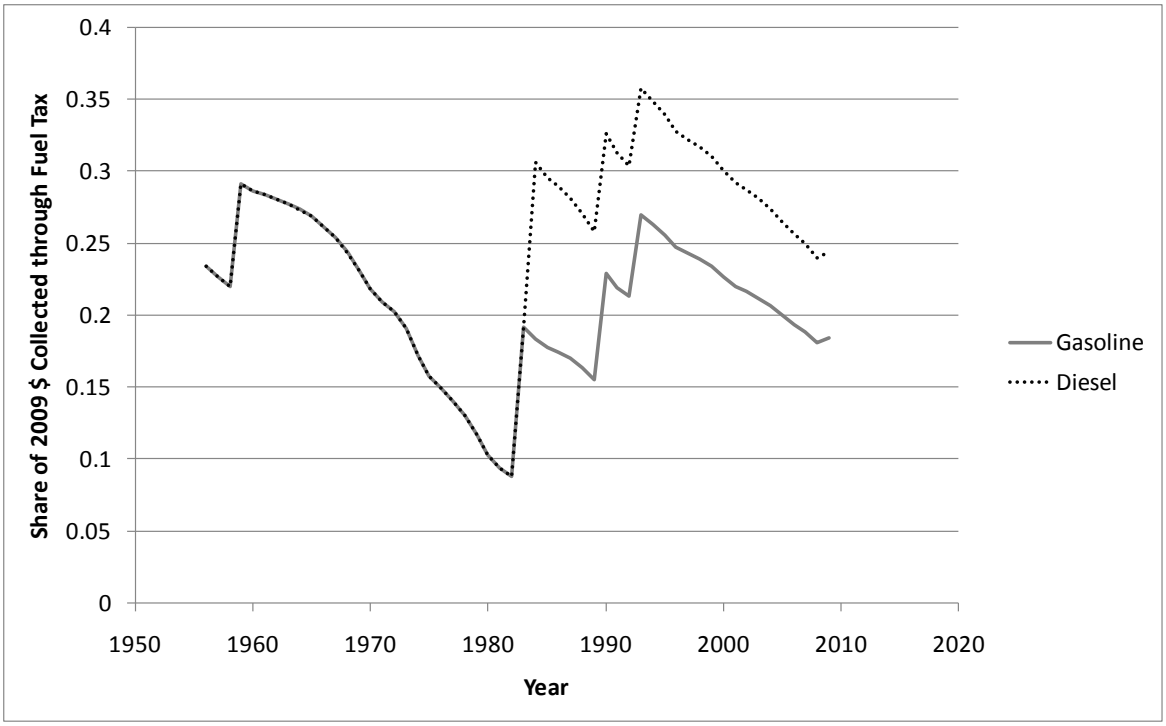


Figure 4. Purchasing Power of Fuel Taxes, 1956-2009

In addition to its decreasing value per vehicle mile due to inflation, the primarily fuel tax-based system of user fees is subject to uncertainties in both demand and supply.[25] Since fuel availability for the U.S. is dependent on international supply as well as demand elsewhere in the world, future prices are subject to international influence. Figure 5 demonstrates the impact of selected world political, economic, and natural events on crude oil prices, as well as the considerable growth in the cost of crude oil.[26]

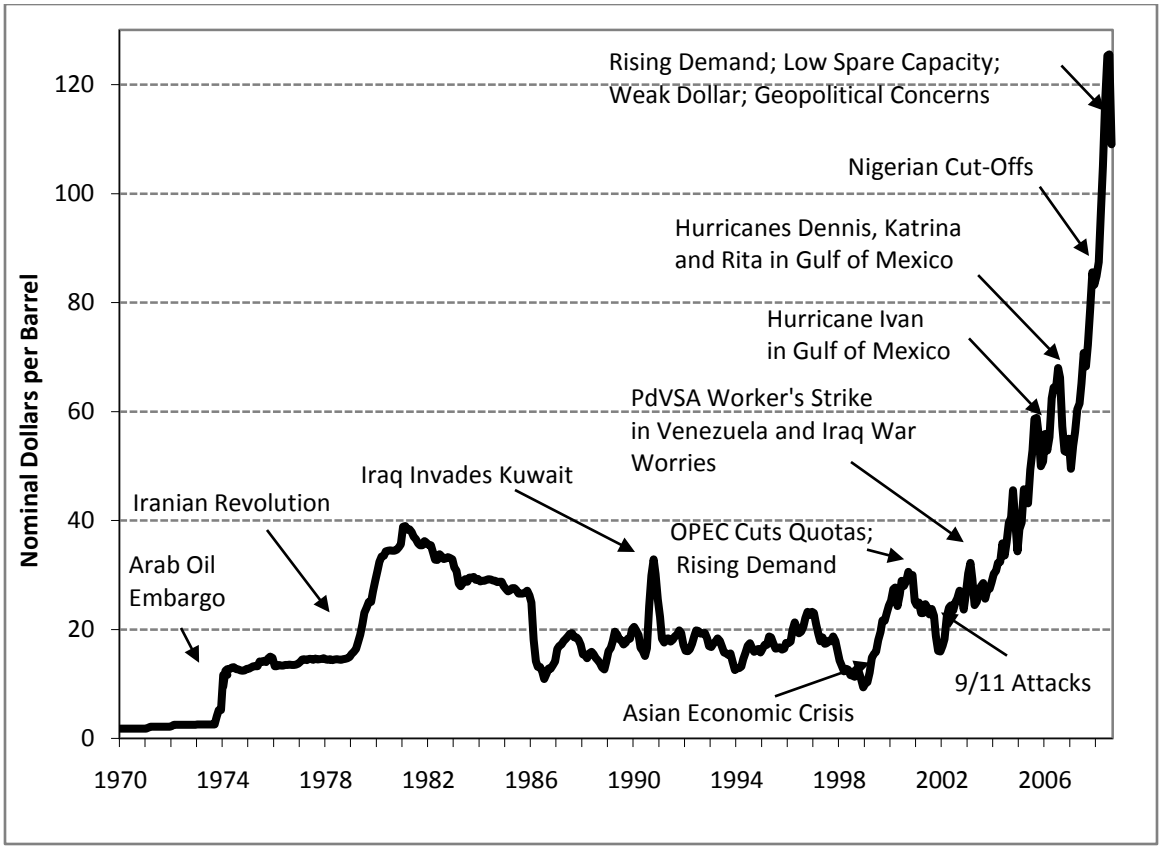


Figure 5. Impact of Selected World Events on Crude Oil Prices
(Source: Energy Information Administration 2009)

As the recent rise in fuel costs in the summer of 2008 demonstrated, when gas prices rise, system users may choose to switch their travel to other modes. Although this result may be desirable for the operational efficiency of the nation's multimodal transportation system, it leads to a real decrease in available funding to operate and maintain the highway system. Also, according to the American Road and Transportation Builders Association's Highway Construction Producer Prices, between 2004 and 2009, the costs of highway construction materials increased by nearly 40 percent.[27]

Additionally, future technology improvements that will improve vehicle fuel economies and increase the market share for alternative-fueled vehicles are difficult to predict. Although current projections do not predict that either price increases or technology improvements will "have a dramatic effect on fleet average fuel economy by 2025," according to the TRB Committee for the Study of the Long-Term Viability of Fuel Taxes for Transportation Finance, "reducing the risk of unintended funding disruptions in the future might be a worthwhile goal of reforms to the transportation finance system."[28]

While the cost of travel per mile is decreasing, use of the system, and as a result, congestion, is rapidly increasing. According to the 2007 Texas Transportation Institute (TTI) Urban Mobility Report, congestion in America's 437 urban areas costs drivers $78 billion in wasted time and fuel.[29] Traffic volumes are only expected to continue to increase. Freight traffic is expected to grow at an even faster rate than passenger traffic. According to a 2003 study by the TRB Committee for the Study of Freight Capacity for the Next Century, highway freight traffic is expected to increase 40 percent from 2003 levels by 2020.[30] While in the U.S., the overall ratio of receipts to expenditures for highways is close to 1:1, in Western Europe, revenues on average exceed expenditures 2:1, and in some countries, outpace expenditures at a rate of 3:1.[31]

The need to establish federal user-fees that achieve adequate revenues for system maintenance and improvement is especially important when considering the Revenue Aligned Budget Authority (RABA) created under TEA-21, the 1998

transportation bill that preceded SAFETEA-LU.[32] When it was introduced in TEA-21, RABA set the annual guaranteed funding limit for highways equal to estimated Highway Account receipts from the previous year. If actual account receipts differed from projections used to establish funding limits, RABA automatically increased or decreased guaranteed funding limits using a formula based on the previous year's revenues and projected revenues for a future budget year. Under SAFETEA-LU, RABA was adjusted so that the new funding level would be calculated based on the previous year's revenues and the estimate for the current year rather than a future budget year. If account receipts are lower than projected revenues and the RABA adjustment is negative, funding will not be reduced if the balance of the HTF is more than $6 billion. However, as the balance is projected to fall below $6 billion during fiscal year 2009, funding for 2009 could be reduced, and inclusion of RABA in a future transportation funding bill could further threaten future funding.

2.2.2 State User Fee Revenues

Most states have finance arrangements "analogous" to those at the federal level, including fuel tax revenues deposited to a dedicated transportation fund.[33] Only Alaska, Georgia, and the District of Columbia deposit highway user fees to a general fund. In Texas, the dedicated account for highway funding is the State Highway Fund (SHF). The sources of revenue to this fund and their levels of contribution during the fiscal year ending in August 2007 are provided in Table 7.[34] The Texas Mobility Fund, which

contributed 21 percent of revenues, is a special fund established in 2001 which allows the state to issue bonds secured by future revenue from the state's toll roads.

Table 7. Revenue Sources, Texas State Highway Fund, FY2007
(Source: TxDOT 2007)

Source	Percent
State Fees, Taxes, and Other	40
Federal Reimbursements	24
Texas Mobility Fund Reimbursements	21
Bonds/Notes Issued	13
Local Contributions	2

Although more recent figures are not available, the percentages of user fee revenues from various sources are likely similar to the 2005 figures, when 51 percent of state user revenues were collected through fuel taxes, 44 percent were from motor vehicle and motor carrier fees, and five percent were collected as direct tolls.[35] State fuel taxes, in general, have better maintained value per vehicle mile than federal fuel taxes, as many states do have fuel tax rates that are automatically adjusted for inflation or that are tied directly to fuel prices.[36] However, while state fees may produce revenues that better recover vehicle costs, these revenues are often diverted for non-highway purposes. In Texas, not all highway user fees are reserved for transportation projects through the SHF. While 72 percent of motor fuel taxes are deposited to the SHF, 24 percent are dedicated for the state's public schools.[37] Similarly, while 69 percent of motor vehicle registration fees are deposited to the SHF, 31 percent are returned to individual counties.

Just as federal transportation funds are falling short of needs, the state of Texas is also lacking the available funding to maintain and provide necessary capacity expansion. According to the 2005 ASCE Infrastructure Report Card, between 1991 and 2002, population in Texas grew by 28 percent and state vehicle miles traveled (VMT) grew by 48 percent, while road capacity only grew by 3 percent.[38] As a result of the state's rapid growth and resulting transportation needs, the Texas Transportation Commission can only provide funding for 40 percent of projects deemed "worthy."

Although in recent years the state has developed a number of innovative methods to address funding shortfalls and streamline construction practices, including establishment of the Texas Mobility Fund, use of design-build Comprehensive Development Agreements, and signing long-term lease agreements with private operators, needs are still far outpacing available funds at the state level. Additionally, the legislature passed a moratorium through September 1, 2009 on public-private partnerships for toll road delivery to allow for review of pending projects and their potential implications for the state; it is unclear how this review will impact the long-term role of private operators in Texas.[39]

2.3 USER FEE EQUITY

2.3.1 Federal User Fee Equity

In addition to failing to provide adequate revenue at both federal and state levels, existing highway user fees are becoming increasingly inequitable for both

passenger and commercial traffic. Recent development of more fuel efficient vehicles has increased the variability of the cost per mile paid through the fuel tax paid by vehicles operating on the U.S. highway network. According to Department of Energy estimates, freight traffic VMT will grow by 70 percent between 2006 and 2025, while truck fuel efficiency will improve by nine to 10 percent per mile over the same period.[40] As a result, truck VMT will grow at a faster rate than truck fuel consumption, and as a result the percentage of user fee payments collected through truck fuel taxes will decline.

The 1997 Federal Highway Cost Allocation (HCA) Study examined the equity of existing user fees both within and between 13 FHWA vehicle classes and identified sources of inequity.[41] Equity ratios were calculated to examine the ratio of share of user fees paid to share of cost responsibilities for each class . While the total ratio of user revenues to costs was close to one, the study found that overall, commercial trucks do not contribute user fee revenues adequate to cover their share of cost responsibilities for construction, maintenance, operations, and agency costs. While the equity ratio for passenger vehicles was found to be about 1.1, the ratios for both single-unit trucks and combination trucks were about .9. Within these broad vehicle classifications, however, it is clear that while many truck classes do pay less than their share of user costs, some classes actually pay more than their share (Table 8). An examination of equity ratios for vehicles of varying weights operating within each of these vehicle classes reveals further inequity: in each class, the lightest vehicles pay considerably more than their share of

user costs, while the heaviest vehicles pay much less than their share (Table 9). One source of this inequity within the vehicle classes is the Heavy Vehicle User Tax (HVUT) (Table 1). Although the rate of this tax increases for additional gross vehicle weight for trucks between 55 thousand and 75 thousand pounds, the rate is capped at $550 annually for all vehicles over 75 thousand pounds; as a result, the heaviest trucks operating on US highways are not charged incrementally for their additional weight. Since trucks pay a higher percentage of their user fees through non mileage-based fees than passenger vehicles, as truck VMT continues to increase, truck equity ratios will only decrease.

Table 8. Equity Ratios and Associated Over/Under-Payment Estimates for Selected Truck Classes, 1997 Federal HCA Study

(Source: FHWA 1997)

Class	Equity Ratio	Over/Under-payment ($1000)
2 Axle Single Unit	1.20	297784.00
3 Axle Single Unit	0.60	-306739.00
4+ Axle Single Unit	0.50	-11115.00
5 Axle Semi-Trailer	0.90	-692624.00
6 Axle Semi-Trailer	0.80	-134212.00
5 Axle Twin Trailer	**1.00**	3499.00
6 Axle Twin Trailer	1.30	11188.00
8 Axle Twin Trailer	0.80	-22659.00
7 Axle Triple Trailer	0.80	-2141.00

Table 9. Equity Ratios by Class and Weight for Selected Truck Classes, 1997 Federal HCA Study

(Source: FHWA 1997)

Reg. Weight (1000 lbs.)	SU2	SU3	SU4+	5 Ax. ST	6 Ax. ST	5 Ax. Twin	6 Ax. Twin	8 Ax. Twin	7 Axle Triple
0-10	1.7								
20	1.5	2.0							
30	**1.0**	1.9	4.3						
40	0.5	1.4	3.3						
50	0.2	0.8	1.2	1.9	2.7				
60		0.5	0.7	1.6	2.3	1.4			
70		0.3	0.5	1.1	1.6	1.1	1.7		1.7
80		0.2	0.4	0.9	1.1	**1.0**	1.4	1.6	1.4
90			0.4	0.5	0.6	0.9	1.1	1.3	1.1
100			0.4	0.5	0.5	0.9	**1.0**	1.1	0.9
110					0.3	0.8	0.9	**1.0**	0.7
120					0.3		0.8	0.8	0.6
130							0.8	0.7	0.5
140								0.6	
150								0.5	0.4
Overall	1.2	0.6	0.5	0.9	0.8	**1.0**	1.3	0.8	0.8

Although the purpose of the federal HCA Study was not to identify a more equitable source of user fee revenues, researchers did perform basic evaluation for potential solutions, including increasing the rate of the diesel fuel tax, restructuring the HVUT, and introduction of a federal weight-distance tax (WDT).[42] Their analyses found that while each of these solutions could achieve some improvements in "vertical" equity between vehicle classes, they caused new inequities within the classes between vehicles of different weights and distances traveled. Introducing a higher diesel tax would reduce the "under-payment" of the single unit and combination trucks currently paying less than their share, but increase the "over-payment" of the lightest vehicles within

these classes. Restructuring of the HVUT to more closely equate costs with weight and removal of the 75 thousand pound cap could achieve considerable gains in equity between truck classes and between weight classes within each class. However, raising the rates of the HVUT could increase the disparity between the per-mile user fees paid by vehicles with different annual VMT. The most promising solution examined was introduction of a WDT. Two rate structures were considered: 1) registered weight and 2) registered weight and number-of-axles. While both rates achieved some equity gains, the structure which considered both registered GVW and number-of-axles was most successful, especially for single unit trucks.

2.3.2 State User Fee Equity

The Federal HCA study suggested that since a primary source of inequity in federal user fees is the HVUT, state user fees provide better mechanisms for equitable cost recovery. Overall, state highway cost allocation studies have found considerable variability on equity for truck users. A review of 26 state HCA studies performed between 1982 and 2007 found that in 6 states, heavy vehicles paid less than 60 percent of their share of costs, while in 3 states, trucks paid more than their share of costs.[43] The most recent Texas HCA Study suggests that, at least in Texas, equity is not much better when additionally considering state user fees (Table 10).[44] Methodologies employed in these federal and state HCA studies are discussed in detail in Chapter 5. It is clear in Table 10 that most truck classes are still paying shares of user fees very different than their cost responsibilities. Only one of the examined vehicle classes, two-

axle single unit trucks, pays more than its share under four of the five allocation methods. Nearly all of the truck classes are estimated to pay considerably less than their share of user costs, and the largest vehicle class, seven+-axle multi-trailers, pay only about one-fifth to one-third of their cost responsibilities.

Table 10. Equity Ratios for Selected Truck Classes, Texas HCA Study
(Source: Texas HCA)

Class	Generalized Method	Modified Incremental Analysis	Proportional ESALs	Variable # Lanes	FHWA State HCA Software
2 Axle Single Unit	1.26	1.11	1.04	1.19	0.94
3 Axle Single Unit	0.73	0.68	0.51	0.68	0.75
4+ Axle Single Unit	0.62	0.71	0.41	0.25	0.18
4- Axle Semi-Trailer	1.02	0.96	0.75	0.86	1.13
5 Axle Semi-Trailer	0.58	0.6	0.5	0.67	0.62
6+ Axle Semi-Trailer	0.65	0.66	0.48	0.45	0.44
5- Axle Multi-Trailer	0.55	0.55	0.44	0.46	1.18
6 Axle Multi-Trailer	0.72	0.81	0.61	0.33	1.51
7+ Axle Multi-Trailer	0.26	0.36	0.33	0.21	0.26

2.3.3 Toll Road Equity

Even on toll road facilities, where trucks are charged directly for their use, considerable inequities likely exist between the rates paid by vehicles and the costs of infrastructure consumption and contributions to congestion for vehicles within these classes. Although little research has been done to examine the equity of existing toll road fee rate structures, a nation-wide study examining toll rates by Holguin-Veras et al. concluded that, in general, commercial vehicles are over-charged relative to their facility use.[45] However, this study could not provide a clear result of whether equity was achieved between and within individual vehicle classes on U.S. toll facilities. As

described in the Toll Road User Fee section of this report, most toll facilities in the U.S. define their rate structures based on vehicle number-of-axles. A few facilities also define toll rates based on vehicle GVW. Neither of these variables provides a good measure of either infrastructure consumption or contribution to congestion. While in general heavy vehicles cause more pavement and bridge damage than lighter vehicles, the distribution of that weight over different numbers and configurations of axles can considerably change the impact of that weight on bridge and pavement infrastructure. Similarly, more axles do not necessarily equate to more infrastructure damage; the addition of an axle to a vehicle carrying a certain amount of weight can actually reduce the impact of that weight on a pavement.

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CHAPTER 3: FUTURE MECHANISMS FOR HIGHWAY FUNDING

3.1 USER FEE ALTERNATIVES

In recent years, inadequacies and inequities in existing user fee structures have become widely acknowledged. A number of recent traffic, freight, and economic studies have recognized the need for new user charging mechanisms to address congestion, improve equity, and raise revenues. In defining solutions to the nation's congestion problems, the TTI Urban Mobility Report calls for adding capacity, changing highway usage patterns, and providing highway users with travel options.[46] With existing funding shortages, providing needed capacity improvements will require innovative funding mechanism, including direct tolling, on both publicly and privately operated facilities. Both changing highway usage patterns and providing users with travel options can be achieved with road pricing. Already, variable tolls (which will be discussed in detail in the next section) are encouraging travelers to move unnecessary trips to less expensive off-peak hours. Similarly, express lanes and high-occupancy toll (HOT) lanes are providing travelers in congested urban areas with more reliable routes in exchange for additional user fees.

In TRB Special Report 271, which examined the freight capacity of the nation's highway network, researchers concluded that "the best way to control all the costs of accommodating existing and future traffic is by coordinating practices in engineering, highway user regulations, and highway user fees".[47] Establishment of user fees more

closely aligned to actual infrastructure consumption and contributions to congestion would allow for better recovery of costs due to trucks and encourage efficient truck operations and use of road-friendly vehicle configurations and technologies. Reducing the under-payment of commercial traffic for road use would provide additional revenues to improve existing facilities and provide additional passenger and freight capacity. Truck-only facilities, which could be provided in the form of managed Truck-Only Toll (TOT) lanes or separate toll roads, could eliminate some of the safety concerns that have prevented the operation of longer-combinations vehicles (LCVs) on most U.S. highways by separating freight and passenger traffic.[48] These facilities could provide more reliable routes on which trucks, including more productive LCVs, could operate.

A U.S. DOT study of the *Issues and Options for Increasing the Use of Tolling and Pricing to Finance Transportation Improvements* concluded that currently, highway travel is viewed as an "un-priced commodity" to users, especially passenger vehicles.[49] Although vehicles operating on congested highways actually do accrue significant costs in wasted time and fuel, since these vehicles are currently operating on facilities that have "zero perceived cost" users recognize little impetus to change their travel behavior. The study suggests that in order to encourage efficient operations, vehicle operators must recognize the costs that they are imposing on the system through their highway use. In order to achieve this recognized cost, a system of "market-based" pricing reflecting each vehicle's highway use should be imposed on the system. In its publication "Transportation Vision for 2030: Ensuring personal freedom and economic

vitality for a Nation on the move," the Research and Innovative Technologies Administration (RITA) of the U.S. Department of Transportation was even more specific in its call for cost-based pricing of road use on all highways.[50]

In *TRB Special Report 285: The Fuel Tax and Alternatives to Transportation Funding*, the TRB Committee for the Study of the Long-Term Viability of Fuel Taxes for Transportation Finance specifically examined the future of the fuel tax and examined alternatives for future transportation financing.[51] While the committee concluded that some revenue improvements could be made by increasing fuel taxes in the short term, they also concluded that in order to address long term transportation financing needs, new user charging methods must be implemented. The study identified road metering and mileage charging as the highway user fee of the future, and recognized that toll roads and toll lanes must play an important role in transitioning between the current fuel-tax based system and the future cost-based system. In addition to potential gains in financial efficiency and equity, the committee identified using cost-based revenues to identify capacity expansions that would provide maximum benefits as an additional benefit to system-wide road pricing.

The need to examine alternative methods for highway user charging and transition to more direct methods was recognized in the SAFETEA-LU legislation. The bill provided funding for a variety of projects that will advance the progress of road pricing initiatives.[52] The legislation created two Transportation Financing Commissions, the National Surface Transportation Policy and Revenue Study Commission and the

National Surface Transportation Infrastructure Financing Commission to make recommendations for future highway financing. SAFETEA-LU also provided funding for a feasibility study of a nation-wide distance-based user fee. The legislation continued the TEA-21 Value Pricing Pilot Program (VPPP), which allows states to convert high occupancy vehicle (HOV) lanes to high occupancy toll (HOT) lanes if automatic toll collection and variable toll prices are implemented to maintain a minimum LOS. It also established the Express Lanes Demonstration Program for 15 projects to toll Interstate facilities using automatic toll collection to manage congestion, reduce emissions, or provide highway expansion for congestion reduction. Additionally, the legislation established the Interstate System Construction Toll Pilot Program (ISCTPP), which allows 3 states or compacts of states to toll an Interstate to finance a construction project if they can demonstrate that tolls are the most economical way to advance the project.

The final report of the National Surface Transportation Policy and Revenue Study Commission was released on January 15, 2008.[53] Like TRB Special Report 285, the Commission's report concluded that while in the short term, the fuel tax should continue to provide the primary source of transportation user revenue, in the long term, user fees that more directly reflect costs should be implemented. The committee recommended that over the next five years, the federal fuel tax should be raised at a rate of five to eight cents per gallon per year, after which it should be indexed to inflation. In addition, the commission recommended that the legislature remove barriers to tolling and pricing that currently exist and provide individual states with the

flexibility to toll as needed, including to fund new capacity on the Interstate Highway System and to price new and existing Interstates in large urban areas to manage system performance. In order to ease operations costs and interoperability on these tolled facilities, the commission also recommended development of a national interoperable electronic toll collection (ETC) system. The committee also encouraged the use of Public-Private Partnerships (PPPs) to fund new capacity and managed lanes and enactment of enabling legislation in states where none is currently in effect.

The commission also provided a number of freight-specific recommendations.[54] In addition to increases in the fuel tax, the commission recommended that existing Federal truck taxes should be adjusted proportionately to "maintain the current allocation of highway cost responsibility." The commission suggested that specific funds should be allocated to a Freight Transportation Program, including diesel tax revenues, tax credits, a portion of customs duty revenues, toll revenues, revenue from private operators of PPPs, as well as introduction of a Federal Freight Fee. This fee should be structured in a way that the "ultimate consumer," not the carrier, bares the cost. The committee additionally recommends changing truck hours of service to allow drivers to take short rest periods during peak hours to take advantage of congestion pricing and prohibiting restrictions that discourage use of a facility by certain vehicle classes.

The study identified a vehicle-mile tax as the preferred option for future user fee collection.[55] The commission determined that rates should be adjusted to reflect congestion levels, to encourage the use of fuel-efficient vehicles, and to "charge trucks

based on factors contributing to infrastructure wear and tear." Finally, the commission recommended that the next surface transportation legislation should require "a major national study to develop the specific mechanisms and strategies for transitioning to an alternative to the fuel tax."

Recent legislation in Europe also indicates a shift toward cost-based pricing for commercial vehicles that considers congestion, infrastructure, and environmental costs. In 1999, Article 7 of Directive 1999/62/EC established rules for tolls and user charges for heavy goods vehicles.[56] This directive limited EU member states to establishing toll rates that could only be applied on motorways (or the nation's highest class of roads), bridges, and tunnels. The directive required that user charges "shall be in proportion to the duration of the use made of the infrastructure" and that the "weighted average tolls shall be related to the costs of constructing, operating and developing the infrastructure network concerned." The directive also allowed member states to vary rates based on emissions class or time-of-day within defined constraints. The directive only allowed for user charges to be applied to trucks weighing more than 12000 kg (26455 lb). In 2006, Directive 2006/38/EC amended the 1999 directive to allow applications of pricing to all trucks over 3500 kg (7716 lb) for broader policy goals.[57] The directive amended the definition of the primary goal of road user charges to the following:

> Tolls shall be based on the principle of the recovery of infrastructure costs only. Specifically the weighted average tolls shall be related to

> the construction costs and the costs of operating, maintaining and developing the infrastructure network concerned. The weighted average tolls may also include a return on capital or profit margin based on market conditions.

The directive also allows for rate variations for the purposes of "combating environmental damage, tackling congestion, minimising infrastructure damage, optimising the use of the infrastructure concerned or promoting road safety" given that the rate remains non-discriminatory based on the truck's nation or place of origin/destination and "is not designed to generate additional tolling revenue." If a rate structure does produce excess revenues, it must be amended within two fiscal years. Specifically, rates may be varied according to EU-defined (Euro) emissions class, time-of-day, type of day, or season with some constraints on maximum rate increases. The directive requires that all member states vary rates according to emissions class by 2010, except in cases where implementing such a rate would be technologically infeasible, would encourage polluting vehicles to divert to alternative routes and negatively impact health and safety, or would "undermine the coherence of the tolling systems in its territory."

3.2 ROAD PRICING MOTIVATIONS

Several types of road pricing have already been implemented in the U.S. and abroad to achieve a variety of system goals. In the US, mechanisms are limited to variable tolls and managed lanes. Systems employed abroad include area and cordon-based congestion tolls, weight-distance truck tolls, and low emissions zones. Due to the political sensitivity of tolling, little research has been published to indicate what factors are considered in establishing rates under most of these tolling structures. However, in their *Review and Synthesis of Road-Use Metering and Charging Systems*, Sorenson and Taylor identify and define nine policy goals that can be achieved through road pricing.[58] These goals include raising or preserving revenue streams, charging users for their "marginal cost of social use," charging external users (e.g. out-of-state or international users), streamlining the toll collection process, reducing road wear, improving safety, optimizing road capacity, reducing demand for scarce resources, and improving the environment. In their analysis, the authors identify which of these goals current applications of each type of pricing seek to realize; their results are provided in Table 11.

Table 11. Road Pricing Policy Goals
(Source: Sorenson 2005)

System Goals	Type of Road Pricing		
	Facility Congestion Tolls	Cordon Congestion Tolls	Weight-Distance Truck Tolls
Raise or Preserve Revenue	X	X	
Charge Users for Marginal Cost of Social Use			X
Charge External Users			X
Streamline Toll Collection Process	X	X	X
Reduce Road Wear			X
Improve Safety		X	X
Optimize Road Capacity	X	X	
Reduce Demand for Scarce Resources	X	X	X
Improve the Environment		X	X

Holguin-Veras at al. established a series of regional and national-level models to examine what motivating factors affect toll rates in the U.S.[59] Although the results of these models were less specific than those in Sorenson and Taylor's policy study, the general conclusion of the authors was that nation-wide, toll facilities follow similar patterns and that in most cases, toll rates appear to be established to generate revenue or to both generate revenue and manage demand.

In addition to examining the policy goals of different types of pricing projects, Sorenson and Taylor also identified the vehicle, time, and location variables considered in rate establishment.[60] Vehicle variables identified include registered weight class, actual GVW, number-of-axles, and vehicle emissions class. Time variables include

congestion and enforcement levels, and location variables include a geographic area, road class, or specific road link.

Conway and Walton performed a similar review of road pricing applications with a specific focus on trucks.[61] Table 12 identifies the policy goals for a number of worldwide road pricing systems. Table 13 identifies the variables considered in the toll rate structures of these systems. The next section provides detailed information about the variables considered, technologies applied, and goals achieved through these specific road pricing applications.

Table 12. Truck-Related Road Pricing Policy Goals
(Source: Conway and Walton 2008)

	Collect Revenue for Profit	Improve Access	Reduce Congestion	Improve Multi-Modal Efficiency	Charge External Users	Recover Truck Costs	Improve Environment
Area-Based Charges							
London Congestion Charge		X	X	X	X		X
London LEZ							X
Milan LEZ			X	X			X
Singapore ERP		X	X	X			X
Cordon-Based Charges							
Bergen Cordon Toll		X	X	X	X		X
Oslo Cordon Toll		X	X	X	X		X
Stockholm Cordon Charge		X	X	X	X		X
Distance-Based Tolls							
Austrian Go Box				X	X	X	
Czech Truck Toll				X	X	X	X
German Toll Collect				X	X	X	X
Swiss Heavy Vehicle Fee				X	X	X	X
Open Toll Roads							
Melbourne CityLink	X	X	X				X
Santiago Open Toll Roads	X	X	X	X			X
Toronto 407	X	X	X	X			X

Table 13. Truck-Related Road Pricing Variables
(Source: Conway and Walton 2008)

	Gross Vehicle Weight	Number of Axles	Vehicle Type	Distance	Time of Day	Emissions Class
Area-Based Charges						
London Congestion Charge					X	
London Low Emissions Zone	Min					X
Milan Low Emissions Zone					X	X
Singapore Electronic Road Pricing	X				X	
Cordon-Based Charges						
Bergen Cordon Toll	X				X	
Oslo Cordon Toll	X				X	
Stockholm Cordon Charge					X	
Distance-Based Tolls						
Austrian Go Box	Min	X		X		
Czech Truck Toll	Min	X		X		X
German Toll Collect	Min	X		X		X
Swiss Heavy Vehicle Fee	X			X		X
Open Toll Roads						
Melbourne CityLink	X	X		X		
Santiago Open Toll Roads			X	X	X	
Toronto 407			X	X	X	

3.3 ROAD PRICING TECHNOLOGIES AND APPLICATIONS

While in the past, the high cost of system operation has prevented implementation of road pricing projects, the recent emergence of a variety of new technologies that allow for relatively inexpensive system establishment and operation has spurred a vast number of pricing projects. To date, the primary source of federal funding for these pricing studies and applications has been the VPPP program established under TEA-21 and continued under SAFETEA-LU. Funds have been allocated for nine different types of projects[62]; these include conversion of HOV lanes to HOT

lanes, introduction of cordon tolls, introduction of fast and intertwined regular (FAIR) lanes which offer parallel tolled and "free lanes" in which those traveling on the more congested lanes receive credits[63], pricing on new lanes, pricing on toll facilities, usage-based vehicle charges, parking pricing, regional pricing, and truck-only toll facilities. The participating states and total number of funded projects of each type is provided in Table 14.

Table 14. VPPP Projects Funded to Date by State and Project Type
(Source: VPPP Quarterly Report 2007)

State	HOV to HOT	Cordon Tolls	Fair Lanes	Priced New Lanes	Pricing on Toll Facilities	Usage-based vehicle charges	"Cash-Out" Strategies / Parking Pricing	Regional Pricing	Truck-Only Toll Facilities	Total
CA	3	1	1	5	1	1	2	1	1	**16**
FL	1	1		1	5	1		1		**10**
MN	1					2	1	2		**6**
TX	1			6	1			2		**10**
WA	1					2	2	1		**6**
GA				2	1	1			1	**5**
MD				2				1		**3**
NC				1						**1**
OR				1		1				**2**
IL					1			1		**2**
NJ					4					**4**
PA					1					**1**
VA								2		**2**
Total	**7**	**2**	**1**	**18**	**14**	**8**	**5**	**11**	**2**	**68**

In addition to VPPP funding, U.S. DOT has established the Urban Partners Program, which provides federal discretionary funding to partner cities to implement pricing for congestion relief.[64] In August 2007, five partner cities and projects were chosen. Chosen cities and projects include a priced, managed multi-lane network in

Miami, a priced, managed multi-lane network with peak-period transit discounts in Minneapolis/St. Paul, full cordon pricing in New York City, partial cordon pricing and parking pricing in San Francisco, and full-facility congestion pricing in Seattle.

In the U.S., many of the VPPP funded projects as well as state and locally funded projects have reached full implementation. Fully implemented projects abroad, particularly in Europe, have also served as an example for the projects currently under study in the U.S. The following are descriptions of the technologies and specific pricing applications that have achieved success worldwide.

3.3.1 Electronic Toll Collection

Since the 1990s, electronic toll collection (ETC) has become increasingly popular on American and international toll roads. Transponder based ETC allows vehicles equipped with a dedicated short range communication (DSRC) device to pass through a toll booth or under an overhead gantry without stopping to pay a toll. Roadside or overhead readers communicate with the onboard transponder to identify the vehicle and charge a pre-paid or credit card linked account for the vehicle's use of the tolled facility. Operators in 22 states currently use transponder-based ETC systems; in 16 of these, as well as in Puerto Rico, these tolled facilities contain part of the Interstate Highway System.[65] The largest of these systems is the EZ-Pass system, currently operational by 23 agencies in 12 eastern states.[66] This system allows users registered in any state to travel throughout the network using a single transponder. On the most recent facility to join the EZ-Pass network, the Indiana Toll Road, ETC was introduced as

part of the lease agreement signed with the private operator, the Indiana Toll Road Concession Company.[67] Systems in the other 11 states using ETC are operated strictly within state borders. At the state level, Texas[68], California, and Florida[69] (although not all of the state's systems are included) use tags that can be used on facilities operated by multiple authorities. Most ETC facilities in the US still require vehicles to slow down, although not stop, when passing through a tolling point. However several states, including Pennsylvania, Delaware, Illinois, and Florida have converted facilities for high-speed electronic toll-collection (ETX), which allow vehicles to pass under gantries at highway speeds.

"Open Road" tolling systems not only take advantage of ETX systems, but also use cameras and optical character recognition (OCR) software for enforcement and tolling of vehicles not equipped with a transponder. Frequent facility users' vehicles are generally equipped with transponders, while infrequent users are identified and tolled using license-plate recognition. In order to cover additional operations costs, vehicles charged through photographic identification are usually charged at a higher rate than those using transponders. "Open Road" tolling was first introduced by a private operator on Canada's Toronto 407[70], although all trucks on that facility are required to be equipped with a transponder.[71] The concept has since been applied on the Melbourne CityLink[72] and Sydney Westlink M7[73] in Australia and on the Central Texas Turnpike system.[74]

3.3.2 Facility Congestion Tolls

Variable Pricing

Variable pricing has been introduced on a number of tolled facilities in the U.S. to manage congestion during peak periods and encourage efficient facility use. Variable pricing systems introduce higher tolls during peak periods to encourage users to move time-flexible trips to less expensive off peak hours. The following are facilities on which variable tolls have been employed:

New Jersey Turnpike

Variable pricing was implemented on the 148-mile New Jersey Turnpike in 2000.[75] At implementation, peak hour tolls were collected at a rate 12 percent higher than off-peak tolls. Although variable pricing did not curb overall traffic growth, it did shift growth rates so that traffic rate increases during off-peak hours are higher than those during peak hours. Additional phased increases in peak hour toll rates are also planned.

Port Authority of NY/NJ

The Port Authority of New York/New Jersey introduced variable tolling in March 2001 on six of its bridges and tunnels.[76] The variable charging scheme that they employed charged a high cash toll and provided discounts for passenger vehicles equipped with EZ-pass at all times; during off-peak hours, passenger EZ-pass users could use the road at an even greater discount, and trucks using EZ-Pass could also receive a

discount. The purpose of this scheme was to increase use of EZ-pass and to reduce traffic during peak hours; as a result of application, EZ-pass use for cars increased 8.7 percent, for trucks increased 7.7 percent, and traffic during the morning peak decreased 7 percent.[77] Ozbay, Yanmaz-Tuzel, and Holguin-Veras examined the truck specific impacts of introducing these tolls.[78] Although analysis of the general traffic impacts had found a 7 percent decrease in traffic during peak periods, the study found that increased toll rates had no significant impact on truck travel hours and that inflexible delivery times prevented trucks from changing their behavior.

San Joaquin Hills Toll Road, Orange County

In California, variable pricing was implemented on the 15-mile San Joaquin Toll Road connecting Interstate 5 near San Juan Capistrano to Interstate 405 in Newport Beach in February 2002.[79] A 25 cent "premium" was introduced for use of the toll facility during peak hours; in July 2005, this "premium" was increased to 50 cents, and in July 2006, it was again increased to 75 cents. The goal of this pricing project is to control congestion while also ensuring adequate revenue collection.

Bridges, Lee County

In Florida, Lee County implemented variable tolling in 1998 on two bridges connecting Fort Meyers and Cape Coral.[80] The tolling scheme charged higher rates during peak hours than during off-peak; in the 30 minutes immediately preceding and the 2 hours following the peak period, a 50 percent discount was offered. Surveys

found that more than 71 percent of motorists shifted their travel times at least once per week to take advantage of lower tolls.

Other Facilities

In California, toll rates at some plazas on the Toll Roads increase for all car and truck users paying by cash or electronic toll collection (ETC) during peak periods.[81] In Delaware, toll rates for all users on SR 1, a road that links the state's densely populated north to its southern beaches, increase on weekends.[82] On the Chicago Skyway, Illinois Tollway, and New York Thruway, variable tolls specifically target commercial truck users. On the Chicago Skyway, vehicles with 3 or more axles pay discounted rates between 8 PM and 4 AM.[83] The Illinois Tollway also discounts toll rates overnight for all trucks, and charges a discounted rate for trucks using ETC during weekend and non-peak weekday time periods.[84] The New York Thruway uses "incentive pricing" for trucks during the morning peak period at the Tappan Zee Bridge and during the evening peak at the Spring Valley Toll Barrier.[85] A two-hour peak period is defined, during which the highest toll is paid. In the 45 minutes before the peak, the toll gradually increases every 15 minutes, and in the 45 minutes after, the toll gradually decreases every 15 minutes. Some discounts on these rates are given to specific ETC users.

HOT Lanes and Express Lanes

Express lanes and high-occupancy toll (HOT) lanes are tolled facilities operated parallel to or in the median of congested "free" facilities. These lanes offer drivers the

opportunity to pay a toll using ETC to use a less congested, more reliable facility. HOT lanes generally allow certain high-occupancy vehicle (HOV) classes to use the tolled facility without paying some or all of the toll rate. HOT and Express lane applications in the US include the SR 91 Express Lanes in Orange County, HOT Lanes on Interstate 15 in San Diego, HOT Lanes in Minneapolis, HOT Lanes in Denver, HOT Lanes on the Katy Freeway in Houston, HOT Lanes on SR71 in Seattle, and Express Lanes on I-95 through Miami. Two major projects in the Washington, D.C. area have also reached advanced stages of development.[86]

Express Lanes, State Route 91, Orange County

The SR 91 Express Lanes, four 10-mile long lanes located in the median of the Riverside/SR 91 freeway in Orange County, California were opened in December 1995.[87] Toll rates charged on these express lanes vary by day and time "to reflect the levels of congestion avoided on the adjacent free lanes" from $1.20 during off peak hours to $10 during the highest "super-peak" hours on Fridays.[88] Since the toll structure is relatively complicated, variable message signs on the adjacent freeway indicate the current toll rate for the use of the facility. Vehicles must be equipped with a FasTrak™ transponder linked to a credit card account. Some discounts are offered during certain periods to vehicles with 3 or more occupants, zero-emissions, and handicapped license plates. By 2005, these Express Lanes were carrying 40 percent of freeway traffic on only one-third

of freeway capacity, achieving a 33 percent increase in lane throughput compared to "free" lanes.

Although trucks are not currently allowed to use these lanes, Kawamura performed a study examining the perceived benefits for trucks which could be achieved through use of the facility.[89] The study found that, with appropriate toll rates, the social costs of truck use of the facility, including pavement damage, air pollution, noise, and accidents, could be recovered. System-wide, truck use of the facility could achieve time and capacity benefits, and benefits to for-hire truck drivers would be particularly evident.

I-15 HOT Lanes, San Diego

Eight-mile long HOT lanes were introduced in the median of I-15 in San Diego in July 1997 (VPPP SOURCE). In these lanes, HOVs with two or more occupants can operate for "free" while enrolled single occupancy vehicles pay a toll for use of the facility. While initially, users were simply provided with a window permit, drivers on these barrier-separated lanes currently pay a toll using a FasTrak™ transponder; overhead gantries interrogate the tag as vehicles pass for charging.[90] While maximum toll rates are established for different day and time periods, a dynamic tolling system uses loop detectors to monitor real-time traffic conditions and adjust toll rates within those limits every six minutes to maintain a level of service (LOS) of C on the lanes.[91] Rates vary from as little as 50 cents during normal off-peak periods to as much as $8

during the most congested periods. Current toll rates are displayed on variable message signs for entering vehicles. Vehicle occupancies are enforced by police who visually inspect vehicles to determine vehicle occupancy and system enrollment. Annually, I-15 generates close to $2 million in revenue; about $1 million of this covers operational costs, while the remainder is used to subsidize express bus service along corridor.[92] Surveys of about 800 corridor users performed by the San Diego Association of Governments (SANDAG) has found broad support from users: 90 percent consider the HOT lanes to be valuable as a time-saving travel alternative, and despite potentially high toll rates, 75 percent consider the tolling structure to be fair.

I-394 HOT Lanes, Minneapolis/St.Paul

In May 2005, the state of Minnesota introduced an HOT lane on I-394 in the twin cities.[93] This facility introduced several innovations to the HOT concept. Because of high costs, as well as impracticality in Minnesota's winter climate, the HOT lane is not barrier separated from the adjacent "free" lanes. While users in California pay one fee to use the length of the facility, the Minnesota system uses dynamic segmented tolling; users pay a different rate, which may change as often as every 3 minutes, for each segment of the road that they drive. Minnesota also uses innovative enforcement technologies; police, who visually inspect occupancy as in California, also have vehicles equipped with a transponder that detects whether a vehicle passing under the toll

gantry sends a successful toll payment signal. Additionally, the Minnesota project was developed as a PPP, with an operational contract renewable every year for five years.

I-25 HOT Lanes, Denver

The I-25 Express Toll Lanes in Denver were opened on June 2, 2006.[94] These two 6.6-mile reversible, barrier separated lanes are located in the median of I-125. Like the I-15 HOT lanes in California, HOV vehicles operate on this facility without paying a toll, while single-occupant passenger vehicles, who constitute about a third of users, can utilize the lanes for a fee paid using ETC. Buses also operate on this facility without toll payment. Toll rates vary across times and days, from 50 cents to $3.25. Introduction of the lanes has improved traffic operations for both buses and passenger traffic by achieving better traffic distribution across existing capacity and encouraging carpooling.

I-10/US 290 TX

The QuickRide program, established in Houston in January 1998, allows 2-occupant vehicles (HOV2) to utilize HOV facilities during the morning and evening peak periods when the lanes are restricted for 3 or more-occupant vehicles (HOV3+). Users enroll in the Quickride program to take advantage of HOV facilities on the Northwest and Katy Freeways. A $2 fee per use is collected automatically using a Toll Tag.[95] The program has encouraged formerly single-occupant travelers to carpool, and revenues from the program are used to fund program operation.[96]

SR 167 HOT Lanes, Seattle

Seattle's SR 167 Express lanes opened in May 2008.[97] Nine-mile lanes in each direction are separated from parallel "free lanes" by striping, not barriers. While 2+ occupancy vehicles can use the lanes without paying a toll, single-occupancy vehicles must be equipped with a transponder. Toll rates on individual segments are adjusted dynamically using real-time traffic information. If the average speed on the facility drops below 45 miles per hour, the toll is automatically increased.

I-95 Express Lanes, Miami

The I-95 Express Lanes in Miami were opened in December 2008.[98] These limited access lanes are also tolled dynamically. Toll rates range from as little as $.25 to as much as $6.20. Rates are adjusted to maintain a speed of 45 to 50 mph. Users are required to pay a toll using a "Sunpass" transponder. Although not considered HOT lanes, these lanes do allow registered vanpools, carpools of 3+, hybrids, motorcycles, buses, and emergency vehicles to use the lane for no charge.

I-95/I-395 and I-495 HOT Lanes, Northern Virginia

Two major HOT projects in the Northern Virginia portion of the Washington, D.C. metropolitan area have reached advanced stages of development.[99] The I-495 (Capital Beltway) project includes plans for introduction of 2 new lanes in each direction connecting from the Springfield Interchange to the Dulles Toll Road. These HOT facilities will provide seamless connection to area's existing HOV network. Once

completed, these lanes are expected to offer improved reliability for both passenger and transit vehicles. The lanes will be operated under a PPP; the final partnership agreement between the Virginia Department of Transportation (VDOT) and Fluor-Transurban to finance, construct, design, operate, and maintain the facility was completed in December 2007. Construction is expected to begin in Spring 2008 and be completed by 2013.

The I-95/395 project, which includes a planned expansion of existing reversible HOV lanes from two to three lanes and extension of the road 28 miles south to Massaponax, is currently under environmental review.[100] An interim PPP agreement between VDOT and Fluor-Transurban has been completed. Pending necessary approvals, construction should begin by the end of 2009.

Additional Studies

Many major US metropolitan areas are currently examining the feasibility of HOT and Express Lane projects.[101] HOT Lane projects currently under study include I-680 carpool lanes in Alameda County, CA, extension of the I-15 lanes in San Diego, new lanes on I-140 in Raleigh, I-30 and LBJ Freeway lanes in Dallas, I-35 and I-10 lanes in San Antonio, and Loop 1 Lanes in Austin. Express lane projects include lanes on the C-740 in Denver, the I-95/JFK Expressway in Baltimore, and Highway 217 in Portland.

TOT Lanes and Truck-Only Facilities

Very few of the managed lane projects introduced on U.S. highways have achieved direct benefits for commercial trucks. None of the HOT or Express lanes currently in operation allow heavy trucks to use the facilities. However, recent research has suggested that considerable benefits in productivity, efficiency, and safety could be achieved through introduction of truck-only toll facilities, including truck-only toll (TOT) lanes and truck-only tollways. A study for the Georgia State Road and Tollway Authority (SRTA) examined the feasibility of applying a dynamic TOT network in the Atlanta region.[102] This study used regional travel demand models to examine the potential benefits of and provide a "proof of concept" for TOT lanes. Benefits identified in the study included increasing transportation options for freight carriers, increasing network-wide freight mobility and productivity, reducing freight congestion, and improving both safety and congestion over the entire network by changing the vehicle mix on non-tolled lanes. The study concluded that both truck travel times and general network congestion could be improved through implementation of a TOT network, and that adequate revenues to maintain and operate the system could be achieved.[103]

A policy study performed by the Reason Foundation and researchers at Rensselaer Polytechnic Institute examined both the feasibility and potential benefits of truck-only tollways.[104] These facilities, financed through user fees, could allow trucks to operate separately from passenger traffic, reducing the risk of accidents in mixed traffic. These truck-only roads could be designed and built to handle heavier and longer-

combination vehicles (LCVs) than are currently allowed to operate on most of the U.S. highway network. The productivity gains for trucking companies that could be achieved by allowing operation of these heavier vehicles would likely outpace the user fees required to build, maintain, and operate such a network; as a result, trucks would likely take advantage of the availability of such facilities.

3.3.3 Cordon and Area Congestion Pricing

Cordon and area congestion pricing systems require users to pay a toll to enter a defined geographic area. While no cordon tolls have yet been implemented in the U.S., major projects have been successfully demonstrated and implemented in London, Stockholm, Singapore, and Rome. As previously discussed, the feasibility of implementing these charges in San Francisco is currently being examined.

London Congestion Charge

The congestion charging scheme in London is area based; vehicles that enter the zone during the 7:00 AM to 6:00 PM peak period pay a daily fixed rate, currently £8.[105] The system uses a series of cameras located at the area's boundaries, as well as within the zone, to enforce payment. The cameras capture license plate images and transmit them to a central computer where the images are processed and a list of vehicles required to pay the toll is generated. Although cameras may only successfully identify vehicles about 80 percent of the time, most vehicles pass more than one camera while traveling in the zone; accuracy increases to 96 percent with 2 camera passes. Users

have 24 hours to pay the toll, either online, by phone or text message, or in person. If they do not pay in the specified time, a £100 penalty is assessed. Since its inception, the London congestion charging scheme has reduced traffic in the zone by 30 percent. About £100 million of net revenue, which is reinvested in the city's transportation system, has been collected.[106] Due to the extremely high costs of system operation, Transport for London (TfL) is currently testing several new technology systems that may change system operations and the structure of the toll rate.[107] While GPS technologies have been essentially ruled out, a transponder-based "tag and beacon" system is still under consideration.[108] TfL's contract with Capita, the system operator, expires in 2010; it is likely that technology changes would be introduced during this period.

Stockholm Congestion Charge

From January 1 to July 31, 2006, Stockholm tested a cordon-based congestion charge.[109] The system utilized a combination of dedicated short range communications (DSRC) transponders and camera/OCR technologies. Vehicles were charged at entry points to the zone during the peak period, which during the testing phase encompassed 11.4 square miles in central Stockholm. Those equipped with transponders were charged automatically; this included 60 percent of payments. Non-equipped vehicles were required to pay the toll online or in stores within 14 days. Toll rates varied by time of day from 10 to 20 SEK, with a maximum daily charge of about 60 SEK. The testing was considered extremely successful, as congestion reduction exceeded expectations:

while a 10 to 15 percent decrease was expected, a 22 percent reduction was achieved for the 6:30 AM to 6 PM peak period. In September 2006, a referendum was held to determine the fate of the scheme; despite initial public outcry before the testing phase, this post-testing referendum passed in the city of Stockholm, with 53 percent of residents supportive. Referendums were also held in 15 of the 26 municipalities in Stockholm's "commuter belt"; they were not as successful in these surrounding regions, where 52 percent of voters voted against the referendum. Since the toll is charged to vehicles entering the city, and not to those traveling within it, it is not surprising that voters residing within the zone support the charge at higher levels than those whose trips originate outside the city. Despite this lack of support in outlying areas and a change of government that was expected to delay implementation, the Stockholm congestion charge was permanently implemented on August 1, 2007.[110]

Singapore Congestion Charge

Singapore also operates a congestion charging system.[111] Vehicles are equipped with DSRC transponders with built-in, pre-paid smart cards. These cards can be purchased at a variety of locations, including banks and gas stations. As a vehicle passes a charging gantry, located at 28 entry points, the toll is deducted from the smart card; toll rates vary according to location and time of day.[112] Toll rates are reviewed every 3 months and adjusted to maintain the desired speeds of 20 to 30 kilometers per hour in the zone. Camera/OCR technologies are used to capture license plates and identify toll

violators. Introduction of this Electronic Road Pricing (ERP) system, which replaced a previous manual payment system, immediately reduced traffic by 13 percent and increased average vehicle speeds by 22 percent. In addition to overall traffic reduction, the scheme also improved the distribution of traffic across peak and off-peak periods.

Rome Limited Access Zone

In Rome, an annual permit is required to enter a limited access zone (historical area) on weekdays between 6:30 AM and 6:00 PM and on Saturday between 2:00 and 6:00 PM.[113] While local residents are exempt from the charge, other vehicles wishing to enter the zone must purchase the permit. Access is controlled with an automated system. Permitted vehicles must be equipped with an on-board unit (OBU) with an integrated SMART card. DSRC technologies at zone entry points interrogate the OBU to ensure permitting. Violators are identified using camera/OCR technologies for license plate recognition. Introduction of this automated access-control scheme has achieved a 10 percent reduction in daily traffic.

Studies for US Cordon Charges

The city of San Francisco is currently performing a Mobility, Access, and Pricing Study to examine the feasibility of a partial cordon charge in the region.[114] The study is examining a variety of technologies and potential rate structures, and estimating the associated potential traffic improvements and revenues. Additionally, researchers are seeking public input.

The city of New York proposed a 3-year pilot study to examine congestion pricing to reduce traffic in the Manhattan CBD.[115] The proposed rate structure included an $8 fee per day to travel into or within the zone for passenger vehicles and a $21 per day charge for trucks. Discounts would be offered for travel strictly within the zone: cars traveling only within the zone would pay $4 per day and trucks would pay $5.50. The proposed technologies for fee collection were EZ-pass readers that can identify transponder-equipped vehicles and camera/OCR technologies for license plate recognition to identify non-transponder equipped vehicles. Users could either pay directly through their EZ-pass account, through a pre-paid account linked to their license plate, or pay within 48 hours of zone entry by internet, phone, text, or cash transaction at retail partners. City models suggested that such a system could achieve reductions in daily vehicle volumes around 7 percent while increasing transit use by 1 percent. However, the program was rejected by the New York State legislature in April 2008, so the future of the plan remains uncertain.[116]

3.3.4 Distance-Based Charges

As discussed previously, the National Surface Transportation Policy and Revenue Study Commission concluded that the best available option for future highway user charging is introduction of a distance-based VMT that that reflects system use for each vehicle.[117] Currently, distance-based charging on non-toll-road facilities is limited to heavy vehicle applications. Only a few U.S. states currently charge a weight-distance tax for heavy vehicle operations, and these charges require user self-reporting of distances

traveled. Germany, Austria, Switzerland, and the Czech Republic have all introduced technology systems for collection of distance information and charging of a distance-based heavy vehicle tax. With several variables considered in toll rate determination, these systems offer a step toward development of distance-based fees that better reflect user costs.

Swiss Heavy Vehicle Fee

In January 2001, the Swiss Customs Authority (SCA) introduced a distance-based heavy vehicle fee charged per mile of travel for all vehicles over 3.5 tons operating on the Swiss public road network.[118] Both registered weight and emissions class are considered in determining the rate per mile for each vehicle.[119] Domestic vehicles operating on the network are required to be equipped with an OBU that includes a SMART card reader and DSRC and GPS communications technologies, and is connected to a digital tachograph, which records vehicle distances traveled.[120] At border crossings, DSRC communications are used to activate and deactivate the OBU's distance counter. The driver must submit the distance data collected on the SMART card from the digital tachograph and GPS to authorities for fee payment. While the tachograph data is legally recognized as the distance traveled, the GPS data is used to check for inconsistencies. International vehicles are not required to use the OBU, but are required to submit distance data manually and pay the heavy vehicle fee. In introducing this system, the Swiss government hoped to not only reduce truck freight traffic and raise revenues, but

also to encourage the use of low-emissions vehicles and shift some traffic to alternative modes.[121] In the first year following introduction of the system, truck freight traffic trends reversed, from an annual increase of seven percent to a decrease of five percent.

Austrian Heavy Vehicle Tax

In January 2004, Austria introduced a DSRC-based technology system for collection of a distance-based heavy vehicle tax on its toll roads.[122] Toll rates are based on vehicle number-of-axles. Trucks are equipped with a GO Box that stores information on the license plate, vehicle class, and mode of payment for the truck. Four-hundred twenty portable and stationary gantries interrogate the GO Box for tax collection, and an additional 120 gantries are used solely for enforcement to ensure truck registration. Trucks may pre-pay or pay after network use. The goals of implementing this system were to raise revenue to fund future transportation projects, to reduce empty-trips by trucks, and to slow the growth in freight traffic that preceded introduction of the system by encouraging use of other modes.

German Toll Collect

In Germany, a system combining DSRC and GNSS technologies is also used for collection of a distance-based heavy vehicle fee for trucks weighing more than 12 tons operating on the Autobahn.[123] Enrolled trucks are equipped with an OBU that collects distance information using GPS; un-enrolled vehicles are not required to use an OBU, but are still required to pay the fee through manual reporting. Both types of users are

required to submit intended routes before travel. DSRC technologies are used to identify vehicles to ensure toll payment and to ensure adherence to the pre-reported route. Toll rates are based on both number-of-axles and emissions class. Unlike in Switzerland, in Germany, the satellite tracking data is actually used directly for fee determination. The primary concern before implementation of this system was the accuracy of GPS-based on-board units (OBU) in determining distance traveled; however, the system has performed extremely well, with the technologies performing at more than 99 percent accuracy consistently.[124]

Czech Republic MYTO CZ

The Czech Republic has also implemented a technology system for collection of a distance-based truck fee on a 600 mile (970 km) long network of roads.[125] Similar to the Austrian system, the Czech Republic system uses overhead gantries to communicate with an on-board DSRC transponder for toll collection. Two different classes of roads are tolled: motorways and class 1 roads. Rates vary by road class, number-of-axles, and emissions rating. Like in Germany, only trucks weighing more than 12 tons are required to pay the toll.

Current Distance-Based User Fee Studies

The United Kingdom was planning to implement its own distance-based lorry charge; however, the government decided to abandon the truck-only charging to instead focus on development of a nation-wide tolling scheme for all vehicles.[126] In the

U.S., the states of Oregon and Washington are both studying mileage based user charging concepts for all vehicles.

The Oregon Road User Fee Task Force (RUFTF) was established in 2001 to identify an alternative form of highway user charging that could be applied in the long term to provide a stable source of funding and replace the gas tax.[127] Researchers developed the Oregon Mileage Fee Concept. Under this concept, users are charged varying distance-based fees for travel within different geographic zones. Under the proposed payment system, referred to by the state as Vehicle Miles Traveled Collected at Retail (VMTCAR), vehicles are equipped with OBUs that use GPS technologies to identify locations in zones and use odometer readings to determine distance traveled. When a user arrives at an equipped gas pump, point-of-sale (POS) technologies recognize that the vehicle is equipped with the mileage charging technology. The vehicle is then charged a value equal to cost of miles traveled calculated for each zone, plus the cost of fuel minus the state fuel tax. By collecting the fee at gas pumps rather than at a centralized location, many of the potential problems of implementing the fee are mitigated. By requiring payment at the gas pump, costs of administration and enforcement are minimized. Since the gas distributor has already paid state tax on the fuel being sold, only the difference between the gas tax already paid and the mileage fee collected must be paid to (or refunded) by the state. Instead of each individual user having to submit payment, only fuel distributors pay directly to the state. Additionally, since cars are still required to pay the mileage fee in order to receive fuel, they will not

be able to evade payment. Results of a recently completed pilot test demonstrate that although some minor technology improvements must be made, application of the system to collect a VMT is definitely feasible. Under the proposed methodology, trucks would not be charged using this concept. Since trucks in Oregon are already charged a mileage-based distance tax variable by weight and do not pay a fuel tax on diesel, they would not be charged under the Oregon Mileage Concept.

Washington has begun a similar pilot study of flexible distance-based charging for the Puget Sound region. In the Washington study, users are charged different rates per mile depending on location and time. Vehicles are equipped with "black boxes" with a $100 credit pre-installed.[128] Satellite monitoring systems deduct road-user fees in real-time from the box based on location, time, or real-time traffic conditions. Drivers can see real-time fee rates on the "in-vehicle meter."

3.3.5 Emissions Based Charges

Button and Pearman recognized that focusing solely on congestion reduction as a goal of road pricing could lead to increased costs in infrastructure damage and pollution.[129] Recently, a number of cities in Europe have introduced specific charges to discourage high polluting vehicles from traveling into congested urban regions. The EU[130], like the US[131], limits emissions for a number of specific pollutants that are potentially harmful to human health and the environment. Regulated emissions in Europe include carbon monoxide (CO), hydrocarbons, including methane (CH_4) and non-methane categories, nitrogen oxides (NO_X), and particulate matter (PM). EU standards

also regulate smoke emissions, which include visible particles larger than invisible PM. More recently, carbon dioxide (CO_2) has also been classified as a greenhouse gas. A vehicle's Euro emissions class is generally determined according to its registration date, which coincides with implementation of Euro I, II, III, IV, and V standards. Use of alternative fuels or on-board technologies may impact its rating.

Low Emissions Zones

Milan

In Milan, a Low Emissions Zone (LEZ) was implemented in January 2008 to reduce PM in the city's air.[132] Entry to the zone for all passenger and commercial vehicles during a weekday peak requires purchase of an "EcoPass." Prices for the pass, which is displayed as a sticker on the truck's windshield, vary from €2 to €10 per day according to Euro emissions class.

London

The London LEZ, which was also introduced in an effort to reduce PM emissions, began in January 2008.[133] Currently, any truck over 3500 kg operating in the zone that does not meet Euro III standards for PM must pay a £250 daily penalty; by 2012, penalties will be assessed to any vehicle not meeting Euro IV PM standards.

Berlin, Cologne, and Hanover

Although not considered tolls, LEZs have also been introduced in Berlin, Cologne, and Hanover.[134] Drivers in these cities are required to purchase a sticker that displays their vehicle's emissions class. Currently, those classified as Euro 0 are banned from entering the zones.

Carbon Charging

London also proposed a plan to incorporate carbon dioxide (CO_2) emissions criteria into pricing for it Congestion Charge.[135] This plan would have increased the congestion charge for any vehicle entering the zone that emitted more than 225 g/km (0.8 lbs/mi) of carbon dioxide (CO_2) from £8 to £25. The plan would also have allowed some low emissions vehicles to enter the zone for free. However, after a change of mayor and a lawsuit brought forth by a car manufacturer, the plan was dropped.

Emissions Criteria in Other Road Pricing Schemes

Although not explicitly introduced to target emissions, a number of the distance-based charges discussed above do use vehicle emissions ratings as criteria for determining a truck's per-kilometer toll rate. Figure 6 shows emissions classifications for each of these charges.

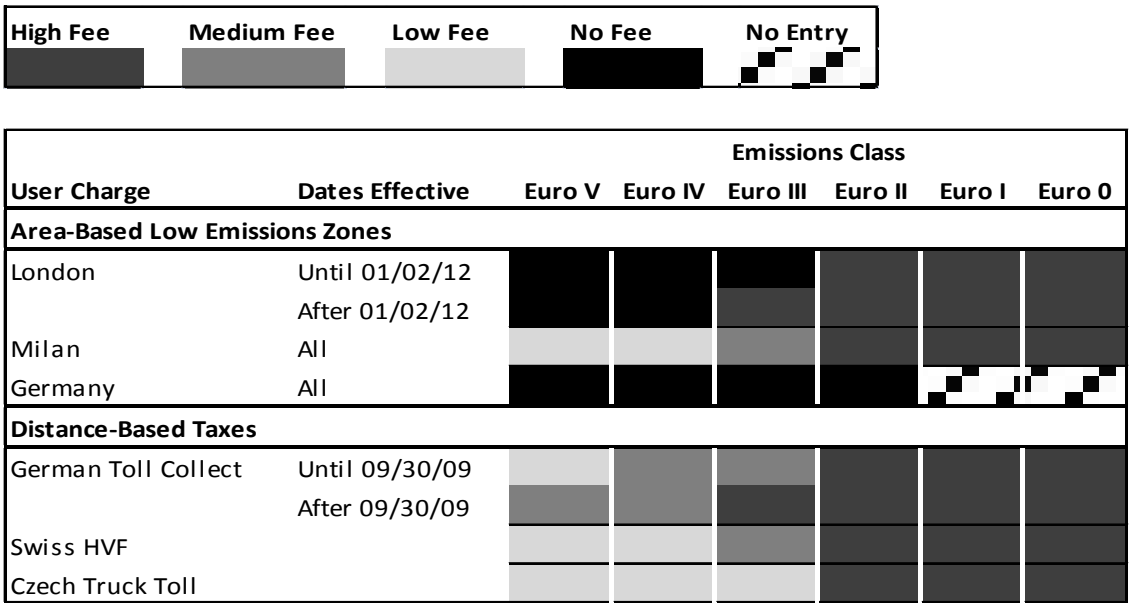

Figure 6. Euro Emissions Criteria for Road Pricing

3.3.6 Truck-Related Road Pricing Impacts

The effectiveness of using road pricing to influence freight traffic is complicated by industry constraints. Button and Pearman identified several factors that might influence the effectiveness of freight road pricing, including the demand elasticity for the products being delivered, the impact of transportation costs on total production and distribution costs, and the market structure.[136] More recently, Vilain and Wolfram[137] and Holguin-Veras et al.[138] have identified a number of challenges that may limit the effectiveness of road pricing in shifting truck traffic to off-peak periods. For example, Holguin-Veras at al. evaluated the impacts of variable pricing on trucks using Port Authority of New York and New Jersey (PANYNJ) facilities.[139,140] Their findings suggest that while local delivery trucks are unlikely to change their travel times due to delivery

time constraints and passing through of toll costs, full truckload traffic traveling through the region to more distant destinations is more likely to respond to higher prices. A survey performed in Atlanta by ATRI also found that inflexible delivery times may limit truck response to time-of-day pricing.[141] Recognizing the ability of carriers to pass through costs to receivers and ultimately consumers, Hicks suggested that congestion charges should be "levied on businesses that generate freight."[142] Building on the PANYNJ results, Holguin-Veras has examined the introduction of tax incentives in addition to road pricing to encourage receivers to accept off-peak deliveries (15).

As is clear from the varied success of a number of road pricing alternatives, it is impossible to determine exactly how future pricing initiatives will impact truck traffic or the recovery of user fees from trucks. A few recent studies have examined how changes in tolling on individual facilities would impact trucks. A study performed for the Virginia Department of Rail and Public Transportation modeled the impact of tolling at various levels on truck diversion from I-81.[143] This study concluded that diversions would increase approximately linearly with cost of tolls per mile; however impacts varied depending on toll rates, length of trip and somewhat on market segment. A toll rate of one to 10 cents per mile diverted little traffic, especially non-local trips. However, once toll rates exceeded 20 cents per mile, a considerable number of trips up to 100 miles in length diverted. While the study found that no specific commodities would be unduly impacted by tolls, it did find that some trucks carrying bulk shipments would likely divert.

Swan and Belzer modeled the impacts of toll increases during the 1990s and decreases in 2004 on traffic levels on the Ohio Turnpike.[144] During the 1990s, truck toll rates were increased considerably on the Turnpike. Legislators concluded that these increases had caused a considerable amount of truck traffic to divert to adjacent "free" roads. As a result, the Turnpike Authority introduced a number of truck friendly strategies in 2004 to draw truck traffic back.[145] These changes included decreases in toll rates averaging 25 percent across all truck classes and as high as 57 percent for the heaviest classes, restructuring and simplification of weight classification, expansion of an existing VMT-based distance program to allow smaller carriers to pool miles with other small carriers to achieve required total VMT for discounts, and turnpike authority negotiations with gas station facilities to provide lower rents in exchange for lower fuel tax rates. In their models, Swan and Belzer estimated truck elasticities to changes in toll rates[146]; they concluded that a toll operator operating under a "profit maximizing" strategy could lead to increases in diversions as high as four times the rate that Ohio realized before subsidizing truck tolls. However, since their models did not account for the other truck-friendly strategies applied at the same time as toll decreases, it is unclear what impact these other strategies realized.

The U.S. DOT study *Issues and Options for Increasing the Use of Tolling and Pricing to Finance Transportation Improvements* identified an additional issue that must be considered in implementing pricing for trucks.[147] In the past, the trucking industry has objected to replacing fuel taxes with more direct forms of user charging because of

the difficulty of estimating fees to pass through to the shipper. In its call for establishment of a Freight Fee to finance freight projects, the National Surface Transportation Policy and Revenue Study Commission recognized a to need to structure the fee in a manner that could be passed on to the ultimate consumer.[148] However, direct forms of user charging, with the possible exception of congestion charges, are not necessarily more difficult to estimate. If user fees can be established that use clearly defined distance and vehicle criteria for rate determination, the cost of transportation fees for specific point to point shipments should not be much more difficult than the fuel tax to pre-estimate.

3.4 FUTURE ROAD PRICING ALTERNATIVES

It is clear from this review that a variety of technologies have already been implemented, with varying degrees of success, to allow for better recovery of user costs for impacts on congestion. On dynamically priced facilities, real-time data is employed to measure real congestion impacts. Technologies have also been employed for distance-based charging to better estimate system use as a functions of mileage traveled. This ability to measure the exact distance traveled has improved system operator ability to match user fees with infrastructure costs. However, these distance-based fees rely on registered GVW and number-of-axle information to distinguish between trucks. No studies have examined the potential for collection of real-time vehicle configuration and weight information using advanced technologies. Weigh-in-

Motion systems, which are already used on highways throughout the world for planning and enforcement, could potentially be used in an integrated technology system for real-time road pricing.

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CHAPTER 4: WEIGH-IN-MOTION SYSTEMS AND TECHNOLOGIES

Although a number of truck road pricing mechanisms use individual vehicle weight or vehicle number-of-axles for rate determination, no system has yet been implemented that uses real-time axle weights for real-time tolling. Axle loads and axle configurations provide a much better measure of both pavement and bridge infrastructure impacts than the registered GVW and number-of-axle variables commonly used for rate determination in existing pricing applications. Weigh-in-motion (WIM) technologies provide a potential means of collecting vehicle axle information from vehicles traveling at highway speeds. Different types of WIM technologies can measure both axle loads and the distances between axles for passing vehicles. As technologies continue to improve, it is feasible that a system combining WIM technologies and vehicle identification technologies could be applied for direct enforcement of a cost-based user fee.

4.1 WIM TECHNOLOGIES

The American Society for Testing and Materials (ASTM) defines WIM as "the process of measuring the dynamic tire forces of a moving vehicle and estimating the corresponding tire loads of the static vehicle."[149] WIM systems can be used to estimate the static loads carried by tires, axles, and axle groups. WIM data is collected throughout the U.S. for a variety of purposes, including overweight vehicle enforcement, transportation and enforcement planning, and highway cost allocation.

The type of WIM system used, and its required level of accuracy, varies according to specific application. ASTM has developed standards for four different classes of WIM systems.[150] While Type I and Type II systems, which exhibit axle load accuracies of ± 20 to 30 percent at a 95 percent confidence level for vehicles traveling at highway speeds, can be used for transportation planning purposes, more accurate systems must be used for weight enforcement. Type III systems, which exhibit accuracies of ± 15 percent at a 95 percent confidence level for vehicles traveling at speeds up to 50 mph, are used for weight pre-screening. Type IV systems, which have been conceptually designed, but not yet approved for use in the U.S. for direct weight enforcement, exhibit accuracies of ± about 4.2 percent at a 95 percent confidence level for vehicles traveling below 10 mph.

Two major types of WIM error can be identified; these include random error and systematic error.[151] Random error is defined as the "statistical fluctuation of measurement" due to the "inability of the device to determine the truth precisely." Systematic errors can result from environmental effects, such as pavement roughness, or from improper calibration. A WIM system experiencing systematic error will consistently overestimate or underestimate loads. Both of these errors represent the amount of differentiation from a measured static load value. However, as a truck moves over a pavement, the dynamic load actually fluctuates due to a number of road, vehicle, and load characteristics.[152] As a result, the value measured is not fixed, but rather represents a sample from a wave form that fluctuates about the static load. For

the purpose of weight classification and comparison, it is necessary to use the sampled dynamic load to estimate a static load.

In the U.S., three types of WIM technologies are widely applied: bending beam plates, load cells, and piezoelectric sensors.[153] Although costs vary heavily from site to site, Table 15 provides estimated construction and maintenance costs for the three commonly used WIM system.[154] These values were estimated in 2000, and provide only a rough estimate of WIM system costs. According to one technology provider, the typical life of a traditional WIM system is about 15 years, a length determined more by pavement conditions than scale life.[155]

Table 15. WIM System Cost Comparison
(Source: IRD)

Technology	Initial Cost ($)	Installation Cost ($/lane)	Installation Time (days)	Life-Cycle Cost ($ per lane)
Bending Beam	8,000	13,500	3	6,400
Load Cell	39,000	20,800	3	6,200
Piezoelectric Sensor	2,500	6,500	<1	4,750

A bending beam plate consists of a single piece of metal with no welding or bolting.[156] Attached strain gauges measure the deflection in the beam when a truck crosses it. For most efficient operation of a bending plate system, staggered plates should be placed in highway lanes to weigh both the left and right side of each axle. The overall axle weight should be calculated as the sum of the axles. Bending beams exhibit an approximate absolute error of 10 percent at a 95 percent conformity rate at highway

speeds.[157] However, the installation of multiple plates may reduce 95th percentile error to as little as 5 percent.[158]

A single load cell system should consist of two independent platforms located adjacent to one another in a single travel lane, with each platform bolted to a scale module.[159] The adjacent placement allows all wheel sets on an axle to be weighed simultaneously; together the platforms should cover the width of a travel lane. The axle weight is calculated as the sum of the left and right wheels. Each scale includes a single hydraulic loading cell, and load transfer torque tubes to transfer the load to the load cell, regardless of the location of the tires on the platform. Load cells provide the lowest probability of error for the commonly used WIM technologies at highway speeds, with approximate error of 6 percent at a 95 percent level of conformity.[160]

Unlike the other technologies which measure only vertical force, piezoelectric sensors measure the total energy transferred to a pavement by a passing truck.[161] Piezoelectric sensors directly measure axle weights, unlike load cells and bending beams which measure individual wheel weights. The force measured is affected by acceleration and deceleration of the trucks. As a result, piezoelectric scales exhibit higher absolute errors of about 15 percent at highway speeds and a 95 percent conformity rate.[162] Like bending beam systems, the installation of multiple sensors may reduce errors by as much as 50 percent.[163] Piezoelectric sensors are typically ceramic, and are often encased in aluminum to reduce effects of lateral forces.[164]

A number of additional WIM technologies are currently in development to address shortcomings of the commonly used technologies. Quartz piezoelectric sensors have been developed to provide a more linear output and demonstrate improved stability over long periods of time and various temperatures compared to traditional ceramic piezoelectric sensors.[165] In addition, quartz is an extremely stiff material that deflects very little; therefore it provides a high frequency response to a truck passage, and is good for fast changing measurements. Under normal conditions, quartz sensors exhibit an improved error rate at a 95 percent confidence interval.[166] However, the error of the sensor is highly sensitive to the flatness of the pavement surrounding it. Technology tests performed under controlled conditions with extremely flat pavements on a straight path achieved a maximum error of only two percent at speeds up to 45 miles per hour.

Although not yet in use commercially, several types of fiber-optic sensors are also in development for WIM. These include fiber grating sensors[167] and forward time division multiplexing (FTDM) dual-core sensors.[168] Fiber-optic sensors have lower power requirements and are less sensitive to harsh environments than traditional sensors.[169] As a result, fiber-optic technology could eventually achieve a highly accurate sensor for about the same cost as a ceramic piezoelectric sensor.

Another system that has been tested for research, but is not yet in commercial use is a seismic WIM system (SWIM).[170] This system uses geophones and speed measurement devices to measure the speed and the strength and spectrum of the

seismic signal emitted from a passing truck. These measurements can be used to derive the weight of the truck. Studies of seismic WIM systems performed in Florida and Alabama found these technologies are most useful when applied on asphalt pavements. Seismic WIM systems are not yet ready for real world application; measurements are highly dependent on truck, pavement, and soil properties, and are highly sensitive to temperature, moisture, and wind.

4.2 WIM APPLICATIONS

4.2.1 Planning

Transportation planning agencies collect WIM data to characterize truck traffic in a given region. Planners use this data to examine relative vehicle classification volumes as well as to establish standard truck profiles within individual vehicle classes. The Federal Highway Administration's (FHWA) Traffic Monitoring Guide recommends that states operate at least 90 WIM sites for collection of truck information, and that at least one third of these sites collect data quarterly each year.[171] The state of California utilizes 90 piezoelectric and bending plate WIM systems to collect data continuously for pavement management and highway monitoring applications.[172] In Texas, the Department of Transportation's (TxDOT) Planning and Programming division collects WIM data from bending plate systems at 15 sites throughout the state.[173] Truck profiles can be used to examine the distribution of loading contributions within each vehicle class. The distribution of total 18-kip equivalent single axle loads (ESALs) applied

to a pavement by a single vehicle pass can be estimated from axle weights collected. When combined with traffic data, WIM data can provide information about the overall ESAL contribution of a vehicle class within a given region. This information is used in highway cost allocation to assign proportional responsibility for highway costs across vehicle classes.[174]

4.2.2 Weigh Enforcement

WIM systems are also widely used in the U.S. for weight enforcement applications. Weigh-station pre-clearance systems combine WIM technologies and vehicle identification technologies to prescreen trucks for weight enforcement while they travel at highway speeds. Pre-clearance systems in the US utilize radio frequency identification (RFID) transponders to identify vehicles. An antenna, generally located about a mile before a weigh station, sends a signal to a transponder located in the truck, triggering the transponder to send its identifying data to a remotely located computer.[175] In addition, weight data is transmitted from WIM scales located in highway main lanes and a height detector verifies that a truck is not over its height limit. The computer then verifies the credentials for the truck and ensures that it is within its weight and height requirements. The computer sends a transmission back to the truck's transponder instructing the driver to either bypass or pull into the weigh station. RFID transponders are easy and accurate devices for identifying vehicles. The largest pre-clearance system in the US is the PrePass system, which operates 280 sites in 28 states. PrePass collects a monthly user fee for enrolled trucks to maintain and operate

its system. PrePass members must be pre-certified, and their safety records and credentials are continuously verified by state agencies.[176] While its technologies are compatible, PrePass is not currently integrated with the other state operated weigh-station bypass systems in the US and Canada because of operational differences.

Several U.S. and Canadian studies have been completed to examine the feasibility and performance of "Virtual Weigh Station" (VWS) systems that combine cameras, OCR technologies, and WIM for remote, portable weight enforcement. As vehicles pass a VWS, the camera is triggered, either by the WIM or by other sensors. The camera then captures an image of identifying numbers on a truck, usually the USDOT identification numbers required on the truck or its license plate. The image is then transmitted with WIM data to a remote system which reads the captured ID numbers and compares them with an existing database to check credentials. Operating these systems in the mainline of a roadway can eliminate the need for off-road weigh stations. A study performed in Indiana identified benefits in the efficiency of identifying overweight trucks for weighing when using mobile enforcement.[177] This enforcement would be particularly useful on secondary roadways to catch trucks evading static stations. Unlike the RFID systems, these systems can be used to check credentials for all trucks, not just enrolled carriers. However, VWS systems have not achieved the accuracies of weigh station bypass systems for vehicle identification. The Kentucky DOT performed tests on a system architecture consisting of two loops for triggering of a fast-shutter, high resolution camera combined with WIM scales. While 92 percent of system

triggers represented actual truck passes, only 78 percent of those valid triggers captured the truck's USDOT numbers.[178] Of those captured, only 44 percent were readable, resulting in only a 34 percent success rate in capturing readable USDOT numbers for trucks. Factors contributing to inability of the system to read the numbers included camera placement, truck speed, lighting conditions, and inconsistencies of the size, font, color, and contrast of the USDOT numbers on the trucks.[179] In addition, researchers faced problems finding a reliable, efficient, and affordable communications network.

A similar study was performed in Saskatoon, Canada, where 2 highway lanes were equipped with WIM and video license plate readers.[180] This study also used cable modems for data transmission from the devices and wireless communications to transmit data to police laptops. This study was able to identify the most frequently weight violating class of users, two-axle trucks.

The most recent application of a VWS is Florida's remotely operated compliance station (Rocs™).[181] The system, installed in July 2006, includes an upstream loop detector, an ASTM Type III quartz-piezo WIM system, and digital camera technologies. WIM measurements are used to identify several types of violating vehicles. These include "off scale," overweight, and speeding vehicles and out-of-balance loads. Truck weight triggers a camera that takes 3 digital photographs that are then transmitted to a remote enforcement site, where violating vehicles are identified.

4.2.3 WIM for Highway Cost Allocation

The same WIM data used for transportation planning is employed in cost-allocation studies. In these studies, which will be discussed in detail in the next chapter, traffic loadings for individual vehicle classes can be identified from WIM data. Load-related costs can then be assigned to individual vehicle classes based on their share of contributions to infrastructure damage, congestion, and other marginal costs. However, in directly applying this WIM data for cost allocation, vehicle dynamic effects are not considered. As was described above, WIM systems measure a vehicle's dynamic load, and convert that force to a static load. Depending on a vehicle's suspension system, axle configuration, and speed at the time of measurement, as well as on the roughness of the pavement at the location of a scale, the dynamic load measured by a WIM system will change. Under current cost allocation methods, all vehicles within a vehicle class, regardless of suspension system, are assigned equal cost responsibilities. Fekpe explored and quantified the potential impacts on cost allocation of different suspension systems for varying speeds and pavement roughness values.[182]

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CHAPTER 5: HIGHWAY COST ALLOCATION STUDIES

Highway cost allocation (HCA) studies are performed to determine the share of system user costs, including operations, infrastructure construction and maintenance, as well as marginal social costs such as contributions to congestion, that should be attributed to individual vehicle classes. These studies are performed at both federal and state levels using a variety of methodologies. In addition to allocating costs, HCA studies can be used to examine the equity of existing user fees. There are several approaches to allocating highway costs; these include a cost-occasioned approach, a benefit-based approach, and a marginal cost approach.[183]

5.1 GENERAL COST ALLOCATION METHODS

A cost occasioned approach relates physical and operational vehicle characteristics to expenditures for infrastructure improvements. Cost occasioned approaches include both an incremental method and the mixed "Federal" Method.[184] An incremental approach calculates the cost of a minimum facility for the smallest user class, and incrementally assigns additional costs to subsequent classes. All vehicle classes pay for a share of the costs for the base facility equivalent to their usage of the system.[185] Research has found that the order in which classes are added using the incremental method impacts the resulting cost responsibility shares[186]; as a result, a modified incremental method has been proposed. This method determines cost portions attributable to individual classes, then determines portions attributable to

groups of vehicles.[187] The final portion of costs attributable to a class is calculated as the sum of total cost portions attributable solely to that class plus the fractions of cost portions attributable to groups to which that class belongs. The "Federal" Method uses a "consumption" method to allocate pavement maintenance costs and uses an incremental approach to allocate other costs.[188]

In a benefit based approach, costs are allocated to vehicle classes based on the relative benefits of highway improvements for those classes. A benefits-based approach actually allocates some costs to non-users of the system, as social and economic benefits of highway improvements extend beyond system users.[189] However, quantification of benefits to apply such an approach is extremely difficult. A marginal cost approach estimates the marginal impacts of vehicle classes on infrastructure, congestion, the environment, and other marginal social costs (e.g. noise).

The 1997 Federal HCA Study, the most recent comprehensive federal study, applied a cost-based approach to assign load and non-load related infrastructure cost responsibilities across 20 passenger and commercial vehicle classes.[190] In the federal study, highway costs were divided into four primary categories: pavement costs, bridge costs, system enhancement costs, and other attributable costs. Within each of these categories, costs were further divided into sub-categories so that different variables could be used to allocate costs. These subcategories and the associated vehicle characteristics used for cost allocation are shown in Table 16.

Table 16. Cost Categories and Allocation Variables, 1997 Federal HCA Study
(Source: 1997 Federal HCA)

Cost Category	Specific Cost	Variable
Pavement	New lane construction, base facility	PCE weighted VMT
	New lane construction, additional thickness	ESALs
	Reconstruction, rehabilitation, and resurfacing	Pavement distress contributions, NAPCOM model
Bridge	New bridge construction, base facility	PCE weighted VMT
	New bridge construction, additional strength	Weight and axle spacings
	Reconstruction and rehabilitation	VMT or weight/axle spacings
System Enhancement	System management, safety improvements, ITS, envronmental mitigation, highway beautification, transit/intermodal/pedestrian projects	Varies by cost, many use PCE
Attributable	Geometric elements, grading, drainage, width, ridesharing facilities, truck specific facilities	Varies based on relationship between cost element and vehicle characteristic

The largest individual cost category for the federal HCA is load-related pavement maintenance costs, which accounted for 25 percent of total federal highway costs in 2000.[191] In the 1997 study, these costs were allocated incrementally using Long Term Pavement Performance (LTPP) data and results from 11 National Pavement Cost Model (NAPCOM) mechanistic pavement distress models.[192] Pavement construction and bridge construction costs were allocated using incremental design methods. Bridge maintenance costs were allocated both incrementally and proportionally depending on the specific maintenance cost.

A 2008 synthesis of state highway cost allocation studies identified 85 studies that have been completed in 30 states.[193] Most of these studies utilized a cost

occasioned approach, using either Incremental or "Federal" methods. A marginal approach has been employed for a study in Ontario.[194]

The most recent Texas HCA study, performed in 2002, examined user revenues and expenditures for Texas Department of Transportation (TxDOT) operated facilities.[195] The study allocated costs across 12 user classes using five different cost allocation methods. Texas costs were also divided into four categories: pavement construction costs, pavement rehabilitation and maintenance costs, bridge costs, and common costs. Common costs, defined as non-load related costs, were allocated according to class VMT. Pavement construction costs attributable to each vehicle class for rigid and flexible pavements were estimated using models to calculate construction costs based on the number of expected ESALs for each class. Regression analysis was performed to estimate a function to determine costs per lane mile as a function of GVW. Class VMT by weight class was then used to allocate bridge construction costs to vehicle classes. Although theoretically superior methods were considered for allocation of load-related rigid pavement costs, a lack of necessary data to implement these methods led researchers to allocate pavement rehabilitation and maintenance costs proportionally using ESAL estimates.[196]

Five allocation methods for flexible pavement rehabilitation costs were examined; these methods include a generalized method, developed by Villarreal to apply the theory of cooperative games for highway costs allocation, a modified incremental method, a proportional ESAL method, the FHWA developed State Highway

Cost Allocation Method, and a variable-lane method that allows the number-of-lanes on a facility to increase.[197] This variable number-of-lanes scenario could increase the share of costs attributable to passenger vehicles, as these vehicles demonstrate much higher volumes than more damaging commercial vehicles. Although it is hard to definitely identify the "most accurate" method of HCA, authors of the Texas study recommend use of the generalized method for load-related pavement cost allocation. Bridge costs were allocated using an incremental design method.

5.2 QUANTIFYING INFRASTRUCTURE COSTS

For this study, which will attempt to directly link tolls with infrastructure costs, a cost-occasioned approach will be employed. Methods of quantifying infrastructure consumption that can be employed to link costs to individual classes, vehicles, and loads are discussed in the following sections.

5.2.1 Pavement Consumption

As the Texas HCA demonstrates, no definitive method for quantifying truck contributions to pavement deterioration has yet been developed. The traditional method for relating vehicle loads to pavement deterioration is empirical estimation of Equivalent Single Axle Loads (ESALs). ESALs represent the ratio of pavement distresses caused by a specific axle load or vehicle to distresses caused by an 18-kip standard axle load. These ratios are calculated using the empirical pavement design formulas developed in the 1950s during the American Association of State Highway Officials'

(AASHO) road tests. These formulas relate axle load and pavement performance in terms of present serviceability index (PSI).[198] This PSI factor integrates different types of pavement distress, including cracking, patching, rutting, and longitudinal profile, into a single term. When two consecutive axles are between 40 and 96 inches apart, they are classified as a tandem axle, and a single ESAL ratio is calculated for the tandem axle group. Three consecutive axles with axle spacings between 40 and 96 inches are classified as a tridem axle. The empirical AASHTO formulas for estimation of ESALs for flexible (Eq. 1) and rigid (Eq. 2) pavements are below.

$$E_x = \frac{1}{\left[\frac{L_{18} + L_{2s}}{L_x + L_{2x}}\right]^{4.79} \left[\frac{10^{G/\beta_x}}{10^{G/\beta_{18}}}\right] \left[L_{2x}\right]^{4.33}}$$

(Eq. 1)

where

E_x = number of ESALs applied to a pavement by load L_x
L_x = axle load being evaluated (kips)
L_{18} = standard axle load (kips)
L_2 = code for axle configuration (1 for single, 2 for tandem, etc.)

$$G = \log\left(\frac{4.2 - p_t}{4.2 - 1.5}\right)$$

p_t = terminal serviceability index

$$\beta = 0.4 + \left(\frac{.081\left(L_x + L_{2X}\right)^{3.23}}{\left(SN + 1\right)^{5.19} L_{2x}{}^{3.23}}\right)$$

SN = Structural Number

$$E_x = \frac{1}{W_{18}\left[\frac{L_{18}+L_{2s}}{L_x+L_{2x}}\right]^{4.62}\left[\frac{10^{G/\beta_x}}{10^{G/\beta_{18}}}\right]\left[L_{2x}\right]^{3.28}}$$

(Eq. 2)

where E_x = number of ESALs applied to a pavement by load L_x
L_x = axle load being evaluated (kips)
L_{18} = 18 kip standard axle load
L_2 = code for axle configuration (1 for single, 2 for tandem, 3 for tridem)

$$G = \log\left(\frac{4.5-p_t}{4.5-1.5}\right)$$

p_t = terminal serviceability index

$$\beta = 0.4 + \left(\frac{3.63\left(L_x+L_{2X}\right)^{5.20}}{\left(D+1\right)^{8.46} L_{2x}^{\ 3.52}}\right)$$

D = Slab Thickness

Empirical ESALs are widely applied in pavement design and in HCA for ease of application. In incremental allocation of pavement construction costs, ESALs can be used directly as a cost allocator to determine class responsibilities for pavement design thickness. In allocation of pavement maintenance costs, many studies assign class responsibilities based on ESAL-miles.

However, there has been much debate in recent years over the utility of the ESAL function. These empirical formulas were developed under very specific environmental conditions using vehicles different than those available in today's fleets. More recently, mechanistic models have been developed to better quantify the impact of loads on specific pavement distresses. Mechanistic models directly relate load repetitions to the progression of different types of distresses such as cracking, rutting, and faulting. Mechanistic models were first used for HCA in the 1982 Federal HCA

Study. The 1997 Federal HCA Study employed the same methods; however for the 1997 study, a new nationwide pavement cost model (NAPCOM) was developed.[199] This model incorporated 11 distress models that were developed using data collected from the Long Term Pavement Performance (LTTP) study.

In 2004, a new Guide for Mechanistic-Empirical (M-E) Design of New and Rehabilitated Structures was developed through a National Cooperative Highway Research Program (NCHRP) Project.[200] The new guide uses mechanistic-empirical models to estimate pavement performance over time or use. Under the new design guide, individual pavement distresses can be examined; for flexible pavements, these include fatigue, rutting, and thermal cracking, and for rigid pavements, these include cracking and faulting.[201] Additionally, the new guide allows the user to calibrate the models for local conditions. The M-E guide can be used to examine long-term pavement performance under varying traffic loading conditions. By entering the axle load spectra for a given class, which can be easily obtained from WIM data, the number of repetitions to a defined type of failure can be calculated.

While this method can be relatively easily applied to compare the impacts of vehicle classes, examining the impact of individual axle loads is more difficult. In mechanistic models, axle load data is input in the form of axle load spectra for vehicle classes. Hong, Pereira, and Prozzi proposed a method for calculation of "mechanistic ESALs."[202] By inputting a single 18-kip axle load in the model, rather than an axle load spectra, the number of repetitions to failure for a "mechanistic ESAL" can be calculated.

A “mechanistic” load equivalency factor for an individual vehicle could be calculated in a similar manner. By inputting the specific axle loads for an individual vehicle, the number of repetitions to failure for that vehicle could be obtained. Expanding on the concept of “mechanistic ESALs”, a load equivalency factor could then be calculated as the ratio of repetitions to failure for the individual vehicle divided by the repetitions to failure for an 18-kip single axle load. While this method for calculating “mechanistic” load equivalency is simple in theory, calculation of “mechanistic” ESALs for a series of individual axle loads would be extremely time intensive using the existing models. However, if specific maintenance and rehabilitation costs could be linked to specific distress types, the ability to calculate distress-specific “mechanistic” load equivalency factors could allow for better allocation of distress-specific costs.

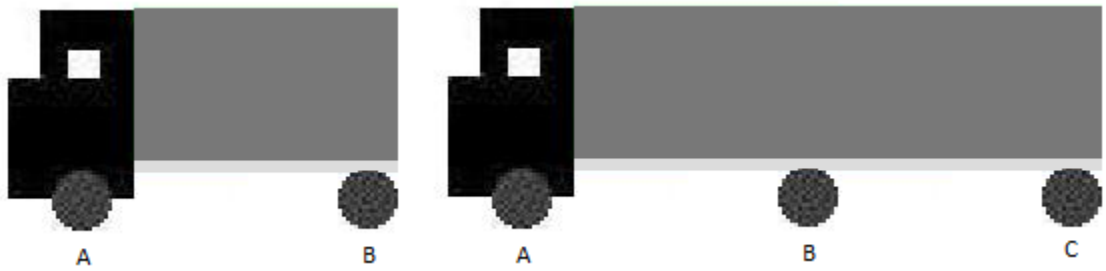
5.2.2 Bridge Consumption

The impact of a truck on a bridge varies depending on both axle loads and the distance between axles.[203] Heavier axle loads increase the stress on bridge girders or beams. In general, the longer the distance between axles, the less impact a truck will have on a bridge (although in some continuously supported bridges, more distantly spaced axles can increase pier stresses). The most commonly used method for allocating bridge construction costs is an incremental approach which relates individual vehicle classes to AASHTO design vehicles.[204] AASHTO has defined a series of vehicles that are used in bridge design. These vehicles do not represent common truck configurations, but rather were specifically designed to simulate the most severe live

loads on a structure. Table 17 provides the axle loads and spacings for these defined vehicles. Like in incremental pavement cost allocation, a base facility required to carry the lightest vehicle class (H2.5) is identified. The costs of additional strengthening elements to allow for each subsequent class to operate are then allocated only to the responsible truck classes.

Table 17. AASHTO Bridge Design Vehicles

Design Vehicle Type	Axle Loads (kips)			Axle Spacings (ft)	
	A	B	C	AB	BC
H2.5	1	4	-	14	-
H5	2	8	-	14	-
H10	4	16	-	14	-
H15	6	24	-	14	-
H20	8	32	-	14	-
HS15	6	24	24	14	14 to 30
HS20	8	32	32	14	14 to 30
HS25	10	40	40	14	14 to 30



Tee, Sinha, and Ting reviewed early methods of incremental bridge cost allocation.[205] The 1982 Federal Highway Cost Allocation study, as well as early studies in Georgia, Florida, Iowa, and Wisconsin, used gross vehicle weight (GVW) to assign study truck classes to bridge design vehicle classes for both simply and continuously supported bridges. A study in Maryland used both axle spacing and axle loads to correlate study classes with design classes for simply supported bridges. Tee, Sinha, and

Ting's own Indiana study used the live-load moment created on simply and continuously supported bridges to correlate study vehicle classes with design vehicle classes. The 1997 Federal HCA Study and the last Texas HCA Study also used an incremental analysis that related study classes to design vehicle classes using live-load moments for different highway classes (defined by mean span length) and support type.[206,207] Both the Indiana study and the 1997 Federal HCA Study introduced intermediate design vehicle classes (e.g. H17.5) to reduce the number of medium-weight trucks paying for the highest cost bridges. Since live-load moment is a function of both axle load and axle spacing, this method cannot be applied to assign bridge cost responsibilities directly for individual loads.

Quantifying a measure to relate truck characteristics with bridge maintenance costs is more difficult. If maintenance includes specific improvement of structures that are "structurally deficient," or unable to carry the required traffic, costs are considered "load-related." These costs can be allocated to responsible classes using the same incremental method,[208] or by some other method of quantifying truck-only costs, such as heavy vehicle miles traveled (HVMT).[209] Laman and Ashbaugh have also examined a method employing Miner's Hypothesis, the same theory used in "mechanistic" pavement design models, for allocation of fatigue-related costs for steel bridges.[210]

If improvements are made to a bridge that is "functionally obsolete" due to capacity, geometric, or other safety deficiencies, no good allocator for these costs can be defined to distinguish between vehicle cost responsibilities. Generally, highway cost

allocation studies assign these costs to vehicle classes according to their system use (VMT).

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CHAPTER 6: METHODOLOGY FOR TOLL RATE DETERMINATION AND ANALYSIS

As discussed in previous chapters, there is a need to develop mechanisms for future road pricing that will better recover infrastructure consumption costs from individual users. Existing user charges rely on number-of-axles or registered GVW to distinguish between classes of users. Generally, a vehicle with more axles or more GVW pays a higher user fee. However, depending on the vehicle's configuration, its bridge and pavement impacts may actually be lower than that of a vehicle paying a lower toll. Weigh-in-motion (WIM) systems have the capability, with varying degrees of accuracy, to collect real-time axle load and axle spacing data from individual trucks. As system accuracies improve, these technologies could be deployed both to collect better information about the types of trucks operating on a given roadway and as part of an integrated road pricing technology system to toll vehicles based on real-time weight and vehicle configuration.

6.2. DETERMINATION OF TOLL STRUCTURE

The first step in implementing a new WIM tolling system that will better recover infrastructure costs is to determine the structure of the toll. Ideally, a vehicle's exact infrastructure impacts could be measured as a function of its axle loads and axle spacings for each bridge and pavement section that it crosses. However, implementing such a toll to exactly recover these costs would require a multi-part structure with separate charges for pavements and individual bridges. Pavement impacts could be

calculated as a function of individual axle loads, whether through empirical or mechanistic methods; an axle-load based structure could be implemented to recover these costs. For each bridge, a truck would have to be classified to a design vehicle class, likely using live-load moment as a measure. Since this variable is calculated as a function of the bridge length, a truck's rating would vary for different bridges. A toll structure to best recover these costs would distinguish trucks by design vehicle class and would be paid for each individual bridge crossing. A third tolling element would need to be paid per vehicle for non-load related costs to use a facility.

Clearly, implementing such a structure would be extremely difficult. Although every driver would pay almost exactly their share of infrastructure consumption costs, the toll structure would no longer be transparent. On a facility such as a toll road, where users choose whether or not to pay to use it, a lack of transparency in the toll structure would serve as a deterrent to potential users. Even on a facility where a driver has no choice, a complex tolling structure would be confusing to drivers.

The toll structure proposed in this study to improve equity while maintaining transparency is a two part toll. An initial base toll is charged to all commercial and passenger vehicles to recover all common costs and the costs of basic infrastructure. Heavy vehicles pay an additional cost per axle-load to recover additional infrastructure costs necessary to accommodate their weight. The toll is designed to recover infrastructure costs from all legally operating vehicles. It is assumed that if overweight

vehicles are allowed to operate, an additional cost would be paid to recover these costs. The problem of pricing for overweight vehicles will not be addressed in this study.

The next step in developing this new toll structure is determination of load class limits. As discussed previously, the two types of infrastructure costs that must be considered in the “Axle-Load” portion of the toll are pavement costs and bridge costs. In general, over the life of a highway facility, the largest type of load-related infrastructure cost that it will incur will be the cost of pavement maintenance. Since pavement impacts are estimated as a function of individual axle loads, initial load classes can be proposed by examining the relative pavement impacts caused by loads belonging to individual classes. In order to examine the relative impacts of each class, the traffic volumes, truck profile, and axle load distributions for the facility must first be identified. Total vehicle volumes over the design life of the facility should be estimated through traffic analysis. The truck profile and axle load distributions are obtained from WIM data. Figure 7 shows the process for estimating the truck profile from raw WIM data.

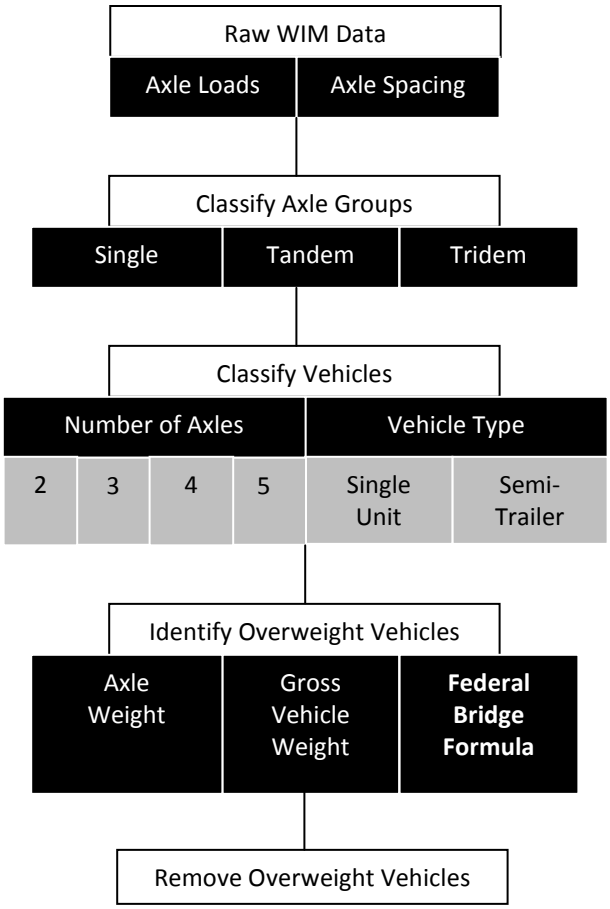

Figure 7. WIM Data Processing

Axle load spectra can also be obtained from the WIM data by examining individual load types. In planning and design applications, axle load spectra are estimated separately for different vehicle classes and axle types. In this study, the distribution of interest is the overall distribution for each axle type: single, tandem, and tridem. The probability that a load of a given type belongs to a given load class can be estimated discretely from the observed data (Eq. 3).

$$P_L = \frac{n_L}{N}$$

(Eq. 3)

where: n_L = number of observed loads belonging to class L
N = total number of observed loads

This probability may also be estimated from a continuous distribution. Research has found that the distribution of axle loads for a given vehicle and axle type can be estimated as a mixed-lognormal distribution.[211,212] The lognormal distribution is described by the following probability density function (PDF):

$$f(x_{v,a} : \mu, \sigma) = \frac{1}{\sqrt{2}\pi\sigma} \exp\left(-\frac{1}{2} \left(\frac{\ln(x_{v,a}) - \mu}{\sigma} \right)^2 \right)$$

(Eq. 4)

where: $x_{v,a}$ = axle load belonging to vehicle type v and axle type a
μ,σ= parameters of the lognormal function

In a mixed lognormal distribution, the overall probability distribution is estimated as a weighted sum of several lognormally distributed probability distributions. Past studies have found that different vehicle and axle loads types are best represented as a sum of two or three lognormal distributions.[213,214] These distributions do have physical meaning, as load spectra may include empty, moderately loaded, and fully loaded vehicles.[215] The weights of the distributions may

represent the share of vehicles that fall into these loading levels. The PDF for the final mixed-lognormal distribution is described by the following function:

$$f(x_{v,a} : \mu_i, \sigma_i) = \sum_i^I \frac{W_i}{\sqrt{2}\pi\sigma_i} \exp\left(-\frac{1}{2}\left(\frac{\ln(x_{v,a}) - \mu_i}{\sigma_i} \right)^2 \right)$$

(Eq. 5)

where: $x_{v,a}$ = axle load belonging to vehicle type v and axle type a
μ_i, σ_i= parameters of the ith lognormal function
W_i = weight of distribution i
I = total number of weight distributions

Once the axle load distributions for each vehicle and axle type are estimated, the overall distribution of each axle type can also be estimated as a mixed lognormal distribution. Weights for each vehicle class can be determined from the observed data and traffic estimates as a conditional probability.

$$P_v = \frac{n_{v,a}}{N_a}$$

(Eq. 6)

where: P_v = probability that an axle load of type a is on a vehicle of type v
$n_{v,a}$= number of axle loads of type a on a vehicle of type v
N_a = total axle loads of type a

Finally, the mixed lognormal distribution representing the entire axle type class can be formulated as:

$$f(x_a : \mu_i, \sigma_i) = \sum_{v}^{V} P_v \times \sum_{i}^{I} \frac{W_i}{\sqrt{2}\pi\sigma_i} \exp\left(-\frac{1}{2}\left(\frac{\ln(x_{v,a}) - \mu_i}{\sigma_i} \right)^2 \right)$$

(Eq. 7)

where: $x_{v,a}$ = axle load belonging to vehicle type v and axle type a
P_v = probability that an axle load is on a vehicle of type v given that it belongs to axle type a
V = total number of vehicle types
μ_i, σ_i= parameters of the ith lognormal function
W_i = weight of distribution i
I = total number of weight distributions

The continuous distribution function (CDF) can then be found by integrating (Eq. 7):

$$F(x_a : \mu_i, \sigma_i) = \int \sum_{v}^{V} P_v \times \sum_{i}^{I} \frac{W_i}{\sqrt{2}\pi\sigma_i} \exp\left(-\frac{1}{2}\left(\frac{\ln(x_{v,a}) - \mu_i}{\sigma_i} \right)^2 \right) dx_a$$

(Eq. 8)

where: $x_{v,a}$ = axle load belonging to vehicle type v and axle type a
P_v = probability that an axle load belonging to vehicle type v given that it belongs to axle type A
V = total number of vehicle types
μ_i, σ_i= parameters of the ith lognormal function
W_i = weight of distribution i
I = total number of weight distributions
dx_a = incremental change in load weight

Although this function cannot be directly evaluated, because it is simply the weighted sum of a number of lognormal functions, it can easily be evaluated using common statistical software programs. The probability of a load belonging to a given weight class can then be calculated by evaluating the CDF at the upper and lower limits of the weight class.

$$P_l = F(x_u) - F(x_l)$$

(Eq. 9)

where: P_l = probability that a load belongs to class l
x_u = upper weight limit of load class l
x_l = lower weight limit of load class l

After the probability that a load belongs to a given class is estimated, some measure of relative pavement impact for each load class must also be estimated. Again, depending on the method of analysis, different methods of estimation can be used. If equivalent single axle loads, estimated through either empirical or mechanistic methods are employed, the relative damage can be estimated discretely from the observed data. First, for each observed load, the number of ESALs contributed by that load should be calculated (Eq. 2). Next, the total pavement impact for a given load class can be estimated:

$$E_l = \sum_X E_x$$

(Eq. 10)

where: E_l= number of ESALs applied to a pavement by load class l
E_x = number of ESALs applied to a pavement by load x
X = the set of all loads belonging to class l

Finally, the expected number of ESALs applied to a pavement by a load belonging to a given class can be estimated:

$$\exp E_l = \frac{E_l}{n_l}$$

(Eq. 11)

where: $\exp E_L$ = expected number of ESALs for a load belonging to class l
E_l= number of ESALs applied to a pavement by load class l
n = number of loads belonging to class l

Once relative impacts have been quantified, load classes should be defined so that classes of different axle types causing the same relative impacts pay equal shares. Iteration of load class limits will be required to identify optimal classes.

Currently, a continuous distribution cannot be used to estimate the relative pavement impacts of individual load classes. Research has found that the pavement damage caused by an individual vehicle and axle class can be estimated as the fourth moment of the load distribution function.[216] However this method cannot be employed in this study for several reasons. First, although the moment function can be used to obtain the overall damage from the load distribution function, it cannot distinguish the damage caused by individual load classes within that distribution. Additionally, in this study, only legal loads are of interest. Because the lognormal distribution is continuous, even if regression analysis to estimate the parameters of the mixed lognormal distribution is performed using only legal loads, some portion of loads will be estimated to be overweight. For example, Table 18 shows the parameters estimated for the distribution functions for the WIM data used in the case study to be described in the next chapter. These distributions were estimated using the non-linear least square

(NLLS) technique previously employed by Prozzi and Hong[217] and Timm, Tisdale, and Turochy[218]. As can be seen from the R^2 values, the data fit for most of the vehicle and axle type classes is very good. However, Figure 8 shows that the resulting functions, especially for tandem axles, predict a noticeable portion of overweight loads. Just as load classes cannot be distinguished, there is currently no good method to determine the share of the estimated ESALs contributed by overweight loads.

Table 18. Estimated Parameters for the Mixed Lognormal Distribution

Truck Type	Axle Type	μ1	μ2	μ3	σ1	σ2	σ3	w1	w2	w3	R^2
2SU	Steering	1.404	1.965	-	0.134	0.292	-	0.806	0.194	-	0.99998
	Single	1.168	1.398	2.247	0.222	0.267	0.369	0.577	0.216	0.207	0.99996
3SU	Steering	2.344	2.397	2.197	0.087	0.169	0.476	0.210	0.670	0.120	0.99961
	Tandem	2.145	2.648	3.333	0.193	0.533	0.136	0.177	0.453	0.370	0.98913
3ST	Steering	1.430	1.893	2.172	0.135	0.144	0.138	0.502	0.144	0.354	0.99995
	Single	0.736	1.434	2.333	0.358	0.224	0.377	0.270	0.224	0.506	0.99783
4SU	Steering	2.021	2.342	2.774	0.038	0.103	0.064	0.348	0.440	0.212	0.90080
4ST	Steering	1.466	2.225	1.678	0.090	0.143	0.362	0.410	0.442	0.148	0.99962
	Single	1.615	1.542	2.399	0.183	0.575	0.425	0.238	0.316	0.446	0.99425
	Tandem	1.552	2.134	2.625	0.250	0.486	0.439	0.142	0.359	0.499	0.99820
5ST	Steering	1.573	2.401	2.284	0.330	0.080	0.119	0.016	0.640	0.344	0.99949
	Single	1.727	2.822	2.558	0.412	0.095	0.236	0.335	0.232	0.433	0.99795
	Tandem	2.592	3.216	3.466	0.331	0.225	0.068	0.408	0.341	0.251	0.99543
ALL	Tridem	1.950	2.288	2.639	0.190	0.088	0.192	0.351	0.091	0.558	0.99096

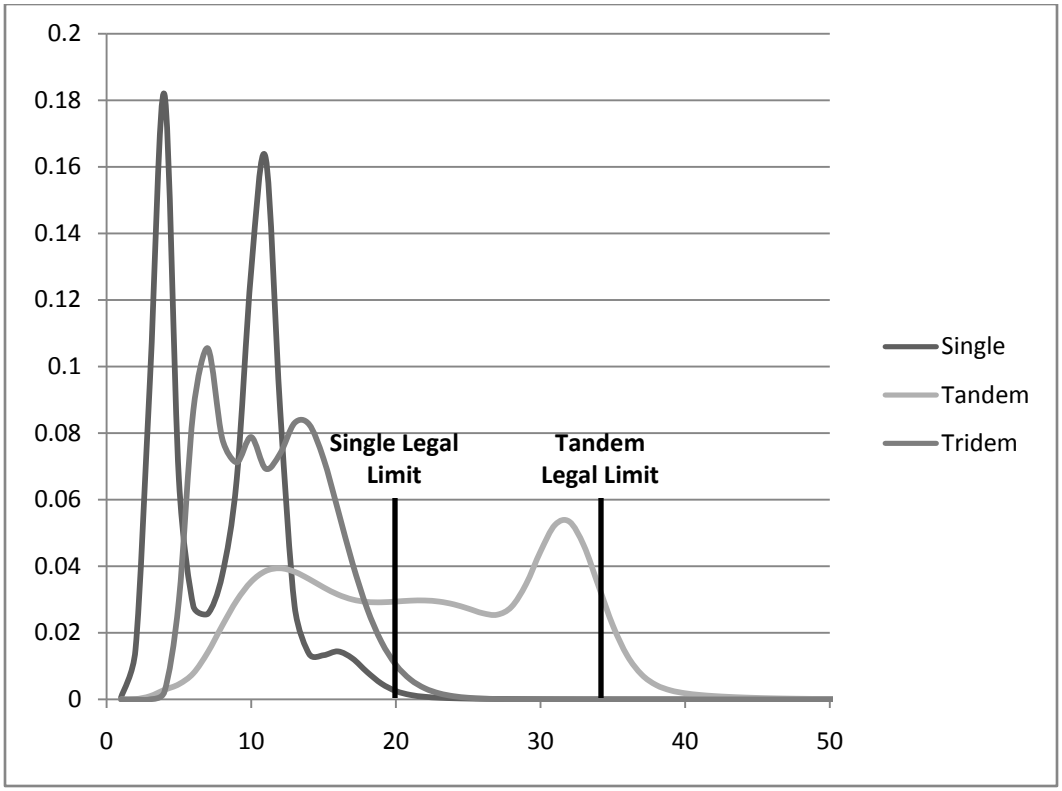

Figure 8. Mixed Lognormal PDFs for Single, Tandem, and Tridem Axles

6.3 AXLE-LOAD TOLL RATE ESTIMATION

Once the individual load classes have been defined, the next step is to estimate the toll rates that should be paid by each class. Figure 9 shows the process used for estimating individual elements of a toll rate.

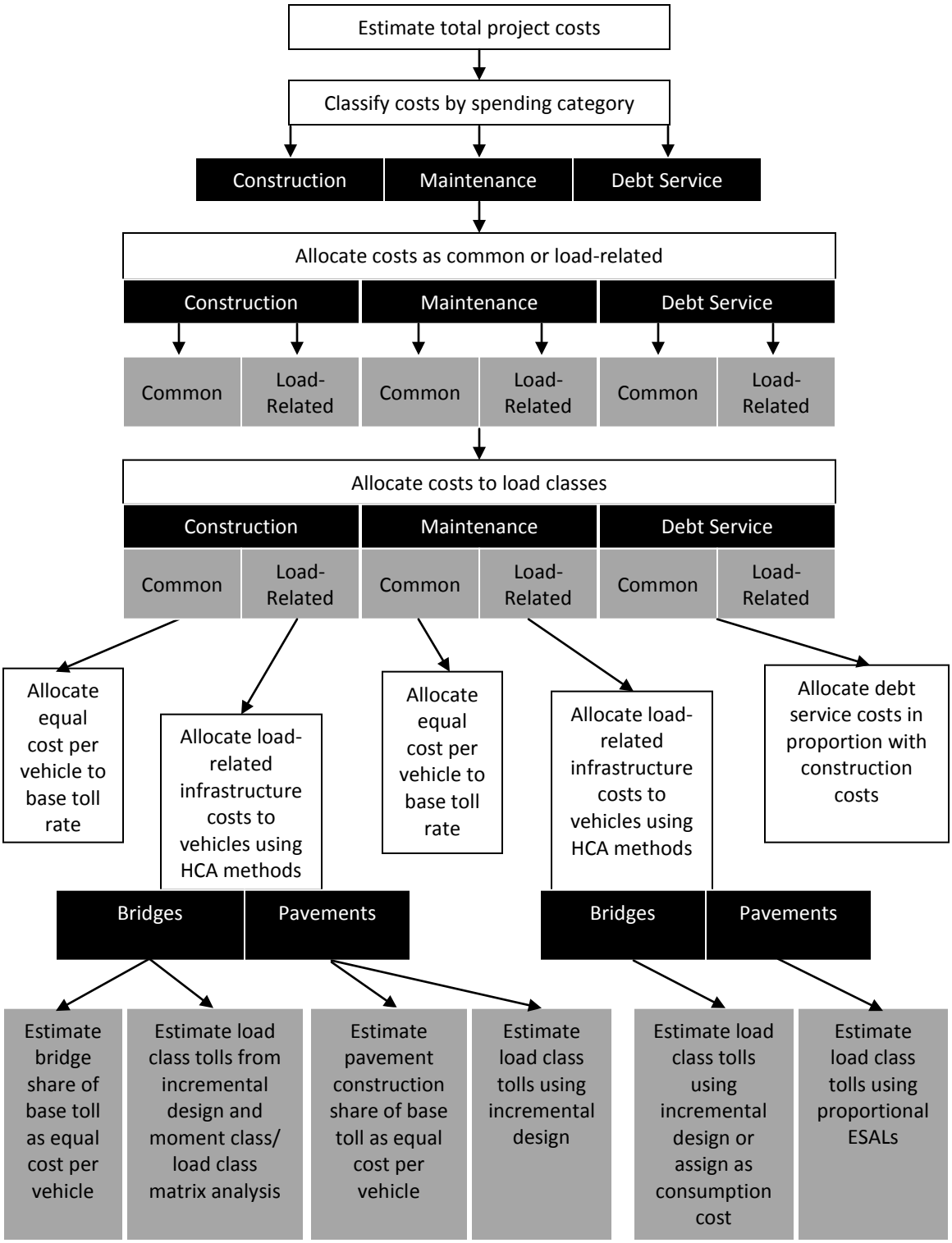

Figure 9. Cost Allocation Method for Toll Rate Determination

First, all construction, maintenance, and operations costs must be quantified for the design life of the toll. Additionally, if new facility construction is being financed through the use of bonds or long-term loans, costs of debt service must also be quantified. If a facility is being operated for profit, desired revenue projections should also be estimated. Once all costs have been identified, individual costs must be classified as common or load-related. In this study, "Load-Related" costs are those that can be directly attributed to heavy trucks.

6.3.1 Common Base Toll Estimation

Common costs are assigned to individual vehicles based on some measure of their use of the facility; for example, a limited access facility could charge a cost per vehicle, while an open facility might charge a cost per vehicle-mile. Here, common costs are assigned to base toll, t_b, as a common cost per vehicle:

$$t_b = \frac{C_c}{n}$$

(Eq. 12)

where: t_b = base toll rate per vehicle ($/vehicle)
C_c = total common costs ($)
n = number of vehicles expected over life of facility

At this stage, in a traditional highway cost allocation (HCA) study, "Load-Related" costs would be assigned to individual vehicle classes, and possibly to GVW classes within those vehicle classes. However, in this study, costs must be assigned to individual axle-load classes. For pavement cost allocation, this process is relatively straightforward.

Since pavement impacts are estimated as a direct function of axle loads whether using empirical or mechanistic methods, both incremental and proportional methods of HCA can be used to assign costs to individual load classes.

6.3.2 Pavement Construction Toll Share

Traditional HCA uses an iterative pavement design method to allocate pavement construction costs. First, a base facility is designed to accommodate the lowest consuming class of vehicles or loads. Depending on the method of design used, this consumption can be quantified by a number of measures. The most commonly used are ESALs and "mechanistic" repetitions to failure . Next, individual classes are added one by one to estimate the total costs of a facility to accommodate each class. As discussed in Chapter 5, in traditional HCA, the order in which vehicle classes are added may impact the results. However, in this study, since it is load classes, not vehicle classes, being added to the base facility, loads belonging to a higher consuming class will definitely be assigned higher cost responsibility than vehicles belonging to lower consuming classes.

Figure 10 shows the iterative pavement design process using the AASHTO traditional design method for a rigid concrete pavement. To estimate load-class ESALs, first ESALs for individual loads are calculated for a given thickness using the empirical ESAL equation (Eq. 2).[219] Total load-class ESALs can then be calculated by summing the contributions of individual vehicles (Eq. 10).

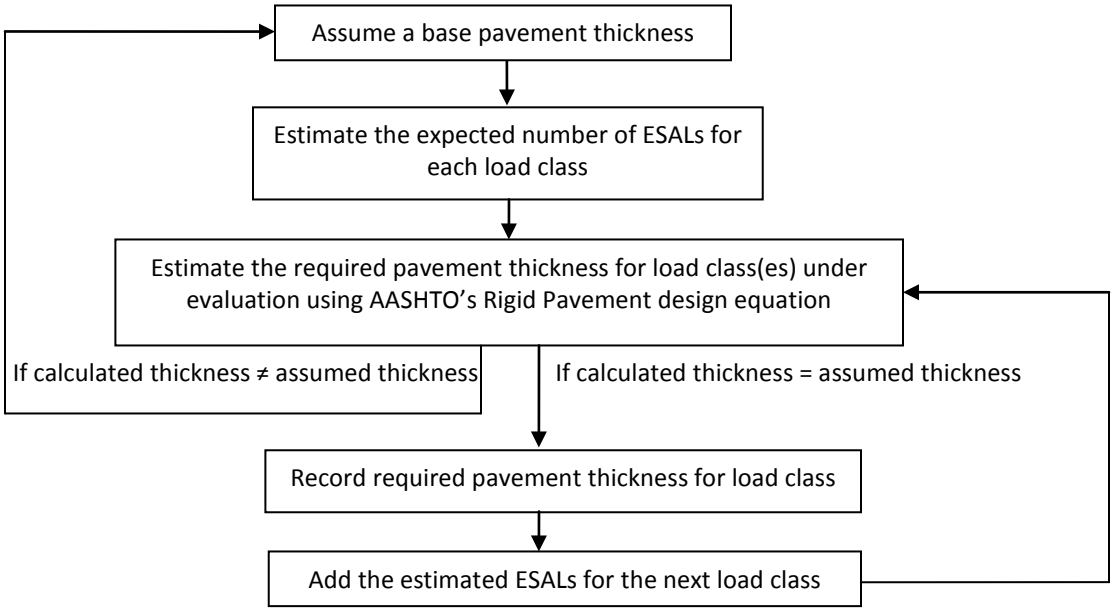

Figure 10. Iterative Pavement Design Process

Once ESALs are estimated for each load class, the required pavement thickness can be estimated by solving for the pavement thickness, D, using AASHTO's pavement design equation:

$$\log(W_{18}) = Z_R \times S_o + 7.35\log(D+1) + \frac{\log\left(\frac{p_o - p_t}{4.2-1.5}\right)}{1+\left[\frac{1.624\times 107}{(D+1)^{8.46}}\right]} +$$

$$(4.22 - .32 p_t)\log\left[\frac{S_c^{'} \times C_d\left(D^{.75} - 1.132\right)}{215.63 \times J\left(D^{.75} - \frac{18.42}{(E_c/k)^{.25}}\right)}\right]$$

(Eq. 13)

where:
- W_{18} = predicted ESALs over life of pavement
- Z_R = reliability
- S_o = combined standard error of traffic and performance prediction
- D = slab depth
- p_o = initial serviceability index
- p_t = terminal serviceability index
- S'_c =modulus of rupture
- C_d = drainage coefficient
- J = load transfer coefficient
- E_c = elastic modulus
- K = modulus of subgrade reaction

Once the total pavement thickness required for each load class has been identified, the total cost of each layer of pavement thickness can be identified. Figure 11 demonstrates how cost responsibilities for layers of thickness of a rigid pavement designed using this procedure would be divided between five classes of vehicles.

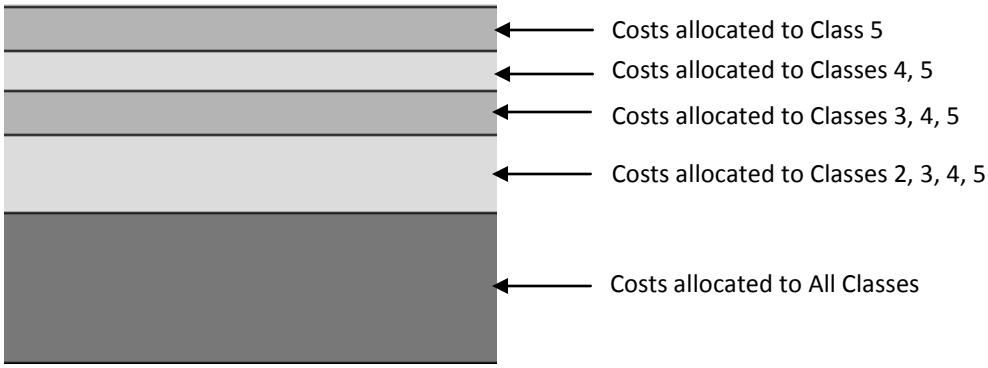

Figure 11. Pavement Construction Cost Responsibility Example

To estimate the pavement construction portion of the load-based toll rate, a cost per load should be determined for each additional incremental thickness. This cost per load is calculated by dividing the total cost of a thickness layer by the number of loads responsible for that layer:

$$c_i = \frac{C_i}{\sum_L n_l}$$

(Eq. 14)

where: c_i = cost per load for increment i ($/load)
C_i = total cost of constructing increment I ($)
n = number of loads belonging to load class l
L = the set of load classes for which i must be constructed

The total pavement construction toll share for each load class can then be calculated by summing the per-load costs across all increments required by that class:

$$t_{PC,l} = \sum_{I} c_i$$

(Eq. 15)

where: $t_{PC,l}$ = pavement construction share of load-related toll for class L ($/load)
c_i = cost per load for pavement increment i
I= the set of pavement increments required to accommodate L

6.3.3 Pavement Maintenance Toll Share

To allocate pavement maintenance costs, the proportional responsibility of vehicles or load classes for pavement distress must be identified. As discussed previously, empirical methods can be used to estimate ESALs directly for individual loads (Eq. 2). Once individual load ESALs are calculated, load class ESALs can be calculated (Eq. 10). Finally, the total number of ESALs applied to a pavement over its design life can be calculated:

$$E_V = \sum_{V} E_x$$

(Eq. 16)

where: E_V = number of ESALs applied to a pavement by all vehicles
E_x = number of ESALs applied to a pavement by load x
V = the set of all vehicles

A cost per ESAL can then be estimated by dividing maintenance costs by the total number of ESALs:

$$c_m = \frac{M}{E_v}$$

(Eq. 17)

where: c_m = maintenance cost per ESAL ($/ESAL)
M = total load-related pavement maintenance costs over design life
E_v = number of ESALs applied to a pavement by all vehicles

Next, the expected number of ESALs applied to a pavement by a load belonging to a given class can be estimated (Eq. 11). Finally, the maintenance toll rate share for a load belonging to a given load class can be estimated by multiplying the estimated cost per ESAL by the expected ESAL:

$$t_{PM,l} = c_m \times \exp E_l$$

(Eq. 18)

where: $t_{PM,l}$ = pavement maintenance share toll for load belonging to class l ($/load)
c_m = maintenance cost per ESAL($/ESAL)
$\exp E_l$ = expected ESAL for load belonging to class l

6.3.4 Bridge Construction Toll Share

For bridges, allocating costs to individual classes is less direct. As discussed in Chapter 5, bridge costs can also be allocated using an incremental design method. In order to estimate a single toll rate share for each class, either one design bridge type or a series of weighted design bridges should be identified for calculation of a toll rate. Once the design bridge(s) have been identified, total bridge costs should be allocated using an incremental design method. Just as in incremental pavement design, a base bridge facility should be identified. The additional cost of adding structural elements to

carry heavier design vehicle classes should then be quantified. In traditional HCA, study vehicle classes are assigned to design vehicle classes by correlating the expected live-load moment (LLM) for that class with the LLM of AASHTO design vehicles. With WIM data, the LLM for individual vehicles can be directly estimated, so vehicles can easily be assigned to design vehicle classes. Once the total number of vehicles belonging to a design class is estimated, a cost per vehicle for each vehicle belonging to that class can be estimated using:

$$c_i = \frac{C_i}{\sum_D n_d}$$

(Eq. 19)

where: c_i = cost per vehicle for increment i ($/load)
C_i = total cost of constructing increment i ($)
n = number of vehicles belonging to design vehicle class d
D= the set of design vehicle classes for which i must be constructed

However, the value required for toll rate estimation is a cost per load, not a cost per vehicle. In order to identify the relationship between vehicle moment classes and load classes, a matrix analysis should be performed. Conditional probabilities should be calculated to examine the likelihood of individual axle types on a vehicle belonging to a certain vehicle moment class:

$$P(l \mid m) = \frac{n_{l|m}}{\sum_{L} n_{l|m}}$$

(Eq. 20)

where: $n_{l|m}$ = number of loads belonging to class l on vehicles belonging to class m
L = set of all axle load classes

These probabilities can then be examined to determine the load class responsibilities for each moment class (Table 19). These probabilities cannot be used to directly allocate costs, as costs for lighter design vehicle classes must be assigned to all load classes, even though it is unlikely that the heaviest load classes will appear on the lightest design vehicles. However, this method does allow for some estimation of the additional cost responsibilities that should be assigned to the heaviest load classes. Using this matrix analysis, load classes can be assigned proportional responsibilities for each design vehicle cost increment.

Table 19. Matrix Analysis: Vehicle Moment Class vs. Axle Load Class

Design Vehicle Class	Load Class			
	1	2	3	...
H2.5	$P_{1,H2.5}$	$P_{2,H2.5}$	$P_{3,H2.5}$	...
H5	$P_{1,H5}$	$P_{2,H5}$	$P_{3,H5}$	...
H10	$P_{1,H10}$	$P_{2,H10}$	$P_{3,H10}$	...
H15	$P_{1,H15}$	$P_{2,H15}$	$P_{3,H15}$	...
HS15	$P_{1,HS15}$	$P_{2,HS15}$	$P_{3,HS15}$	...
H20	$P_{1,H20}$	$P_{2,H20}$	$P_{3,H20}$	...
HS20	$P_{1,HS20}$	$P_{2,HS20}$	$P_{3,HS20}$	...
HS25	$P_{1,HS25}$	$P_{2,HS25}$	$P_{3,HS25}$	...

A cost per load for each design increment can then be estimated for each load class:

$$c_{i,l} = \frac{p_l C_i}{n_l}$$

(Eq. 21)

where: $c_{i,l}$ = cost per load for increment i for load belonging to class l ($/load)
p_l = share of cost responsibility for increment i assigned to load class l (%)
C_i = total costs for increment i ($)
n_l= total number of loads of class l

The total bridge construction toll share for each load class can then be calculated by summing the per-load costs across all increments required by that class:

$$t_{BC,l} = \sum_{L} c_{i,l}$$

(Eq. 22)

where: $t_{BC,l}$ = bridge construction share of load-related toll for class l ($/load)
$c_{i,l}$ = cost per load of type l for pavement increment i ($/load)
L= the set of increments required to accommodate l

6.3.5 Bridge Maintenance Toll Share

As was discussed in Chapter 5, no definitive method for bridge maintenance cost allocation to individual load classes has been developed. If maintenance activities can be specifically linked to individual vehicle classes, incremental costs can be estimated using the same method as for bridge construction. The total bridge maintenance toll share for each load class can then be calculated by summing the per-load costs across all increments required by that class:

$$t_{BM,l} = \sum_{L} c_{i,l}$$

(Eq. 23)

where: $t_{BM,l}$ = bridge maintenance share of load-related toll for class l ($/load)
$c_{i,l}$ = cost per load of type l for pavement increment i ($/load)
L= the set of pavement increments required to accommodate l

If not, costs can be assigned according to system use as part of the base toll. In general, cost allocation studies indicate that load-related bridge maintenance costs will be very low compared to other cost categories over the life of the system, particularly for newer bridge construction.

6.3.6 Final Axle-Load Toll

The final toll rate for each load class can then be estimated by simply summing the toll rate shares for each load class across all cost types.

$$t_l = t_{PC,l} + t_{PM,l} + t_{BC,l} + t_{BM,l}$$

(Eq. 24)

where: t_l = final "Axle-Load"-based rate for toll class l ($/load)
$t_{PC,l}$ = pavement construction share of load-related toll for class l ($/load)
$t_{PM,l}$ = pavement maintenance share of load-related toll for class l ($/load)
$t_{BC,l}$ = bridge construction share of load-related toll for class l ($/load)
$t_{BM,l}$ = bridge maintenance share of load-related toll for class l ($/load)

The final toll rate paid by an individual vehicle can then be calculated by summing the base toll rate per vehicle and the individual per-axle tolls paid for each axle belonging to that vehicle:

$$t_{AL,v} = t_b + \sum_A t_l$$

(Eq. 25)

where: $t_{AL,v}$ = total toll paid by vehicle v in "Axle-Load" structure ($)
t_b = base toll paid per vehicle ($)
t_l = toll paid for load l ($)
A= the set of all axles belonging to vehicle v

6.4 NUMBER-OF-AXLE TOLL RATE ESTIMATION

In a "number-of-axle (n-1)" tolling structure, each vehicle pays a toll equal to a base two-axle toll rate multiplied by a value z, which is equal to its number of axles minus one:

$$z_v = a_v - 1$$

(Eq. 26)

where: z_v = toll multiplier for toll rate paid by vehicle v
a_v= total number of axles on vehicle v

The total toll paid by vehicle v is then calculated by multiplying the toll multiplier by a base two-axle vehicle toll rate:

$$t_{NA,v} = z_v \times t_2$$

(Eq. 27)

where: $t_{NA,v}$= toll paid by vehicle v in "number-of-axle" structure
z_v = toll multiplier for toll rate paid by vehicle v
t_2= base toll rate for two-axle vehicle

For the purpose of equity comparison, this toll rate should be set so that the total toll collected over the life of the facility is equal to that collected using the "Axle-

Load" based toll rate, and for this analysis, the sum of all costs. The following equation can be used to solve for the value of t_2:

$$C = \sum_{A} n_a \times z_a \times t_2$$

(Eq. 28)

where: C= sum of all costs over life of facility
n_a = expected number of vehicles with number of axles a
z_a= toll multiplier for vehicles of number of axles a
t_2= base toll rate for two-axle vehicle
A = set of all number of axle classes a

6.5. COST RESPONSIBILITY ESTIMATION

Once the new toll structure and rates have been established, an equity analysis can be performed to compare the share of cost responsibilities paid by individual vehicles and vehicle classes under a "number-of-axle (n-1)" tolling structure and the proposed "axle-load" toll rate structures. The first step in the equity comparison is to determine the cost responsibility for each vehicle. The process used for assigning individual vehicle cost responsibilities is very similar to that used for allocation of costs to different toll classes. Figure 12 show the process used for allocating cost responsibilities.

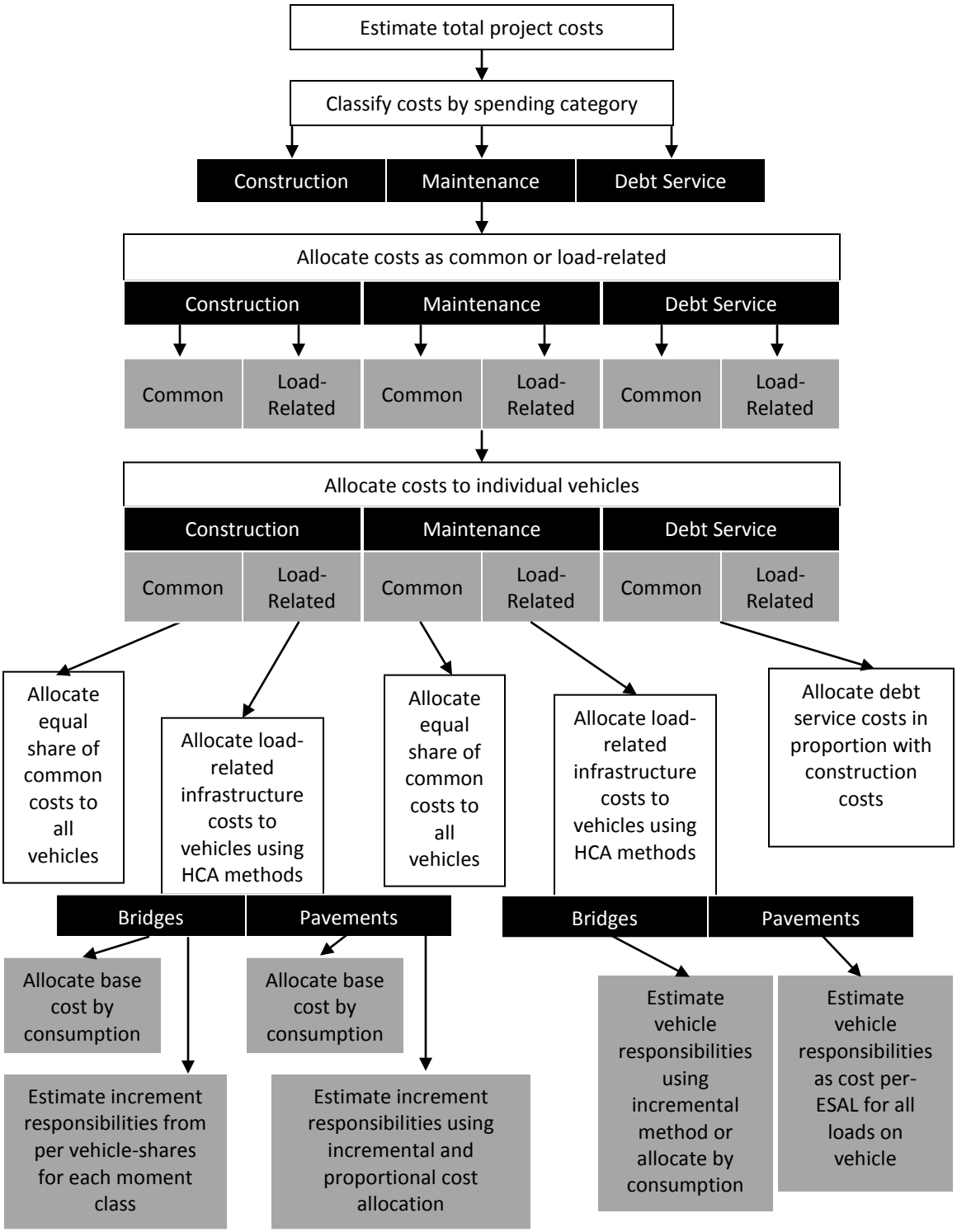

Figure 12. Cost Allocation Method for Estimating Cost Responsibilities

As can be seen from the figure the same methods of cost allocation are used to determine the "Common" and "Load-Related" costs. "Common" costs are assigned to all vehicles based on their share of consumption. Here this cost is assigned as common cost per vehicle r_c. However, unlike in the toll estimation, "Load-Related" costs must be allocated to individual vehicles rather than load classes.

6.5.1 Pavement Construction Cost Responsibility Estimation

To determine the pavement construction cost responsibility for each individual vehicle, a combined incremental/proportional method can be employed. The same iterative design process is used to estimate the design cost for individual pavement increments. However, instead of estimating an average cost per vehicle within each load class for each increment (Eq. 14), a cost per ESAL for the total ESALs contributed by all classes responsible for that class is estimated:

$$c_j = \frac{C_j}{\sum_L E_l}$$

(Eq. 29)

where: c_j = cost per ESAL for increment j ($/ESAL)
C_j = total cost of constructing increment j ($)
E_l = total ESALs contributed to pavement by load class l
L = the set of load classes for which j must be constructed

To determine the pavement cost responsibility for each individual load, the costs per ESAL are then summed across all increments for which that load's class shares responsibility:

$$c_{E,x} = \sum_{J} c_j$$

(Eq. 30)

where: $c_{E,x}$ = cost per ESAL for load x ($/ESAL)
c_j = cost per ESAL for pavement increment j
J = the set of pavement increments required to accommodate load x

The total cost responsibility for a given load can then be estimated by multiplying the estimated cost per ESAL by the total ESALs contributed to the pavement by that load:

$$r_{PC,x} = c_{E,x} \times E_x$$

(Eq. 31)

where: $r_{PC,x}$ = pavement construction cost responsibility for load x($)
$c_{E,x}$ = cost per ESAL for load x ($/ESAL)
E_x = ESALs contributed by load x

Finally, the total cost responsibility can be estimated by summing the individual load costs across all loads contributed by an individual vehicle:

$$r_{PC,v} = \sum_{V} r_{PC,x}$$

(Eq. 32)

where: $r_{PC,v}$ = pavement construction cost responsibility for vehicle v($)
$r_{PC,x}$ = pavement construction cost responsibility for load x($)
V = the set of loads belonging to vehicle v

6.5.2 Pavement Maintenance Cost Responsibility Estimation

A vehicle's pavement maintenance cost responsibility, like the pavement maintenance toll rate, is estimated as a proportional share of total maintenance costs. The cost per ESAL estimated from (Eq. 17) can be directly applied to individual loads to estimate a maintenance cost share for that load:

$$r_{PM,x} = c_m \times E_x$$

(Eq. 33)

where: $r_{PM,l}$ = pavement maintenance cost responsibility for load x ($)
c_m = maintenance cost per ESAL($/ESAL)
E_x = ESALs contributed to pavement by load x

The vehicle's total cost responsibility can then be estimated by summing the individual load costs across all loads contributed by an individual vehicle:

$$r_{PM,v} = \sum_{V} r_{PM,x}$$

(Eq. 34)

where: $r_{PC,v}$ = pavement maintenance cost responsibility for vehicle v($)
$r_{PM,x}$ = pavement maintenance cost responsibility for load x($)
V = the set of loads belonging to vehicle v

6.5.3 Bridge Construction Responsibility Estimation

A vehicle's bridge cost responsibility can be estimated directly from the incremental bridge design process. No good allocator exists for distinguishing between individual vehicles within a given design vehicle moment class, so cost responsibilities

per vehicle for each design increment can be estimated directly from Eq. 19. The vehicle's total cost responsibility can then be estimated by summing the increment costs across all bridge design type increments which are required to accommodate the vehicle:

$$r_{BC,l} = \sum_{D} c_i$$

(Eq. 35)

where: $r_{BC,v}$ = bridge construction cost responsibility for vehicle v($)
c_i = cost per load for bridge design vehicle increment i
D= the set of all bridge design vehicle increments required to accommodate v

6.5.4 Bridge Maintenance Responsibility Estimation

Like the bridge maintenance toll rate share, bridge maintenance cost responsibilities per vehicle, $r_{BM,v}$, may be estimated using the same incremental method used for bridge construction costs (Eq. 19, 34, 35). These costs may also be allocated as common costs, where each vehicle pays a share in proportion to its consumption (e.g. per vehicle, per vehicle-mile).

6.5.5 Final Vehicle Cost Responsibility

The final vehicle cost responsibility for each vehicle can then be estimated by summing the cost responsibilities for each type of cost.

$$r_v = r_c + r_{PC,v} + r_{PM,v} + r_{BC,v} + r_{BM,v}$$

(Eq. 36)

where: r_v = final cost responsibility for vehicle v ($)
r_c = common cost responsibility per vehicle ($)
$r_{PC,v}$ = pavement construction cost responsibility for vehicle v($)
$r_{PM,v}$ = pavement maintenance cost responsibility for vehicle v($)
$r_{BC,v}$ = bridge construction cost responsibility for vehicle v($)
$r_{BM,v}$ = bridge maintenance cost responsibility for vehicle v($)

6.6 TOLL RATE EQUITY ANALYSIS

The equity of tolls paid under each tolling structure can then be estimated by calculating "responsibility ratios" for toll structure for each vehicle. These ratios are calculated according to the following formulas:

$$R_{AL,v} = \frac{t_{AL,v}}{r_v}$$

(Eq. 37)

where: $R_{AL,v}$ = "Axle-Load responsibility ratio" for vehicle v
$t_{AL,v}$ = "Axle-Load" toll paid by vehicle v
r_v= total cost responsibility of vehicle v

$$R_{NA,v} = \frac{t_{NA,v}}{r_v}$$

(Eq. 38)

where: $R_{NA,v}$ = "Number-of-Axle responsibility ratio" for vehicle v
$t_{NA,v}$ = "Number-of-Axle" toll paid by vehicle v
r_v= total cost responsibility of vehicle v

In a perfectly equitable toll structure, R would equal exactly one for every vehicle. The overall equity of these toll structures can be examined by estimating both

the mean and standard deviation of these "responsibility ratios". The means are calculated by:

$$\exp R_{AL} = \frac{\sum_{V} R_{AL,v}}{n_V}$$

(Eq. 39)

where: $\exp R_{AL}$ = mean "Axle-Load responsibility ratio" for all observed vehicles
$R_{AL,v}$ = "Axle-Load responsibility ratio" for vehicle v
V = the set of all observed vehicles
n_v= total number of observed vehicles

$$\exp R_{NA} = \frac{\sum_{V} R_{NA,v}}{n_V}$$

(Eq. 40)

where: $\exp R_{NA}$ = mean "Number-of-Axle responsibility ratio" for all observed vehicles
$R_{NA,v}$ = "Number-of-Axle responsibility ratio" for vehicle v
V = the set of all observed vehicles
n_v= total number of observed vehicles

The standard deviations can then be estimated as:

$$sdR_{AL} = \sqrt{\frac{1}{n_v}\sum_{V}\left(R_{AL,v} - \exp R_{AL}\right)^2}$$

(Eq. 41)

where: sdR_{AL} = standard deviation of "Axle-Load responsibility ratio"
n_v= total number of observed vehicles
$R_{AL,v}$ = "Axle-Load responsibility ratio" for vehicle v
$\exp R_{AL}$ = mean "Axle-Load responsibility ratio" for all observed vehicles
V = the set of all observed vehicles

$$sdR_{NA} = \sqrt{\frac{1}{n_v}\sum_{V}\left(R_{NA,v} - \exp R_{NA}\right)^2}$$

(Eq. 42)

where: sdR_{NA} = standard deviation of "Number-of-Axle responsibility ratio"
n_v= total number of observed vehicles
$R_{NA,v}$ = "Number-of-Axle responsibility ratio" for vehicle v
$expR_{NA}$ = mean "Number-of-Axle responsibility ratio" for all observed vehicles
V = the set of all observed vehicles

The mean values are used to compare overall which toll rate is more equitable; the rate for which expR is closer to one is more equitable. The equity of tolls paid by individual vehicle classes can also be examined by replacing n_v and V in equations 39 and 40 with n_{vc} and V_c, where n_{vc} is the number of vehicles belonging to a class c and V_c is the set of all vehicles belonging to that class.

The standard deviation is a measure of the dispersion of equity ratios. The sdR values are used to examine the comparative equity of tolls paid by individual vehicles. A low value of sdR indicates that most vehicles will pay a toll close to their share of costs. A high sdR value indicates that more vehicles will pay a value more or less than their share of costs. Again, the dispersion of R values for individual vehicle classes can be examined by replacing n_v and V in equations 41 and 42 with n_{vc} and V_c.

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CHAPTER 7: CASE STUDY

The design facility considered in this case study is based on Texas State Highway (SH) 130 Segments 1-4, a 49 mile toll road that provides an alternative route to IH-35 through Austin. The design facility in this study is assumed to have opened in 2008, and a 30 year life, through 2037, will be used for toll rate analysis. Currently, SH 130 tolls vehicles using a "Number-of-Axle (n-1)" toll rate structure.

7.1 PROPOSED TECHNOLOGY SYSTEM FOR TOLLING

Currently, tolls are collected on SH 130 using an "Open Road" tolling system. There are four mainline gantries: one located in each of the four segments. It is assumed that for axle load identification, a bending plate WIM system will be installed in each lane and integrated with the fiber-optic communications systems at the location of these gantries to measure and communicate the truck axle weights for each passing vehicle.

7.2 TRAFFIC VOLUME ESTIMATION

Before construction of the facility began, daily, weekly, and annual screenline traffic volumes for each segment of SH 130 were estimated.[220] Since this analysis requires estimation of a single toll rate to be applied to the entire length of the facility, these screenline volumes were averaged to estimate a single projected volume for trucks traveling the length of the facility. These trucks were also assumed to be traveling at a single free flow speed.

The exact share of vehicles classified as trucks is not provided in the report for every analysis year; however, the truck share for the first year of operation is provided as 10 percent.[221] Back-calculating from the other truck share years provided, an annual growth in truck share of 3 percent was estimated. No information is provided in the report to estimate a split between truck types. The truck and passenger volumes and shares for each design year are shown in Table 20.

Table 20. Estimated Truck and Passenger Car Volumes, Case Study Facility

Design Year	Trucks		Passenger Cars		Total
	Volume	Share	Volume	Share	
2008	406,944	0.100	3,662,496	0.900	4,069,440
2009	567,464	0.103	4,941,896	0.897	5,509,360
2010	716,990	0.106	6,041,330	0.894	6,758,320
2011	893,029	0.109	7,279,451	0.891	8,172,480
2012	1,031,119	0.113	8,130,241	0.887	9,161,360
2013	1,178,147	0.116	8,984,653	0.884	10,162,800
2014	1,305,462	0.119	9,627,578	0.881	10,933,040
2015	1,439,356	0.123	10,263,924	0.877	11,703,280
2016	872,153	0.087	9,178,727	0.913	10,050,880
2017	894,320	0.089	9,111,840	0.911	10,006,160
2018	969,057	0.092	9,557,503	0.908	10,526,560
2019	1,065,345	0.095	10,170,095	0.905	11,235,440
2020	1,166,545	0.098	10,777,855	0.902	11,944,400
2021	1,272,851	0.101	11,380,429	0.899	12,653,280
2022	1,384,485	0.104	11,977,675	0.896	13,362,160
2023	1,573,568	0.107	13,171,152	0.893	14,744,720
2024	1,757,597	0.110	14,231,843	0.890	15,989,440
2025	1,937,567	0.113	15,175,713	0.887	17,113,280
2026	1,519,627	0.092	14,975,253	0.908	16,494,880
2027	1,672,867	0.095	15,956,493	0.905	17,629,360
2028	1,833,935	0.098	16,929,905	0.902	18,763,840
2029	2,003,169	0.101	17,895,231	0.899	19,898,400
2030	2,102,923	0.104	18,177,957	0.896	20,280,880
2031	2,250,836	0.107	18,824,284	0.893	21,075,120
2032	2,427,072	0.110	19,636,288	0.890	22,063,360
2033	2,606,871	0.113	20,400,729	0.887	23,007,600
2034	2,788,869	0.117	21,108,091	0.883	23,896,960
2035	2,971,555	0.120	21,749,165	0.880	24,720,720
2036	2,582,651	0.111	20,724,149	0.889	23,306,800
2037	2,729,378	0.114	21,184,142	0.886	23,913,520
Total	47,921,753		401,226,087		449,147,840

As can be seen in this table, truck shares are projected to drop in 2016, 2026, and 2036. These years coincide with the implementation of higher toll rates. Toll rates are expected to be increased by 50 percent in 2016, 33.3 percent in 2026, and 16.7

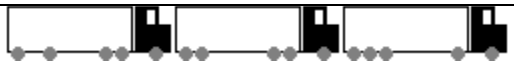
percent in 2036. The traffic analysis performed for SH130 estimated toll rate elasticities of -.44 for two-axle vehicles and -.71 for multi-axle vehicles. These elasticities were estimated by evaluating a single design year, therefore eliminating the effects of inflation. In this study, it is assumed that the toll rate will be inflated annually according to the consumer price index (CPI), so that it will maintain the same value in 2008 dollars throughout the design period, except where it is increased by the previously discussed amounts in 2016, 2026, and 2036. It is assumed that volume changes resulting from inflation are negligible. Although in the past, toll rates have not generally been indexed for inflation, many recent public-private partnership agreements for privately operated toll roads explicitly allow operators to index toll rates to account for inflation effects.[222,223] For the purpose of volume estimation, these elasticities were assumed to remain valid regardless of the structure of the toll. These values were employed for this case study to estimate the drops in vehicle volumes that would result from increasing the toll rate in each year when a change occurred.

Since SH 130 has only recently opened, truck profile data is not yet available for the facility; however, data is available to establish the truck profile for IH-35, the interstate which the toll road parallels. Data from two TxDOT WIM Stations located on I-35 north and south of SH-130 were analyzed to establish the truck profile for this case study. Station 513 is located on I-35 near the Williamson County line, about 15 miles north of SH-130's northern terminus at I-35. Station 516 is located on I-35 southwest of San Antonio, approximately 30 miles southwest of the southern terminus of Segment 6

(one of two segments yet to be constructed under a PPP contract) at I-10. Data for the years 2000, 2001, and 2002 were analyzed.

Table 21 shows the truck profile estimated for the case study facility, including projected volumes for each truck types. These values were estimated from the WIM data using the process described in Figure 7. These six truck types constituted more than 99 percent of all trucks on I-35. Other truck classes, including vehicles with more than five axles, were not considered in this study.

Table 21. Case Study Truck Profile

Number of Axles	Configuration	Trucks	
		Total	Percent
2	SU	14,579,569	30.4
3	SU	2,342,292	4.9
	ST	342,716	0.7
4	SU	60,012	0.01
	ST	2,095,096	4.4
5	ST 	28,555,386	59.6
	Total	**47,921,753**	

Once the truck profile was established, axle type profiles could also be estimated for steering, single, tandem, and tridem axles within each axle group. The resulting axle

type estimates are provided in Table 22. Because the toll rate changes over the design life, vehicle and axle volumes during each tolling period must also be identified. These are provided in Tables 23-26.

Table 22. Vehicle and Axle Load Type Estimates, Design Life

Vehicle Configuration	Estimated Vehicles	Estimated Axle Loads			
		Steering	Single	Tandem	Tridem
2 SU	14,579,569	14,579,569	14,579,569	-	-
3 ST	342,716	342,716	685,433	-	-
3 SU	2,342,292	2,342,292		2,342,292	-
4 ST - All Single	60,012	60,012	180,037	-	-
4 ST - 1 Tandem	2,035,084	2,035,084	2,035,084	2,035,084	-
4 SU	6,693	6,693		-	6,693
5 ST - All Single	1,154,413	1,154,413	4,617,652	-	-
5 ST - 1 Tandem	1,979,156	1,979,156	3,958,312	1,979,156	-
5 ST - 2 Tandems	25,278,537	25,278,537		50,557,073	-
5 ST - 1 Tridem	143,281	143,281	143,281	-	143,281
Total	**47,921,753**	**47,921,753**	**26,199,367**	**56,913,605**	**149,974**

Table 23. Vehicle and Axle Load Type Estimates, 2008-2015

Vehicle Configuration	Estimated Vehicles	Estimated Axle Loads			
		Steering	Single	Tandem	Tridem
2 SU	2,293,494	2,293,494	2,293,494	-	-
3 ST	53,912	53,912	107,825	-	-
3 SU	368,463	368,463		368,463	-
4 ST - All Single	9,440	9,440	28,321	-	-
4 ST - 1 Tandem	320,137	320,137	320,137	320,137	-
4 SU	1,053	1,053		-	1,053
5 ST - All Single	181,599	181,599	726,397	-	-
5 ST - 1 Tandem	311,339	311,339	622,677	311,339	-
5 ST - 2 Tandems	3,976,535	3,976,535		7,953,070	-
5 ST - 1 Tridem	22,539	22,539	22,539	-	22,539
Total	**7,538,511**	**7,538,511**	**4,121,390**	**8,953,008**	**23,592**

Table 24. Vehicle and Axle Load Type Estimates, 2016 to 2025

Vehicle Configuration	Estimated Vehicles	Estimated Axle Loads			
		Steering	Single	Tandem	Tridem
2 SU	3,922,676	3,922,676	3,922,676	-	-
3 ST	92,209	92,209	184,418	-	-
3 SU	630,201	630,201		630,201	-
4 ST - All Single	16,146	16,146	48,439	-	-
4 ST - 1 Tandem	547,545	547,545	547,545	547,545	-
4 SU	1,801	1,801		-	1,801
5 ST - All Single	310,598	310,598	1,242,393	-	-
5 ST - 1 Tandem	532,498	532,498	1,064,995	532,498	-
5 ST - 2 Tandems	6,801,264	6,801,264		13,602,529	-
5 ST - 1 Tridem	38,550	38,550	38,550	-	38,550
Total	**12,893,488**	**12,893,488**	**7,049,016**	**15,312,772**	**40,351**

Table 25. Vehicle and Axle Load Type Estimates, 2026 to 2035

Vehicle Configuration	Estimated Vehicles	Estimated Axle Loads			
		Steering	Single	Tandem	Tridem
2 SU	6,747,284	6,747,284	6,747,284	-	-
3 ST	158,606	158,606	317,212	-	-
3 SU	1,083,990	1,083,990		1,083,990	-
4 ST - All Single	27,773	27,773	83,319	-	-
4 ST - 1 Tandem	941,817	941,817	941,817	941,817	-
4 SU	3,098	3,098		-	3,098
5 ST - All Single	534,251	534,251	2,137,005	-	-
5 ST - 1 Tandem	915,934	915,934	1,831,868	915,934	-
5 ST - 2 Tandems	11,698,663	11,698,663		23,397,326	-
5 ST - 1 Tridem	66,309	66,309	66,309	-	66,309
Total	**22,177,725**	**22,177,725**	**12,124,814**	**26,339,067**	**69,406**

Table 26. Vehicle and Axle Load Type Estimates, 2036 to 2037

Vehicle Configuration	Estimated Vehicles	Estimated Axle Loads			
		Steering	Single	Tandem	Tridem
2 SU	1,616,116	1,616,116	1,616,116	-	-
3 ST	37,989	37,989	75,979	-	-
3 SU	259,638	259,638		259,638	-
4 ST - All Single	6,652	6,652	19,957	-	-
4 ST - 1 Tandem	225,585	225,585	225,585	225,585	-
4 SU	742	742		-	742
5 ST - All Single	127,964	127,964	511,857	-	-
5 ST - 1 Tandem	219,385	219,385	438,771	219,385	-
5 ST - 2 Tandems	2,802,074	2,802,074		5,604,149	-
5 ST - 1 Tridem	15,882	15,882	15,882	-	15,882
Total	**5,312,029**	**5,312,029**	**2,904,146**	**6,308,757**	**16,624**

7.2 COST ESTIMATION

The next step in the analysis was to estimate construction costs and project maintenance costs over the 30 year analysis period. Generalized costs estimated for SH 130 construction were available from the 2002 Project and Engineering Report for the Central Texas Turnpike System.[224] The total construction element costs for SH130 were estimated to be approximately $985 million. However, this value was not directly employed in this study. This estimate includes construction of frontage roads, which are not included in this analysis. Additionally, since SH 130 was developed under a Comprehensive Development Agreement (CDA), no further breakdown of costs to identify specific element costs was available. However, the report did include an itemized cost breakdown for construction of the other elements of the Central Texas Turnpike System, SH 45 and Loop 1, which were built during the same period but were not constructed under a CDA.

7.2.1 Bridge Cost Estimation

Based on the detailed cost breakdown for the other elements of the CTTS, bridge construction costs for SH 130 were assumed to be one fourth of total element costs for SH 130.[225] A total of 19 bridges constructed for SH130 were identified from the National Bridge Inventory, totaling about 18.42 centerline miles.[226] While the shortest bridges were constructed to HS20 standards, the majority of bridges were constructed for HS25 design vehicles. According to the 2002 Texas Highway Cost Allocation Study, HS20 bridge construction per centerline mile was estimated to cost five percent less than HS25 bridge construction; this study assumed this value to remain true.[227] Costs per centerline mile were estimated for both HS20 and HS25 bridges from the total bridge costs. These values were adjusted for inflation using the CPI for final bridge costs of $12,705,295 per centerline mile for HS20 bridges and $13,373,995 per centerline mile for HS 25 bridges in 2008 dollars. Although they were included to determine the cost per centerline mile, bridges constructed on the frontage road were not included in the cost estimation for this study. Table 27 provides statistics for the 3 types of bridges, short, medium, and long, examined in this study. All short bridges were constructed for HS20 vehicles, while all other bridges were constructed for HS25 vehicles. In this study, all bridges are assumed to be simply supported.

Table 27. Case Study Bridge Statistics

Bridge Type	Total Number	Maximum Span Range (ft)	Average Maximum Span (ft)	Average Length (ft)	Total Length (ft)	Total Lane-Miles (mi)
Short	9	15 to 24	18.3	140.8	1267.0	0.48
Medium	4	27 to 37	31.0	131.0	524.0	0.20
Long	94	244 to 524	370.4	1959.8	184218.0	69.78
Total	107				186009.0	70.46

7.2.2 Pavement Cost Estimation

While SH 130 was constructed using rigid concrete pavement, the other elements of the CTTS were constructed using flexible asphalt pavement; as a result, pavement costs were not estimated as a share of actual construction costs for SH 130. Instead, a cost per mile was estimated for a typical rigid pavement section of urban freeway in Central Texas. Pavement structure information and material costs were provided by Dr. Mike Murphy from the Center for Transportation Research at the University of Texas. Figure 13 shows the design pavement cross section used for this study. Table 28 provides the estimated material costs for pavement construction.

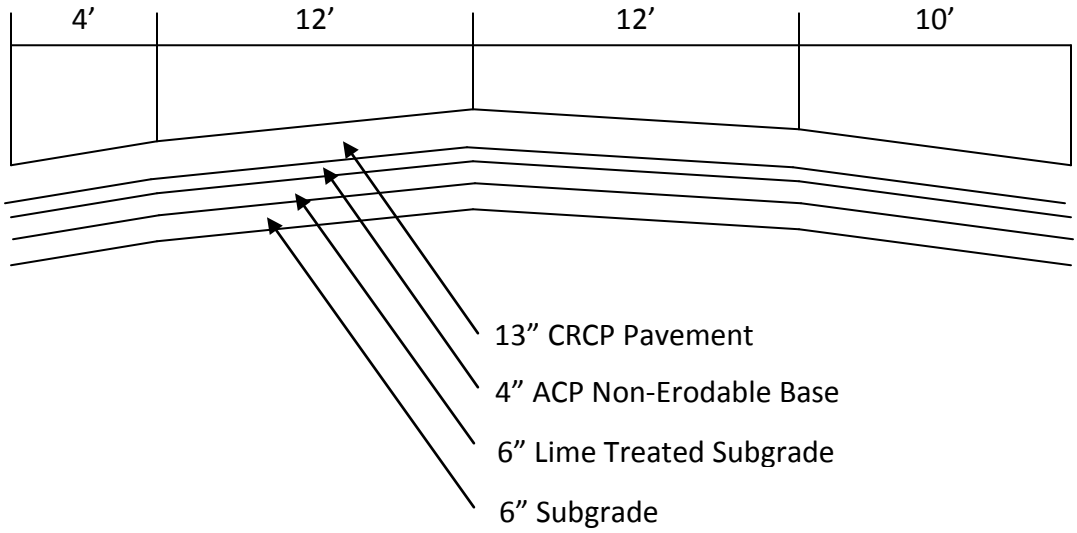


Figure 13. Case Study Pavement Design Cross-Section

Table 28. Case Study Pavement Construction Costs

Material	Thickness (in)	Cost ($ per square yard per inch thick)	Cost per Centerline Mile ($)	Total Cost ($)
CRCP	13	4.75	2,753,227	134,908,107
ACP Non-Erodable Base	4	3.85	686,635	33,645,099
Lime Treated Subgrade	6	0.26	69,555	3,408,205
Subgrade	6	0.17	45,478	2,228,442
Total				**174,189,852**

7.2.3 Other Construction Costs

Based on data from the other CTTS toll roads, Earthwork, Drainage, Retaining Walls, and Mobilization cost about one and a half times the cost of constructing an asphalt pavement; however, because rigid concrete pavement is more expensive, a multiplier of one was assumed to estimate the total cost for these elements for this

case study. All other element construction costs were estimated to cost about 2 times as much as “Earthwork, Drainage, Retaining Walls, and Mobilization” so a multiplier of 2 was used to estimate the cost of remaining construction elements. Costs for tollbooths, toll technologies, the fiber optic network, construction management, and engineering were taken directly from the SH130 report. WIM technologies were assumed to be located in each lane at each main line toll booth, costing $28,000 per bending plate system (as discussed in Chapter 4, and adjusted for inflation) for a total cost of $448,000.

Final cost estimates for all construction costs are provided in Table 29. Although some additional costs, such as Earthwork or engineering, could potentially be allocated to trucks only, because of the lack of availability of detailed data, in this study, only bridge construction costs and pavement material costs are initially considered as “Load-Related” costs. These “Bridge and Pavement” costs also include the costs of the base facility, which will be allocated to both passenger vehicles and trucks.

Table 29. Final Construction Cost Estimates

Construction Costs	Total Cost ($)
Earthwork, Drainage, Retaining Walls, and Mobilization	174,189,852
Other	348,379,704
Right of Way	152,000,000
Toll Booths	4,202,000
Toll Technologies	27,600,000
WIM Technologies	448,000
Fiber Optic Network	15,350,000
Construction Management	115,352,000
Engineering	160,000,000
Common Costs	***997,521,556***
Pavements	174,189,852
Bridges	**235,435,812**
Bridge and Pavement Costs	***409,625,664***
Total Construction Costs	**1,407,147,220**

7.2.4 Operations and Maintenance Cost Estimation

Average annual operations and maintenance costs were assumed to be five percent of total construction costs, a value estimated from previous research examining toll road maintenance expenditures.[228] The Project and Engineering report for SH130 provided cost estimates for Operations Costs, Major and Routine Technology Maintenance, and Major and Routine Bridge/Building/Pavement Maintenance.[229] The shares for each of these costs identified from the report were retained in this study: 50 percent of costs were allocated for operations, 18 percent for technology maintenance, and 32 percent for infrastructure maintenance. Although WIM operations and maintenance will add some technology costs, these costs are extremely low compared to toll system costs, so no additional share is assumed for these costs.

No detailed information was provided to estimate the share of infrastructure costs contributed by building, bridge, and pavement maintenance. For routine road and building maintenance, pavement shares were assumed to be 70 percent, bridges 15 percent, and buildings 15 percent. In the 1997 Federal HCA study, system-wide, pavement rehabilitation costs were estimated to be about 4.5 times the cost of major bridge rehabilitation and other bridge maintenance costs.[230] No information is available on building maintenance costs, so these costs are assumed to be equal to bridge costs. Of the 70 percent of costs assumed for routine pavement maintenance, about 28 percent is assumed to be for non-load related pavement maintenance and 42 percent for load-related routine pavement maintenance.

For major road and building maintenance, a higher share, 80 percent, was assumed for pavement costs, and a lower percentage, 5 percent, was assumed for bridges. This change was assumed after discussion with bridge experts who indicated that new HS25 bridges are very unlikely to require major reconstruction during the first thirty years in use with the projected bridge loadings. All major pavement maintenance costs were considered to be load-related. Total estimated maintenance costs are shown in Table 30.

Table 30. Final Maintenance Cost Estimates

Maintenance Costs	Total Cost ($)
Operations	1,055,360,415
Routine Toll/WIM Maintenance	147,750,458
Major Toll/WIM Maintenance	232,179,291
Environment-Related Routine Pavement Maintenance	153,660,476
Routine Bridge Maintenance	82,318,112
Routine Building Maintenance	82,318,112
Major Bridge Maintenance	6,332,162
Major Building Maintenance	18,996,487
Total Common Costs	***1,778,915,515***
Load-Related Routine Pavement Maintenance	230,490,715
Load-Related Major Pavement Maintenance	101,314,600
Total Load-Related Costs	***331,805,314***
Total Maintenance Costs	**2,110,720,829**

7.2.5 Debt Service Cost Estimation

Most toll roads are funded through debt, either by issuing bonds or through a long-term loan. SH 130 construction was funded through state-issued bonds and a federal TIFIA loan.[231] The annual blended interest rate for debt service on SH 130 was 5.14 percent. For this case study, it was assumed that a $900 million loan with an annual interest rate of five percent was used to finance construction. Annual payments on this loan were assumed to begin in 2013 at a rate of $77,618,840 per year. Total interest accrued was estimated to be $1,040,470,994 over the life of the loan. Since this debt was acquired to finance construction, it should be allocated proportionally to individual construction cost elements.

7.3 LOAD-RELATED CLASS DETERMINATION

As was discussed in Chapter 6, before cost allocation for toll rate determination can begin, the load-class structure for the "Axle-Load" toll must be determined. The first step in allocating costs to load-classes was to define the load classes. Although the load-based toll that will be estimated in this study will include both bridge and pavement components, only pavement impacts can be directly estimated as a function of individual loads. Additionally, pavement maintenance costs are by far the largest cost being allocated to trucks. As a result, the ESAL was chosen as the measure to be used for load class determination.

First, five load classes were chosen at the 20th percentiles of the legal load ranges for each of the three load types. Next, the expected ESAL for a given load within the range was estimated from the observed data (Eq. 11). The expected ESALs were then compared across load types. For the purpose of this analysis, steering and single axles were both classified into one "single" axle category. Generally, steering axles are equipped with single tires while other single axles are equipped with dual tires. In this ESAL analysis, no distinction in pavement impacts is made based on number of tires; however, more advanced methods of analysis, including mechanistic models, could differentiate the pavement impacts of different loading points due to different tire configurations. If a mechanistic method was employed, steering axles could be segregated from single axles for the purpose of tolling.

The ranges were iterated in 500 pound increments until the expected ESALs across the single and tandem load types within each class were approximately equal. Two additional load classes were also introduced during the iterating process to improve the equity across load ranges. Because of the very small number of observations of tridem axles, particularly in the higher load classes, the expected ESAL was not used to determine the limits of the tridem load classes. For tridem load classes, minimum and maximum weights were approximated by comparing the estimated ESALs for these weights with the limits of the single and tandem load classes. The final load classes determined through this iterative process, as well as the expected ESAL for a load belonging to each class, are provided in Table 31.

Table 31. Final Load Classes

Load Class	Single Axles		Tandem Axles		Tridem Axles		Weighted
	Weight (kips)	Expected ESAL	Weight (kips)	Expected ESAL	Weight (kips)	Expected ESAL	Expected ESAL
Class 1	< 4	1.282E-03	< 5.5	8.218E-04	< 8	2.531E-04	1.239E-03
Class 2	4 to 6.5	0.005	5.5 to 10	0.007	8 to 12.5	0.004	0.006
Class 3	6.5 to 9	0.034	10 to 15.5	0.035	12.5 to 20	0.020	0.026
Class 4	9 to 12	0.107	15.5 to 18.5	0.106	20 to 25	0.082	0.101
Class 5	12 to 15	0.258	18.5 to 23.5	0.256	25 to 31.5	0.217	0.242
Class 6	15 to 18	0.650	23.5 to 28.5	0.642	31.5 to 38.5	0.735	0.646
Class 7	> 18	1.223	> 28.5	1.401	> 38.5	1.148	1.301

7.4 AXLE-LOAD TOLL RATE DETERMINATION

Once the “Axle-Load” classes are defined for each axle type, the next step in the analysis is to estimate the toll rates paid for axles within each given class. In this analysis, it is assumed that all costs – construction, maintenance, and debt service – are

paid off at the end of the 30 year analysis period. The 30 year analysis period was chosen as the estimated life of the roadway's pavements. Many construction elements, including both buildings and bridges, will likely have a longer life period, and as a result, will have remaining service life at the end of the 30 year analysis period. However, the value of these remaining elements is not considered in the zero sum calculation used to estimate toll rates.

As was discussed in Chapter 6, once costs have been estimated, the first step in toll rate determination is to decide which costs should be allocated as "Common Costs" and which should be allocated as "Load Related". As was discussed in the previous section, for this study, all costs except Bridge Construction, Pavement Construction, Load-Related Pavement Maintenance, and the cost of debt associated with Bridge and Pavement Construction were allocated as "Common Costs." It is likely that in future applications of this method, additional costs could be allocated as "Load-Related" if better cost estimating data was available. If this value was considered as revenue, toll rates resulting from the following analysis would decrease.

7.4.1 Common Toll Share Determination

Total "Common Costs" were calculated by summing the costs identified as common for construction and maintenance. Additionally, since 71 percent of construction costs were allocated as "Common Costs," 71 percent of Debt Service costs were also allocated as common. Table 32 shows the total value of costs identified as common within each category.

Table 32. Total Common Costs

Common Costs	Total Cost ($)
Construction	997,521,556
Debt	738,734,406
Maintenance	1,778,915,515
Total Common Costs	***3,515,171,477***

As was discussed in Chapter 6, a base toll rate to recover common costs can be estimated using equation 12. However, because toll rates are expected to be increased at three different times over the design life of the facility, these percentage increases must be considered in estimating the base toll rate, and the increased rates to be charged during the three later tolling periods. In order to estimate the starting base toll rate, the volumes of vehicles expected during each rate period must be estimated. Rearranging equation 12, we see that:

$$C_c = t_b \times n$$

(Eq. 43)

where: C_c = total common costs ($)
t_b = base toll rate per vehicle ($/vehicle)
n = number of vehicles expected over life of facility

Adding an additional variable, a toll rate multiplier for each tolling period, we can write the equivalent equation:

$$C_c = \sum_T t_1 \times m_t \times n_t$$

(Eq. 44)

where: C_c = total common costs ($)
t_1 = base toll rate per vehicle during period 1 ($/vehicle)
m_t = toll rate multiplier for time period t
n_t = number of vehicles expected on facility during time period t
T = the set of all tolling periods

Solving for t_1 and multiplying this base rate by the toll rate multipliers for subsequent periods, we obtain the following base common toll rates for each period:

Table 33. Base Common Toll Shares

Toll Period	Rate ($)
2008 to 2015	4.49
2016 to 2025	6.74
2026 to 2035	8.98
2036 to 2037	10.48
Weighted Average	**7.83**

7.4.2 Pavement Construction Toll Share Determination

Pavement construction toll shared were estimated using the incremental method described in section 6.3.2. Table 34 shows the total pavement costs allocated using this method.

Table 34. Total Pavement Construction Costs

Pavement Costs	Total Cost ($)
Pavement	135,274,052
Pavement Debt	100,025,679
Pavement Base Costs	***235,299,731***
Pavement Increments	38,915,800
Pavement Increment Debt	28,212,371
Incremental Pavement Costs	***67,128,171***
Total Pavement Construction Costs	**302,427,902**

Standard TXDOT input values for Austin were employed in the rigid pavement design equation (Eq. 13). These values are shown in Table 35.

Table 35. TxDOT Rigid Pavement Design Input Values

Variable	Input Value
28-Day Concrete Modulus of Rupture (psi)	620
28-Day Concrete Elastic Modulus (psi)	5,000,000
Effective Modulus of Subbase/Subgrade Reaction (pci)	3
Initial Servicability	4.5
Terminal Servicability	2.5
Load Transfer Coefficient	3.2
Drainage Coefficient	1.05
Overall Standard Deviation	0.39
Reliability (%)	95

The base pavement thickness was determined to be 5.5 inches; this thickness was required to accommodate passenger cars, and no additional thickness was required to accommodate Class I truck loads. The cost of this base facility was allocated as part of a base toll for all vehicles. The per-vehicle share for each rate period was determined by replacing the total common cost in equation 44 with the base pavement facility cost and solving for the first period toll rate.

$$C_{PB} = \sum_{T} t_{PB1} \times m_t \times n_t$$

(Eq. 45)

where: C_{PB} = total pavement base costs ($)
t_{PB1} = base toll rate per vehicle during period 1 ($/vehicle)
m_t = toll rate multiplier for time period t
n_t = number of vehicles expected on facility during time period t
T = set of all time periods

The total pavement base shares calculated per vehicle for each time period are shown in Table 36.

Table 36. Pavement Base Toll Share

Tolling Period	Cost ($/vehicle)
2008 to 2015	0.30
2016 to 2025	0.45
2026 to 2035	0.60
2036 to 2037	0.70
Weighted Average	**0.52**

Additional increment costs were then allocated to individual load classes using equation 14. The costs for each pavement increment and the resulting costs per load are shown in Table 37.

Table 37. Increment Costs for Pavement Construction

Pavement Thickness (in)	Cost ($)	Responsible Classes	Total Expected Loads	Cost Per Load ($)
6	4,512,754	2,3,4,5,6,7	18,941,108	0.04
7.5	13,538,261	3,4,5,6,7	20,341,132	0.14
10	22,563,769	4,5,6,7	35,009,109	0.30
10.5	4,512,754	5,6,7	14,686,242	0.12
11.5	9,025,507	6,7,	10,662,350	0.37
13	13,538,261	7	13,769,153	0.98

Per-axle costs for pavement construction were then estimated for each load class using equation 15. However, because costs must be obtained for each tolling period, these costs were used to estimate toll multipliers for each class as a ratio of the Class 2 toll:

$$m_{PC,l} = \frac{t_{PC,l}}{t_{PC,2}}$$

(Eq. 46)

where: $m_{PC,L}$ = toll multiplier for load class l
$t_{PC,l}$ = estimated pavement construction share of load-related toll for class l

($/load)
$t_{PC,2}$ = estimated pavement construction share of load-related toll for class 2 ($/load)

Individual tolling period rates were then obtained by solving the following equation for the Class 2 incremental toll rate for the 2008-2015 tolling period.

$$C_{PI} = \sum_{T} t_{C2,1} \times m_{PC,l} \times n_{t,l}$$

(Eq. 47)

where: C_{PB} = total pavement increment costs ($)
$t_{C2,1}$ = class 2 toll rate per load during period 1 ($/vehicle)
$m_{PC,L}$ = toll multiplier for load class l
$nt,_{l}$ = number of loads of class l expected on facility during time period t
T = set of all time periods

The resulting per-axle toll shares for pavement construction during each tolling period are provided in Table 38.

Table 38. Pavement Construction Toll Shares

Load Class	Rate ($)				
	2008 to 2015	2016 to 2025	2026 to 2035	2036 to 2037	Weighted Average
Class 1	0.00	0.00	0.00	0.00	0.00
Class 2	0.02	0.03	0.05	0.05	0.04
Class 3	0.10	0.16	0.21	0.24	0.18
Class 4	0.28	0.42	0.55	0.65	0.48
Class 5	0.34	0.51	0.69	0.80	0.60
Class 6	0.55	0.83	1.11	1.29	0.96
Class 7	1.11	1.67	2.22	2.59	1.94

7.4.3 Pavement Maintenance Toll Share Determination

Load-related pavement maintenance toll shares were estimated using the process described in section 6.3.3. The total costs allocated using this process are provided in Table 39.

Table 39. Total Load-Related Pavement Maintenance Costs

Load-Related Pavement Maintenance Costs	Total Cost ($)
Load-Related Routine Pavement Maintenance	230,490,715
Load-Related Major Pavement Maintenance	101,314,600
Total Load-Related Costs	***331,805,314***

An initial estimated cost per ESAL of $9.62 was calculated using equations 16 and 17. Estimated costs per load were then estimated for each load class using equations 18, and 19. However, these values again cannot be applied directly but must be used to estimate toll multipliers to calculate the expected toll rate during each tolling period. For pavement maintenance, Class 1 vehicles do pay an additional toll cost, so the Class 1 toll is defined as the base rate for calculation of the multiplier.

$$m_{PM,l} = \frac{t_{PM,l}}{t_{PM,1}}$$

(Eq. 48)

where: $m_{PM,L}$ = toll multiplier for load class l
$t_{PM,l}$ = estimated pavement maintenance share of load-related toll for class l ($/load)
$t_{PM,1}$ = estimated pavement maintenance share of load-related toll for class 1 ($/load)

Individual tolling period rates were then obtained by solving the following equation for the Class 1 incremental toll rate for the 2008-2015 tolling period.

$$C_{PM} = \sum_{T} t_{C1,1} \times m_{PM,l} \times n_{t,l}$$

(Eq. 49)

where: C_{PM} = total pavement maintenance costs ($)
$t_{C1,1}$ = class 1 toll rate per load during period 1 ($/vehicle)
$m_{PM,L}$ = toll multiplier for load class l
$n_{t,l}$ = number of loads of class l expected on facility during time period t
T = set of all time periods

The final resulting pavement maintenance toll shares per load for each class during each time period are provided in Table 40.

Table 40. Pavement Maintenance Toll Shares

Load Class	Rate ($)				
	2008 to 2015	2016 to 2025	2026 to 2035	2036 to 2037	Weighted Average
Class 1	0.01	0.01	0.01	0.02	0.01
Class 2	0.03	0.05	0.06	0.07	0.05
Class 3	0.19	0.28	0.38	0.44	0.33
Class 4	0.59	0.89	1.18	1.38	1.03
Class 5	1.42	2.13	2.83	3.31	2.47
Class 6	3.55	5.33	7.10	8.29	6.20
Class 7	7.71	11.57	15.43	18.00	13.46

7.4.4 Bridge Construction Toll Share Determination

The bridge construction toll share was estimated using the incremental design method described in section 6.3.4. The total bridge construction costs to be allocated are provided in Table 41.

Table 41. Total Bridge Construction Costs

Bridge Costs	Total Cost ($)
Bridge	181,109,295
Bridge Debt	133,593,874
Bridge Base Costs	***314,703,169***
Bridge Increments	54,326,517
BridgeIncrement Debt	39,904,664
Incremental Bridge Costs	***94,231,180***
Total Bridge Costs	**408,934,350**

Incremental bridge costs were developed using the relative cost estimates for bridges of each design type provided in the 2002 Texas Highway Cost Allocation Study.[232] The relative costs of an HS25 bridge used to calculate increment costs are provided in Table 42.

Table 42. Relative Costs for Design Bridge Types

Design Bridge Type	Share of HS25 Cost
H2.5	0.77
H5	0.78
H10	0.82
H15	0.86
HS15	0.9
H20	0.91
HS20	0.95
HS25	1.00

In this study, the base bridge costs were defined as the cost of constructing an H2.5 bridge for all bridge segments. As was discussed in the Cost Estimation Section, in this study, bridges were categorized into 3 length types: short, medium, and long. The total estimated base and increment costs for bridges of each type, as well as the design vehicles responsible for those classes, are provided in Table 43.

Table 43. Bridge Type Increment Costs

	Short Bridges		Medium Bridges		Long Bridges	
Design Bridge Type	**Total Cost ($)**	**Responsible Classes**	**Total Cost ($)**	**Responsible Classes**	**Total Cost ($)**	**Responsible Classes**
Base Facility						
H2.5	2,139,198	PC, H2.5, H5, H10, H15, H20, HS20	893,179	PC, H2.5, H5, H10, H15, HS15, H20, HS20, HS25	311,540,887	PC, H2.5, H5, H10, H15, HS15, H20, HS20, HS25
Additional Cost						
H5	48,462	H5, H10, H15, H20, HS20	20,907	H5, H10, H15, HS15, H20, HS20, HS25	7,292,244	H5, H10, H15, HS15, H20, HS20, HS25
H10	103,544	H10, H15, H20, HS20	42,975	H10, H15, HS15, H20, HS20, HS25	14,989,614	H10, H15, HS15, H20, HS20, HS25
H15	103,544	H15, H20, HS20	42,975	H15, HS15, H20, HS20, HS25	14,989,614	H15, HS15, H20, HS20, HS25
HS15	n/a	n/a	46,459	HS15, H20, HS20, HS25	16,204,988	HS15, H20, HS20, HS25
H20	142,207	H20, HS20	12,776	H20, HS20, HS25	4,456,372	H20, HS20, HS25
HS20	111,223	HS20	46,459	HS20, HS25	16,204,988	HS20, HS25
HS25	n/a	n/a	55,751	HS25	19,445,985	HS25
Total	**2,648,177**		**1,161,481**		**405,124,691**	

Like base pavement costs, base bridge costs were allocated to all vehicles as a share of the per-vehicle base toll. An estimated cost per vehicle was determined using equation 19. Individual tolling period rates were again obtained by replacing the common costs in equation 44 with the total bridge base cost.

$$C_{BB} = \sum_{T} t_{BB1} \times m_t \times n_t$$

(Eq. 50)

where: C_{BB} = total bridge base costs ($)
t_{BB1} = base toll rate per vehicle during period 1 ($/vehicle)

m_t = toll rate multiplier for time period t
n_t = number of vehicles expected on facility during time period t

The resulting bridge base toll shares per vehicle for each time period are provided in Table 44.

Table 44. Bridge Base Toll Share

Toll Period	Rate ($)
2008 to 2015	0.40
2016 to 2025	0.60
2026 to 2035	0.80
2036 to 2037	0.93
Weighted Average	**0.70**

In order to allocate costs to individual vehicles, each vehicle must be classified to one of the design vehicle class categories. In this study, three design span lengths were used to represent all bridges. Simply supported span lengths of 18, 31, and 370 feet were evaluated to determine moment classes for short, medium, and long bridges. In order to estimate the maximum live-load moments (LLM) for each individual truck observation, a C++ program was developed using a series of basic moment functions to "virtually" run a truck across the design bridge. Figure 14 describes the program. A detailed description of the program, as well as source code, is provided in Appendix A. In order to ensure the success of the program in estimating maximum LLMs, results from the program were compared to known values provided in AASHTO's Standard Specification for Highway Bridges for the design vehicles.[233]

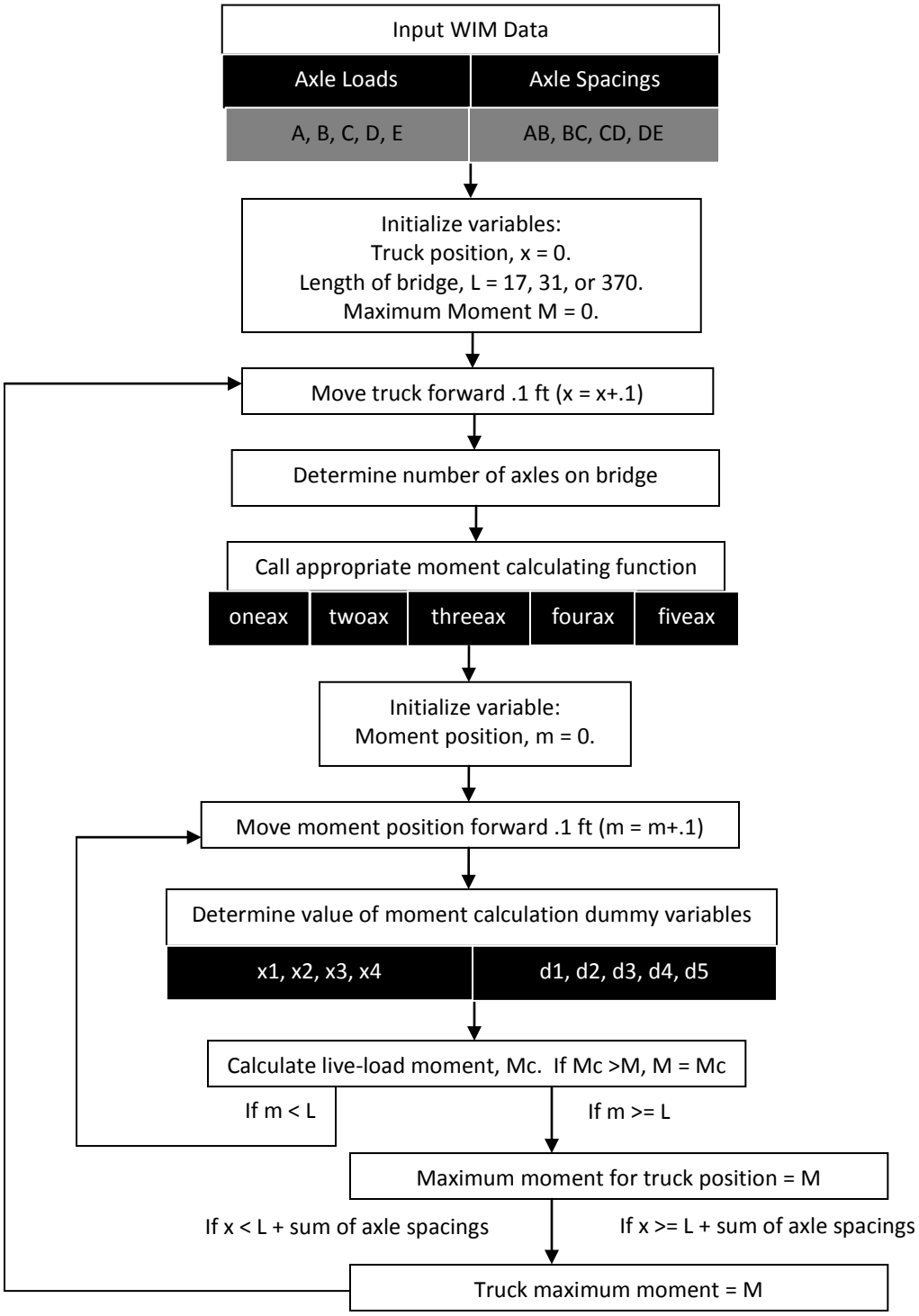


Figure 14. Program for Calculating Maximum Live-Load Moment

First, maximum live-load moments were estimated for each design vehicle type for each design bridge. Table 45 shows the LLM values for the design vehicles for each bridge type.

Table 45. Design Vehicle Live Load Moments

Design Vehicle	Bridge Length		
	17	31	370
	Live Load Moment (kip-ft)		
H2.5	18.0	32.1	455.0
H5	36.0	64.1	910.1
H10	72.0	128.3	1820.1
H15	108.0	192.4	2730.2
H20	144.0	256.5	3640.2
HS 15	108.0	216.5	4785.8
HS 20	144.0	288.6	6381.0
HS 25	180.0	360.8	7976.3

These values were used to determine the design vehicle class for each observed vehicle. After the maximum LLM for each bridge type was calculated for each observation, each truck was classified according to its live-load moment. Vehicles were classified to the smallest design truck category whose design LLM it did not exceed. For short and medium span bridges, there was some overlap in the moment categories for two and three axle design vehicles. When overlap occurred, two axle vehicles were assigned to the two axle design vehicle class, while three or more axle vehicles were assigned to the three axle design class. The classification criteria are shown in Table 46.

Table 46. Bridge Type Design Moment Classification Criteria

Design Vehicle	Bridge Span Length (ft)					
	17		31		370	
	Live Load Moment (kip-ft)					
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
H2.5	0.0	18.0	0.0	32.1	0.0	455.0
H5	18.0	36.0	32.1	64.1	455.0	910.1
H10	36.0	72.0	64.1	128.3	910.1	1820.1
H15	72.0[a]	108.0[a]	128.3[a]	192.4[a]	1820.1	2730.2
H20	108.0[a]	144.0[a]	192.4[a]	256.5[a]	2730.2	3640.2
HS 15	72.0[b]	108.0[b]	128.3[b]	216.5[b]	3640.2	4785.8
HS 20	-	-	256.5[a]	288.6[a]	-	-
	108.0[b]	144.0	216.5[b]	288.6[b]	4785.8	6381.0
HS 25	144.0	180.0	288.6	360.8	6381.0	7976.3

a Two Axle Trucks Only

b Three or more axle trucks

As was discussed in section 6.3.4, for determining toll rates, load-related bridge costs must not be assigned to design bridge vehicle classes but to individual load classes. More than 99 percent of total bridge construction costs are for long bridges; as a result, long bridge moment classes were evaluated for toll rate estimation. In order to determine which costs should be assigned to which classes, a matrix of the conditional probabilities estimated by equation 20 was developed; this matrix is shown in Table 47.

Table 47. Design Vehicle Moment Class vs. Axle-Load Class Matrix

Design Vehicle Moment Class	Axle-Load Class						
	1	2	3	4	5	6	7
H2.5	1.00	0.00	0.00	0.00	0.00	0.00	0.00
H5	0.83	0.17	0.00	0.00	0.00	0.00	0.00
H10	0.32	0.44	0.16	0.07	0.01	0.00	0.00
H15	0.05	0.29	0.50	0.14	0.02	0.01	0.00
HS15	0.01	0.07	0.48	0.36	0.07	0.02	0.00
H20	0.00	0.01	0.06	0.30	0.47	0.15	0.01
HS20	0.00	0.00	0.01	0.15	0.07	0.25	0.53
HS25	0.00	0.00	0.00	0.11	0.06	0.01	0.83

Although exact shares to allocate to each class cannot be determined from this matrix, some decisions can be made about how to allocate design bridge costs to individual load classes. The percentages shown in this table indicate the share of axle loads of each type contributed within each moment class. For example, 83 percent of the loads on vehicles classified as HS25 vehicles are Class 7 loads. For H5 to H20 bridges, costs were allocated equally to all load classes identified as responsible for a given moment class. For the heaviest design classes, HS20 and HS25, the heaviest load classes were allocated a higher share of responsibility than other responsible classes. The class responsibilities, expected loads, and estimated costs per load within each given class are provided in Table 48. These costs per load were estimated using equation 21.

Table 48. Increment Costs for Bridge Construction

Bridge Increment	Cost ($)	Responsible Load Classes	Total Expected Loads	Cost Per Load (%)
H5	7,364,653	All	131,184,699	0.06
H10	15,142,383	All	131,184,699	0.12
H15	15,142,383	All	131,184,699	0.12
HS15	16,258,158	2,3,4,5,6,7	113,409,113	0.14
H20	4,613,259	3,4,5,6,7	94,467,998	0.05
HS20	16,369,427	4 and 5 (22%), 6 (25%), 7 (53%)	49,695,370 (4 and 5), 10,662,348 (6), 13,769,148(7)	.07 (4 and 5), .38 (6), .63 (7)
HS25	19,509,790	4,5, and 6 (17%), 7 (83%)	60,357,718 (4, 5, and 6), 13,769,148(7)	.06 (4,5, and 6), 1.17 (7)

Total construction cost shares for each load class were calculated using equation 22. Again, these values were used to calculate toll multipliers for estimation of final toll

rates during each tolling period. The Class 1 rate is used as the base for calculation of the multiplier:

$$m_{BC,l} = \frac{t_{BC,l}}{t_{BC,1}}$$

(Eq. 51)

where: $m_{BC,l}$ = toll multiplier for load class l
$t_{BC,l}$ = estimated bridge construction share of load-related toll for class l ($/load)
$t_{BC,1}$ = estimated bridge construction share of load-related toll for class 1 ($/load)

Individual tolling period rates were then obtained by solving the following equation for the Class 1 incremental toll rate for the 2008-2015 tolling period:

$$C_{BC} = \sum_{T} t_{C1,1} \times m_{BC,l} \times n_{t,l}$$

(Eq. 52)

where: C_{BC}= total bridge construction costs ($)
$t_{C1,1}$ = class 1 toll rate per load during period 1 ($/vehicle)
$m_{BC,l}$ = toll multiplier for load class l
$n_{t,l}$ = number of loads of class l expected on facility during time period t
T = set of all time periods

The final bridge construction toll shares for each time period are provided in Table 49.

Table 49. Bridge Construction Toll Shares

Load Class	Rate ($)				
	2008 to 2015	2016 to 2025	2026 to 2035	2036 to 2037	Weighted Average
Class 1	0.16	0.25	0.33	0.38	0.29
Class 2	0.25	0.37	0.49	0.57	0.43
Class 3	0.27	0.41	0.55	0.64	0.48
Class 4	0.35	0.52	0.70	0.81	0.61
Class 5	0.35	0.52	0.70	0.81	0.61
Class 6	0.53	0.79	1.05	1.23	0.92
Class 7	1.30	1.96	2.61	3.04	2.28

7.4.4 Final Axle-Load Toll Rate

The final base toll rate for each vehicle within the "Axle-Load" toll was calculated by summing the base toll shares for common costs, pavement construction, and pavement maintenance. The resulting estimated base toll for each period is provided in Table 50. Since toll rates need to be easily understood and toll elements easily added, these values were rounded up to the nearest five-cent increment. A weighted average of this final toll was calculated for use in the equity analysis.

Table 50. Final Base Toll Rate

Toll Period	Estimated	Rounded
2008 to 2015	5.19	5.20
2016 to 2025	7.79	7.80
2026 to 2035	10.38	10.40
2036 to 2037	12.11	12.15
Weighted Average	**9.06**	**9.08**

The final per-load tolls for each class were calculated by summing the estimated per-load toll shares for pavement construction, pavement maintenance, and bridge construction. These values were also rounded to the nearest five-cent increment for

user ease of calculation. The final load class toll, as well as the weighted average for equity analysis, are provided in Table 51.

Table 51. Final Toll Rate per Load

Load Class	Weight (kips)			Toll per Load ($)				
	Single	Tandem	Tridem	2008 to 2015	2016 to 2025	2026 to 2035	2036 to 2037	Weighted Average
Class 1	< 4	< 5.5	< 8	0.20	0.30	0.35	0.40	0.32
Class 2	4 to 6.5	5.5 to 10	8 to 12.5	0.30	0.45	0.60	0.70	0.52
Class 3	6.5 to 9	10 to 15.5	12.5 to 20	0.60	0.90	1.15	1.35	1.02
Class 4	9 to 12	15.5 to 18.5	20 to 25	1.25	1.85	2.45	2.85	2.14
Class 5	12 to 15	18.5 to 23.5	25 to 31.5	2.15	3.20	4.25	4.95	3.71
Class 6	15 to 18	23.5 to 28.5	31.5 to 38.5	4.65	6.95	9.30	10.85	8.11
Class 7	> 18	> 28.5	> 38.5	10.15	15.20	20.30	23.65	17.70

7.5 NUMBER-OF-AXLE TOLL RATE

Rates for a number-of-axle based toll rate were also estimated using equations 26 and 27. Equation 28 was restructured with an additional toll multiplier to allow for calculation of rates within each time period. The values of the new toll multiplier are provided in Table 52.

Table 52. Time Period Toll Multipliers

Time Period	Multiplier
2008 to 2015	1.00
2016 to 2025	1.50
2026 to 2035	2.00
3067-2037	2.33

Rewriting equation 28, we get:

$$C = \sum_{T} n_{a,t} \times z_a \times m_t \times t_2$$

(Eq. 53)

where: C= sum of all costs over life of facility
$n_{a,t}$ = expected number of vehicles with number of axles a during time t
z_a= toll multiplier for vehicles of number of axles a
m_t = toll multiplier for vehicle in time period t
t_2= base toll rate for two-axle vehicle

Individual time period rate estimates were again rounded to the nearest five-cents for clarity. The final rates for each time period, as well as a weighted average paid by each class over the design period, are provided in Table 53.

Table 53. Final Number-of-Axle Toll Rates

Number of Axle Class	Toll per Vehicle ($)				
	2008 to 2015	2016 to 2025	2026 to 2035	2037-2037	Weighted Average
2	4.85	7.25	9.65	11.30	8.43
3	9.65	14.50	19.30	22.55	16.85
4	14.50	21.70	28.95	33.80	25.26
5	19.30	28.95	38.60	45.05	33.68

7.6 COST RESPONSIBILITY ESTIMATION

Individual vehicle cost responsibilities were estimated using the methods described in section 6.5. Since in this study, common costs are allocated using the same method for both toll rate estimation and cost allocation, all vehicles are assumed to have paid exactly their share for "Common Costs," base pavement construction, and base bridge construction. As discussed previously, because of the the assumed 30 year

analysis period, shares of construction costs are allocated only to users during this period, regardless of the actual service life of individual elements.

7.6.1 Pavement Construction Cost Responsibility Determination

As was discussed in section 6.5.1, pavement construction cost responsibilities are estimated using both incremental and proportional methods. The same pavement increments identified for toll rate determination (Table 37) were used for allocation of cost responsibilities to individual load classes. However, within each load class, rather than a cost per vehicle, a cost per ESAL was estimated (Eq. 29). Total costs per ESAL for individual load classes were then estimated by summing across all increments for which the class shares responsibility (Eq. 30). The resulting costs per ESAL for each load class are provided in Table 54.

Table 54. Incremental Pavement Cost Responsibilities

Load Class	Cost Responsibility ($/ESAL)
Class 1	0.00
Class 2	0.13
Class 3	0.52
Class 4	1.19
Class 5	1.34
Class 6	1.68
Class 7	2.38

For each individual vehicle, the overall pavement construction cost responsibility was then calculated by multiplying the total ESALs contributed by each load by its corresponding cost per ESAL, and summing the costs for all loads on a vehicle. (Eq. 31, 32)

7.6.1 Pavement Construction Cost Responsibility Determination

Pavement maintenance cost responsibilities were estimated directly using proportional allocation. Each truck was assigned a cost responsibility directly in proportion to its share of total truck ESALs (Eq. 33, 34). The estimated cost per ESAL for pavement maintenance was $9.62.

7.6.1 Bridge Construction Cost Responsibility Determination

Bridge construction cost responsibilities were estimated directly as a cost per vehicle within each bridge design increment. The same bridge increment costs and class responsibilities identified for toll rate estimation were used for cost responsibility allocation (Table 43). Using equation 18, costs per vehicle for each design increment were calculated; these are provided in Table 55.

Table 55. Incremental Bridge Cost Responsibilities

Bridge Design Increment	Bridge Type		
	Short	Medium	Long
	Cost Responsibility ($)		
H2.5	0.000	0.000	0.000
H5	0.001	4.369E-04	0.152
H10	0.004	0.002	0.561
H15	0.010	0.004	1.028
HS15	n/a	0.006	1.645
H20	0.019	0.007	1.879
HS20	0.038	0.018	3.273
HS25	n/a	1.344	24.843

Individual vehicle responsibilities were identified by summing the incremental costs across all increments required to support the vehicle (Eq. 35).

7.6.1 Final Cost Responsibility

The vehicle's final cost responsibility was then calculated by summing its cost responsibilities for "Common Costs," pavement construction, pavement maintenance, and bridge construction (Eq. 36).

7.7 TOLL EQUITY ANALYSIS

For the purpose of toll equity analysis, the weighted mean tolls collected over the design life of the facility under each tolling structure were analyzed. Tolls paid under each structure were calculated for each observed truck. A "responsibility ratio" was then calculated for each truck under each tolling structure (Eq. 37 and 38).

The overall equity of the tolls paid under each structure can be examined by estimating the average responsibility ratio for the tolls paid by the entire truck population (Eq. 39 and 40). Table 56 shows the estimated mean responsibility ratios for each class. Clearly, in general, vehicles paying the "Axle-Load" toll are paying a share of costs much closer to their consumption than when paying the "Number-of-Axle" toll. Under the "Axle-Load" toll, the average vehicle pays about 5 percent more than its share of costs. A value greater than one is expected here for two reasons. First, because pavement consumption increases exponentially with weight, and pavement construction cost responsibilities within each load class were allocated according to ESALs, most loads within each load class will be paying for an amount of consumption higher than that for which they are responsible. Additionally, since toll rates were

rounded up to the nearest 5 cents, a very small amount of excess revenue will be expected due to rounding error. Under the "Number-of-Axle" structure, the average vehicle pays more than one and a half times its cost responsibilities.

Table 56. Mean Responsibility Ratios

Truck Type	Axle-Load	Number-of-Axle
2SU	1.07	0.88
3SU	1.05	1.21
3ST	1.09	1.49
4SU	1.04	2.01
4ST	1.08	2.17
5ST	1.04	1.83
Total	**1.05**	**1.52**

More detailed information about the equity of these toll structures can be examined by looking at individual vehicle class equities. As can be seen from Table 56, the only class which underpays for its use under either tolling structure is the two-axle single unit truck. The value of common costs allocated to all vehicles, $9.05, was higher that the base toll calculated for two-axle trucks under the "Number-of-Axle" scenario, $8.43. Since most two-axle trucks have axle loads that fall into the lowest load categories, the load-related tolls paid are very low. As a result, nearly all two-axle trucks underpay for their use (Figure 15). If fewer costs were allocated as common costs, it is likely that this value would be closer to one.

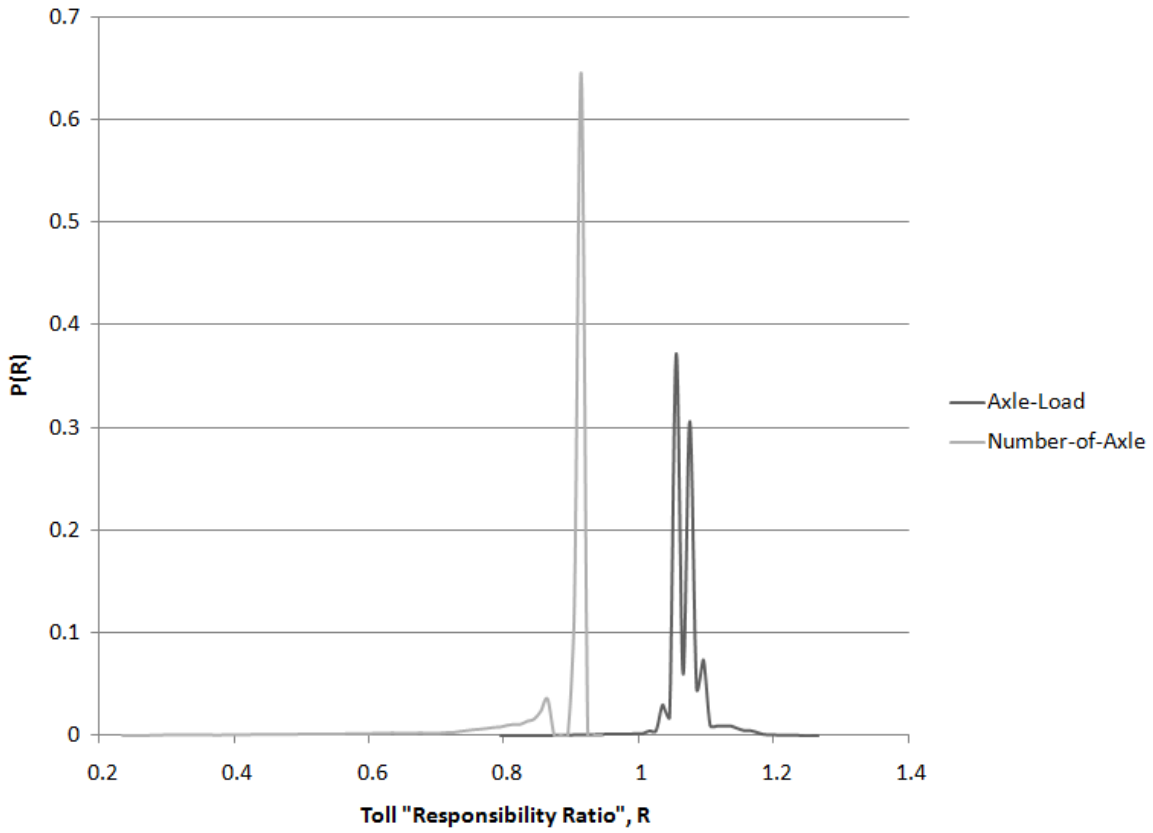


Figure 15. Distribution of R for 2 Axle Single Unit Trucks

However, from examining the ratios across all classes, it is clear that the "Axle-Load" toll provides a more equitable means of recovering costs. While the equity ratios paid by different truck classes under the "Number-of-Axle" toll range from .88 to 2.17, all of the mean values for the "Axle-Load" classes are between 1.04 and 1.09.

The equity of the tolls within each class can be examined by looking at the dispersion of R values within each class. In addition to the minimum and maximum observed values, the standard deviation provides a measure of this dispersion. Table 57

shows the minimum and maximum "responsibility ratios" observed within each class, as well as the standard deviation of R, for each toll rate structure.

Table 57. Toll Rate Dispersion Measures

Truck Type	Axle-Load			Number-of-Axle		
	Minimum	Maximum	Standard Deviation	Minimum	Maximum	Standard Deviation
2SU	0.79	1.26	0.03	0.24	0.93	0.09
3SU	0.77	1.28	0.08	0.36	1.83	0.39
3ST	0.84	1.27	0.06	0.51	1.82	0.34
4SU	0.88	1.17	0.05	0.68	2.61	0.61
4ST	0.79	1.29	0.06	0.53	2.74	0.52
5ST	0.52	1.33	0.11	0.37	3.49	0.86
Total	**0.52**	**1.33**	**0.09**	**0.24**	**3.49**	**0.82**

Again, it is clear from this table that under the "Axle-Load" structure, most vehicles will pay a toll much closer to their share of allocated costs than under the "Number-of-Axle" structure. For every vehicle class except two-axle trucks, the maximum value of R is higher under the "Number-of-Axle" toll, and the minimum is lower. This means that the vehicles that are most severely under-paying are paying even less of their share under the "Number-of-Axle" scenario, and those over-paying are over-paying by even more. Even for two-axle trucks, the minimum R value identified for the "Number-of-Axle" scenario was much lower than for the "Axle-Load" scenario. Examining the standard deviation values, we see that across all truck classes, the dispersion of R values is much lower in the "Axle-Load" scenario. Figure 16 shows the distribution of R values for five-axle semi-trailers. It is clear from this graphic that even in the vehicle class with the highest standard deviation under the "Axle-Load" scenario,

the majority of vehicles are paying much closer to their share of costs than under the "Number-of-Axle" scenario.

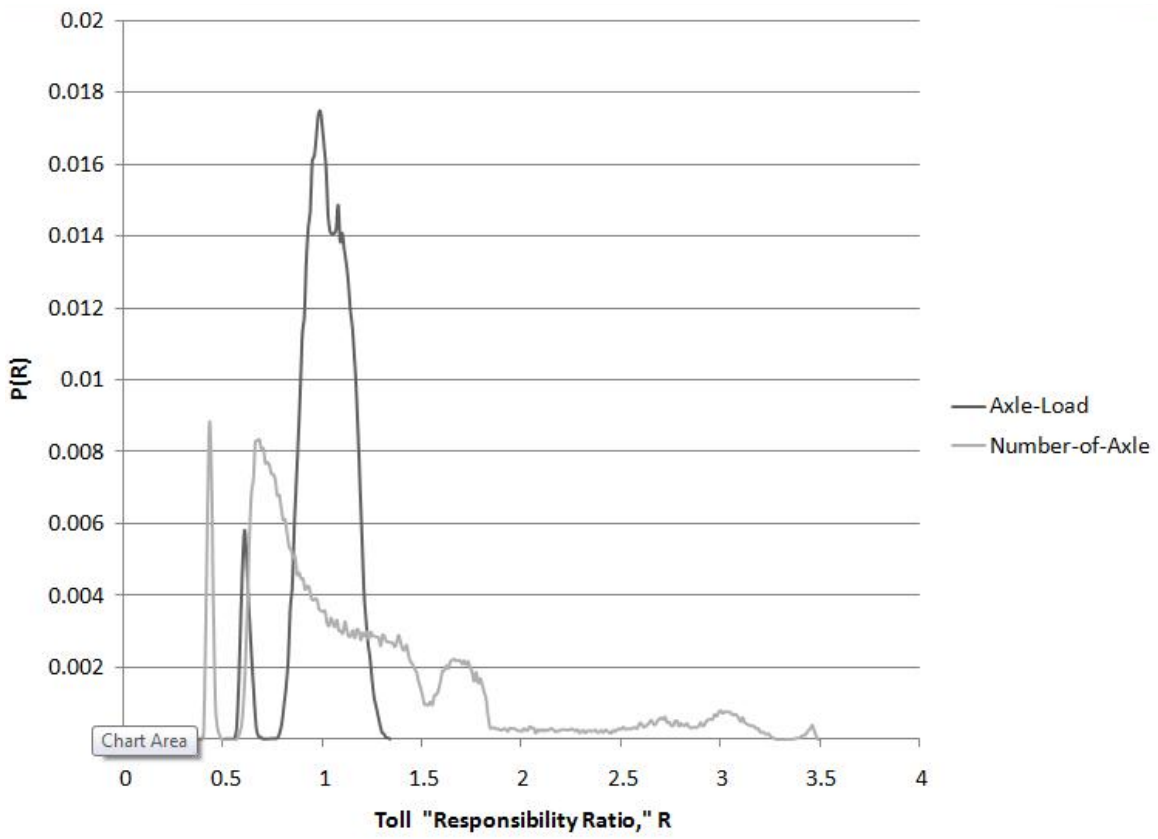


Figure 16. Distribution of R for 5 Axle Semi-Trailer Trucks

7.8 SENSITIVITY ANALYSIS

A number of types of sensitivity analysis can be performed to examine the revenue impact of changes in different variables under these different toll rate structures. This study will focus on the impact of three different measures: change in truck share, change in truck profile, and WIM scale error. Table 58 summarizes the revenue information for the existing toll rate structures.

Table 58. Toll Rate Summary

Variable	Trucks			Cars		
	Revenue	Revenue Share	Average Toll	Revenue	Revenue Share	Average Toll
Axle-Load	931,023,144	0.20	19.42	3,643,132,868	0.80	9.08
Number-of-Axle	1,182,950,427	0.26	24.68	3,382,335,911	0.74	8.43

It is clear from this table that trucks pay a much higher share of costs under the "Number-of-Axle" Toll Structure than under the "Axle-Load" structure. Because the toll rate for passenger cars (and two-axle trucks) under the "Number-of-Axle" structure is less than the base toll determined from allocation of common costs, under the "Number-of-Axle" toll, some passenger car common costs are allocated to trucks. As a result, the average truck toll paid under this structure is more than $5 more expensive than the average truck "Axle-Load" toll. Because of this higher cost and the higher share of total revenue collected from trucks, it is expected that revenue from the "Number-of-Axle" toll will be more sensitive to changes in volume.

7.8.1 Truck Share Sensitivity

Table 59 examines the impacts of changes in truck share on revenue for each toll structure. Since trucks pay a higher toll than cars, revenue will increase when truck share is increased, and decrease when truck share is decreased. As expected, the "Number-of-Axle" toll is more sensitive to changes in truck volume share, with a two percent increase in truck share resulting in a 3.2 percent increase in revenue. When

truck share is decreased by two percent, the impact on revenue is much more severe. Because trucks pay a toll close to four times as expensive as cars under the "Number-of-Axle" structure, a two percent decrease in truck share results in a more than 11 percent decrease in revenue. The "Axle-Load" toll is also very sensitive to the decrease in truck share, with a revenue decrease of 10.7 percent.

Table 59. Truck Share Revenue Sensitivities

Vehicle Type	Volume Share	Axle-Load			Number-of-Axle		
		Revenue	Change in Revenue	% Change in Revenue	Revenue	Change in Revenue	% Change in Revenue
Truck	0.107	4,574,156,012			4,565,286,338		
Car	0.893						
Truck	0.127	4,667,111,522	92,955,510	2.0	4,711,304,666	146,018,328	3.2
Car	0.873						
Truck	0.087	4,083,794,463	-490,361,549	-10.7	4,050,310,642	-514,975,697	-11.3
Car	0.913						

7.8.2 Truck Profile Sensitivity

The next variable examined for toll rate sensitivity was change in the truck profile. Table 60 shows the average toll rate paid by each vehicle type under each toll structure.

Table 60. Average Vehicle Type Toll Rates

Truck Type	Average Axle-Load Toll	% Increase from 2SU Toll	Average Number-of-Axle Toll	% Increase from 2SU Toll
2SU	10.45		8.43	
3SU	16.59	0.59	16.85	1
3ST	13.12	0.26	16.85	1
4SU	15.1	0.44	25.26	2
4ST	13.75	0.32	25.26	2
5ST	24.74	1.37	33.68	3

Again, from this table, it appears that revenue for the “Number-of-Axle” toll will be more sensitive to changes in truck profile than that for the “Axle-Load” toll. Under the “Axle-Load” Toll, percentage rate increases for additional axles are much lower than in the “Number-of-Axle” toll. Even for the most expensive class, the five-axle semitrailer, the percentage increase in toll rate for the “Axle-Load” toll is less than half the increase in the “Number-of-Axle” toll.

Table 61 shows the expected revenues under different truck split scenarios. Shares for the two most populous classes, the two-axle single unit truck and the five axle semi-trailer, were increased and decreased to determine the change in revenue.

Table 61. Truck Profile Revenue Sensitivites

		Axle-Load			Number-of-Axle		
Vehicle Type	Volume Share	Revenue	Change in Revenue	% Change in Revenue	Revenue	Change in Revenue	% Change in Revenue
2SU 5ST	0.30 0.60	931,023,144			1,182,950,427		
2SU 5ST	0.35 0.55	896,790,545	-34,232,599	-3.68	1,122,446,646	-60,503,781	-5.11
2SU 5ST	0.25 0.65	965,251,677	34,228,533	3.68	1,243,449,073	60,498,646	5.11
2SU 5ST	0.28 0.62	944,713,338	13,690,194	1.47	1,207,148,345	24,197,918	2.05
2SU 5ST	0.32 0.58	917,328,885	-13,694,259	-1.47	1,158,747,374	-24,203,053	-2.05

As expected, the “Number-of-Axle” toll is more sensitive to the change in profile. A five percent increase in two-axle single unit volume share, with a corresponding five percent decrease in five-axle semitrailer volume share, results in more than a five

percent decrease in revenue under the “Number-of-Axle” toll. The effect is much less under the “Axle-Load” structure, for which revenues decreased by only 3.68 percent.

7.8.3 WIM Error Sensitivity

The final variable examined to determine toll rate sensitivity was WIM measurement error. As was discussed in Chapter 4, two different types of error can occur in a WIM system, random error and systematic error. This examination focuses on systematic calibration error. When a WIM system is not properly calibrated, it systematically overestimates or underestimates the weight of individual axle loads. Weight measurement will not have any impact on the revenue collected by a “Number-of-Axle” toll, but it could potentially have a very serious impact on “Axle-Load” revenues. Table 62 shows the changes in load classification that would result from systematic WIM error and the resulting impacts on revenue.

Table 62. WIM Error Sensitivities

	Overestimates				Underestimates			
	10%		5%		5%		10%	
Load Class	Load Share	% Change	Load Share	% Change	Load Share	% Change	Load Share	% Change
Class 1	0.08	-0.38	0.11	-0.17	0.15	0.14	0.17	0.27
Class 2	0.17	0.18	0.15	0.06	0.14	-0.04	0.14	-0.04
Class 3	0.13	-0.17	0.14	-0.10	0.17	0.11	0.21	0.34
Class 4	0.21	-0.21	0.25	-0.08	0.27	0.00	0.24	-0.10
Class 5	0.18	0.61	0.14	0.27	0.10	-0.10	0.10	-0.11
Class 6	0.08	-0.01	0.08	0.00	0.09	0.07	0.10	0.19
Class 7	0.15	0.40	0.13	0.21	0.08	-0.25	0.05	-0.57
Revenue	1,039,932,465		987,690,509		874,322,435		803,655,929	
Change in Revenue	108,909,321		56,667,365		-56,700,709		-127,367,215	
% Change in Revenue	11.7		6.1		-6.1		-13.7	

If a WIM system overestimates axle loads, then the toll paid for each load could potentially be higher than the toll actually owed for that load. For the truck population examined in this case study, a 10 percent overestimation of weight results in a 40 percent increase in the number of loads classified to the most expensive load class, and a 38 percent decrease in those classified to the lightest class. As a result of these and other shifts in load class, total revenues increase by more than 11 percent.

An even more severe impact on revenue results from underestimation of weight. A systematic 10 percent underestimation of axle load weights results in a 57 percent decrease in the number of loads classified as Class 7 loads. This shifting of load classes results in more than a 13 percent decrease in revenues. In estimation and implementation of an “Axle-Load” toll, potential for this loss in revenue is likely to be a primary concern. Real implementation of an “Axle-Load” toll will require improvements

in WIM accuracy or inclusion of significant factors of safety in estimation of load-class toll rates.

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CHAPTER 8: CONCLUSIONS AND FUTURE RESEARCH

8.1 GENERAL FINDINGS

In general, the case study results indicate that Highway Cost Allocation (HCA) methods can be used for estimation of an "Axle-Load" based tolling structure that recovers costs for heavy vehicle consumption more equitably than a commonly employed "Number-of-Axle (n-1)" structure. In the case study, the tolls paid by individual vehicle classes, as well as the tolls paid by individual vehicles within those classes, more closely mirror their estimated consumption costs under the proposed "Axle-Load" structure than under the "Number-of-Axle" structure. It is clear from this analysis that the potential infrastructure impacts of different vehicles, all operating legally, within each number-of-axle class, are very different.

Within a "Number-of-Axle" toll structure, vehicles pay a higher toll for each additional axle; however, addition of an axle can potentially reduce pavement and bridge impacts by lessening the load being applied at a given point. Since pavement consumption increases exponentially, splitting a single load across two axles will severely reduce the pavement impact; for example, for the design pavement examined in this case study, applying two-10 thousand pound loads instead of a single 20 thousand pound load will reduce the estimated equivalent single axle loads (ESALs) by nearly 90 percent. It is clear in examining Figure 17 that the "Axle-Load" structure captures this exponential relationship.

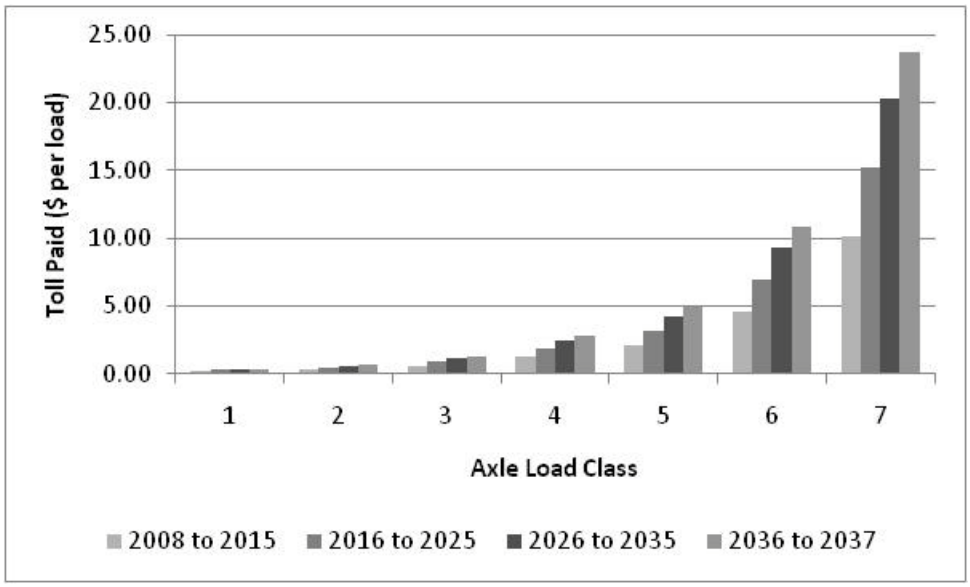

Figure 17. Axle-Load Toll Rates by Class

Table 63 shows the toll rates paid by each vehicle class, as well as the average ESALs, loads, and axle spacings observed in each class. Comparing the three-axle single unit truck and the four-axle semi-trailer, it is clear that the "Axle-Load" toll better relates a vehicle's toll cost and its consumption. Here, the average three-axle single-unit truck carries more gross vehicle weight (GVW) distributed over fewer axles and a shorter distance. Despite clearly lower levels of infrastructure consumption, in the "Number-of-Axle Structure," the four-axle truck pays a 50 percent higher average toll than the four-axle truck. However, under the proposed "Axle-Load" structure, the four-axle truck pays a toll that is about 83 percent of the three-axle single unit truck toll.

Table 63. Vehicle Type Toll Rates and Configurations

Truck Type	Average Axle-Load Toll	Average Number-of-Axle Toll	Expected ESALs	Average Axle Load			Average GVW	Average Length
				Single	Tandem	Tridem		
2SU	10.45	8.43	0.04	4810			9619	12.9
3SU	16.59	16.85	0.50	10633	17970		28603	23.0
3ST	13.12	16.85	0.21	6615			19845	33.4
4SU	15.1	25.26	0.38	9707		19869	29576	25.6
4ST	13.75	25.26	0.24	7459	11265		26123	43.8
5ST	24.74	33.68	1.12	10418	20948	11474	52294	58.2
Average			0.72	8566	20105	11849	36773	41.9

Despite the clear improvement in equity that results from the new structure, a number of improvements will need to be made to this model for real estimation and implementation of an "Axle-Load" tolling structure. The purpose of this study was to demonstrate that HCA methods can be employed to better relate toll rate variables and measures of infrastructure consumption. This study also demonstrates that methods used to allocate costs to vehicle classes can also be used to allocate costs to load classes. However, this study employed basic methods of both cost estimation and cost allocation that could be improved with more detailed models. The following sections detail the future improvements that could be implemented for applications of this method, as well as future areas of research that will be required for their realization.

8.2 IMPROVED COST ESTIMATION

It is clear from the final toll rates identified in this study that the resulting toll structure will be heavily dependent on the share of costs allocated as common costs and load-related costs. In this study, only about 11 percent of total system construction,

operation, and maintenance costs were determined to be “Load-Related.” This value was determined by making a number of assumptions based on information from a variety of sources. Additionally, in this study, all bridge maintenance costs were considered to be non-“Load-Related”, and were allocated as common costs. As a result of the small share of costs allocated to trucks only, the total share of revenue collected from truck users is five percent lower under the “Axle-Load” toll than under the “Number-of-Axle” toll. Under the proposed structure, all passenger cars and two-axle trucks pay a higher share of costs than under the “Number of Axle” toll employed on SH130; this may indicate that an insufficient share of costs was allocated in the “Load-Related” toll. In future applications of this method, the availability of much more detailed construction and maintenance estimates – including a breakdown of specific bridge and pavement maintenance costs expected over the facility life – would allow for more accurate determination of costs to be allocated under each cost type for both toll rate and cost responsibility estimation.

8.3 IMPROVED METHODS OF COST ALLOCATION

8.3.1 Pavement Cost Allocation

In this study, the primary allocator used to determine load class and vehicle shares of pavement and construction maintenance costs was the ESAL. This method was chosen because the empirical ESAL formula provides a direct method for calculation of a single measure of pavement consumption for each observed load. However, as was

discussed in Chapter 5, a number of more advanced “mechanistic” pavement models have been developed in recent years for cost allocation and other purposes. “Mechanistic” models directly relate axle load repetitions to the progression of different distress types. Ideally, if individual maintenance cost estimates could be linked to different distress types, these models would provide a much more accurate means of allocating specific pavement maintenance costs. These models also allow for inclusion of variables representing local environmental conditions; this addresses one of the primary concerns of using the empirical ESAL equation, which was developed using 1950-s era trucks in Illinois.

Both the NAPCOM model developed for the 1997 Federal Highway Cost Allocation Study and the Mechanistic-Empirical Design Guide require inputs of axle load spectra; in HCA, axle load spectra are estimated for different axle types for each class of vehicle. However, in this study, it is load classes and individual vehicles, not vehicle classes, for which consumption must be examined. Since each load class will represent the sum of pieces of a number of mixed-lognormally distributed axle load spectra for different vehicle classes, statistical estimation of the distribution within each class will be very difficult.

Additionally, for cost responsibility estimation, a measure of consumption must be estimated for each individual load. As discussed in Chapter 5, Hong, Pereira, and Prozzi developed a method for estimation of “mechanistic ESALs” that could be used to develop a single measure of consumption from multiple distress types.[234] If each

observation could be evaluated, “mechanistic” load class ESALs could also be estimated discretely using this method. Currently the computation time required for evaluation of individual loads using “mechanistic” models is extremely high; as a result, this method was not employed in this study. However, as “mechanistic” models continue to evolve, they will provide a better method for linking pavement costs to individual loads and load classes for future toll estimation and cost allocation.

8.3.2 Bridge Cost Allocation

The bridge cost allocation methods employed in this study were also very basic. In this study, because of the complexity of estimating live-load moments for long bridges and the resulting long computation time, spans of three different lengths were used to characterize all short, medium, and long bridges. Additionally, all bridges were assumed to be simply supported. The costs of individual structural elements were not identified; rather, relative bridge type costs from the most recent Texas Highway Cost Allocation Study were used to estimate the share of additional costs required to accommodate subsequent design vehicles.[235] Because these relative costs were only provided for eight design bridge types, additional intermediate costs which have been used to improve allocation of costs to medium weight trucks in other studies could not be estimated here.[236,237]

Additionally, in the absence of detailed maintenance information and an appropriate allocator to assign bridge maintenance costs to individual load classes, and because all of the bridges on this facility are newly constructed, this study assigned all

bridge maintenance costs equally to all vehicles as non-load related costs. Most HCA studies allocate non-load related bridge rehabilitation costs using a similar method.[238] Because a truck's stress impacts on a bridge are determined both by its axle weights and by its axle spacings, no good measure for allocating shares of bridge costs to individual vehicles within design increments has been identified. In future studies, bridges should be distinguished as simply supported or continually supported, and additional intermediate design increments should be evaluated.

8.3.3 Common and Base Infrastructure Cost Allocation

This study allocated common costs to all vehicles equally: the share for all operational costs, non-load-related maintenance, and base facility construction was assumed to be the same for all vehicles. Since all vehicles in this study are assumed to travel the same distance, this is equivalent to the measure used in many HCA studies to allocate these - vehicle-miles traveled (VMT). In order to account for the additional space requirements of heavy trucks in providing highway capacity, the 1997 Federal Highway Cost Allocation did not assign base facility construction costs according to VMT; instead, the study assigned costs to individual classes according to passenger-car equivalent (PCE) weighted VMT.[239] PCEs provide a measure of the additional space requirements, and resulting traffic impacts, for longer and heavier vehicles. For the 1997 study, PCEs for individual vehicle classes were estimated using simulation models under different traffic loadings.[240] It is likely that in the future, simulation modeling

could be used to develop functions for estimating individual vehicle PCEs for determining cost responsibilities.

However, integrating a PCE variable into the existing “Axle-Load” toll structure would be difficult. Assigning higher shares of non-load related costs to individual vehicles classes would require introduction of multiple base toll rates, adding a layer of complexity for system users to estimate their toll. If just a few PCE-related classes can be distinguished, application of multiple base toll rates might be feasible. Future analysis should be performed to determine the impacts of weighting base facility costs by PCE and the toll structure that would be required to equitably incorporate these costs.

8.4 ADDITION OF LARGER VEHICLE CLASSES

This study focused only on legally operating two to five axle trucks, which constituted more than 99 percent of the vehicles observed in the WIM data. However, future studies should explore the application of this same methodology to incorporate larger vehicle classes. With the nation’s highway system becoming increasingly congested, and freight flows expected to increase at a rate even higher than general traffic, several concepts for improving the productivity of the nation’s freight transportation system are being explored. Two potential solutions for improving trucks freight productivity include 1) changing regulations to allow longer, heavier, more productive vehicles to operate and 2) constructing separate capacity for trucks, where

more productive vehicles would likely operate. With federal and state governments struggling to fund system improvements, it is likely that if these truck-only facilities are constructed, they will need to be funded through user fees. In an environment where extremely heavy vehicles would be operating regularly, it will be important to ensure that costs recovered from users will be sufficient to construct and maintain the system. If new capacity is not constructed, but more productive vehicles are allowed to operate on existing capacity, future methods for recovering infrastructure costs from these users will also be required. In addition to expanding on this existing methodology to account for larger vehicle classes for direct-toll estimation, methods for employing HCA methods to estimate other types of user costs, such as overweight permits, should also be explored.

8.5 DYNAMIC LOAD MEASUREMENT

This study assumed that all vehicles would be traveling at the same free-flow speed when crossing over a WIM system. As a result, dynamic effects of load measurement were not considered. However, as was discussed in Chapter 4, suspension systems, pavement roughness, and speeds can all affect load measurement. Since WIM is used directly to classify loads, loads on vehicles using more road-friendly suspension systems, such as air suspension systems, will be classified to lower classes than vehicles with the same real static load using steel suspension systems. Pavement roughness impacts in WIM error can be controlled by maintaining a high pavement

quality in the area of the WIM; however, if the pavement of the system is not maintained at a high quality, then the impacts of roughness on load classification will need to be quantified. This problem should be explored in future research.

Vehicles traveling at different speeds will impose different dynamic forces on a pavement and on a WIM system. If a WIM system is employed for load classification in an environment with variable travel speeds, then it may be necessary to estimate the dynamic effect of a vehicle traveling at a higher or lower speed, and to convert the measured load to an adjusted value for a design speed before toll rate classification. Classifying vehicles under dynamic loading conditions would require collection of real-time vehicle speeds as well as weights. Future research should explore the effects of changes in speed on measured loads, and the potential misclassification of loads that would result.

Speed implications for toll estimation must also be explored. If an entire system is priced for a given design speed, but traffic operates at much slower speeds on some of its elements, then the actual cost of pavement damage may exceed the revenue recovered by the toll. Similarly, if trucks crossing a bridge are moving slower than was expected in estimating costs, then the real damage is likely to exceed that which was estimated. Future research should explore the impacts of dynamic effects on cost estimation and allocation, and the changes in toll rate and structure that would result for different design speeds.

8.6 TOLL ELASTICITIES

An additional measure that could not be estimated in this study, but that will be important to examine in future research, is the impact that the change in toll structure will have on overall vehicle volumes and revenue. In this study, toll rates for the majority of road users (passenger vehicles) would increase under the "Axle-Load" structure. However, toll rates for trucks would generally decrease. The percentage of truck users paying an increased toll under the "Axle-Load" structure varies across truck classes, with a total of 49 percent of trucks paying a higher toll (Table 64). The maximum tolls paid within each class by the highest consuming users are much higher than the "Number-of-Axle" toll rates.

Table 64. Vehicle Class Extreme Tolls

Truck Type	Minimum	Maximum	Share Paying Higher Toll
2SU	9.72	34.89	1.00
3SU	9.72	44.48	0.36
3ST	10.04	32.63	0.15
4SU	9.92	34.89	0.14
4ST	10.04	32.63	0.05
5ST	10.04	58.44	0.28
Total	**9.72**	**58.44**	**0.49**

Because some vehicles will be paying a higher toll and some paying a lower toll, it is impossible to use the elasticities identified through stated preference surveys for SH 130 to estimate changes in volume. Additionally, the elasticities estimated for SH130 were only aggregately estimated for all two-axle and all multi-axle vehicles. Much more detailed data will be required to understand the response of road users within each

class to changes in the toll structure. Since the rates for the "Axle-Load" toll structure increase exponentially, it will be especially important to understand the behavior of the heaviest vehicles, and to estimate the likelihood that they will divert from a facility to avoid paying a toll.

In examining the impacts of diversion, the policy goals of the system should be considered. If a user-charge is going to be implemented system-wide for the primary purpose of recovering infrastructure costs, then diversion should not be a major consideration in setting toll rates. However, if users do not have a choice of whether or not to pay, then it is likely that they would adjust vehicle configurations for more road-friendly loading. Future research should examine the potential impacts of changes in truck configuration that would result from a load-based toll.

If a tolling structure is being implemented on a facility where users choose whether or not to pay, and where the primary goal is revenue maximization, then diversion would be very likely. While diversion of the heaviest trucks from a facility would lead to considerable loss of revenue, it would also lead to considerable savings in maintenance costs on the facility in question (although it would have the opposite effect on alternative routes, especially if they are lower classes of road). Economic analysis should examine the potential impacts of resulting diversion not only on the priced facility, but also on alternative routes.

8.7 INTEGRATION OF CONGESTION AND EMISSIONS COSTS

This research focused specifically on using HCA methods to develop a more equitable toll structure for recovery of infrastructure costs. However, as was discussed in Chapter 3, there are two other costs that will be important to consider in future road pricing for trucks: emissions impacts and congestion. Recent cost allocation studies, including the 1997 Federal HCA, have allocated marginal social costs, such as congestion, to individual vehicle classes.[241] Future research should explore the possibility of using HCA methods to allocate congestion and emissions costs as part of the base or per-load toll in an "Axle-Load" tolling structure. These costs might be included as part of the basic toll rate, or they might be imposed as a multiplier. In order to determine the exact structure to recover these costs, it is likely that research examining the relationships between length, GVW, or axle loads and traffic impacts (possibly using PCE as a measure), and length, GVW, or axle load and emissions levels will be required.

8.8 QUANTIFICATION OF WIM ERROR

Weigh-In-Motion system error will be important to quantify for toll rate estimation, cost allocation, and toll rate collection. In the previous section, the high sensitivity of revenue collected under the proposed tolling structure to systematic WIM error was quantified. However, future research should explore the how both random and systematic WIM error would affect the toll rate structure and rates. It is assumed

that the same WIM data used to design a pavement will be used to estimate the toll rate for that structure; if loads are underestimated, then the pavement will be under-designed, and maintenance costs will likely be much higher than estimated. However, if a correctly calibrated scale is used for toll classification, then a higher share of vehicles than expected will be classified to higher load classes. Relative and absolute net changes in revenue will need to be quantified for different levels of error. If loads are overestimated, maintenance costs will likely decrease, but the number of vehicles classified to the highest load class will be fewer than expected, resulting in less toll revenue. Again the net change in revenue will need to be evaluated for a variety of levels of error.

In addition to examining potential impacts for toll estimation, future research should further examine the impacts of WIM error on toll rate classification. For a WIM system to be directly applied for tolling, a very high level of accuracy in load classification must be achieved. Research should be performed to explore methods for quantifying the likelihood of misclassification due to both random and systematic scale error. An important policy question that must be answered in implementation of an "Axle-Load" tolling structure will be to determine what error tolerance must be achieved before WIM can be used directly for tolling at highway speeds. Currently, no WIM system in the U.S. has been approved for direct weight enforcement; however, as discussed in Chapter 4, a number of new technologies are being explored for future

WIM applications. Future research must also examine the impact of environmental conditions on any new technology proposed for WIM applications.

8.9 DATA UNCERTAINTY

In this analysis, toll rates were estimated simply to recover costs; in solving for the basic toll rates, expected revenue was set equal to the expected costs. However, in real implementation, an operator will not implement a toll structure that could potentially lead to a loss in revenue. Future research should examine methods for quantifying all of the uncertainties in estimating toll rates for a load-based structure: these include overall vehicle volumes, truck share, truck profile, axle load spectra, random and systematic scale errors, and toll rate elasticities. If these uncertainties can be quantified, then a reliability-based method of analysis can be developed for better measurement and management of risk. Safety factors can then be introduced into the toll rate to guard against net losses in revenue.

8.10 FINAL CONCLUSIONS

As the United States moves toward new “cost-based” forms of user-charging, whether in the form of distance-based fees, congestion charges, or some other yet-to-be determined method, it will be necessary to link the costs imposed on the system by individual vehicles with the rates that these vehicles pay. The three major costs that will likely be necessary to measure are infrastructure consumption, contributions to congestion, and vehicle emissions. Already, advanced technologies have been

employed in user-charging mechanisms to measure congestion contributions using real-time traffic data. This dissertation provides a theoretical framework for a user-charging mechanism that would use real-time weight data to measure infrastructure consumption for heavy vehicles. The results of this research indicate that employing WIM systems for real-time load classification would allow system operators to better measure and recover the costs of infrastructure consumption from individual users. Looking ahead, this research provides a basis upon which future research in toll rate estimation and technology implementation for real-time truck tolling can be built.

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APPENDIX A: PROGRAM FOR LIVE-LOAD MOMENT CALCULATION

This program was developed to estimate the maximum live-load moment for individual vehicles crossing a simply supported bridge span of a user-defined length. The program "virtually" runs the truck over the bridge span by incrementing its axle load positions by a user-defined distance. In this study, three lengths – 18, 31, and 370 feet - were evaluated, and trucks were moved across the bridge in .1 ft increments.

Five different moment calculating functions were defined for estimation of the live-load moment when one, two, three, four, or five of a truck's axles are on a bridge. "While" loops using boundary conditions estimated as a function of bridge length and axle spacing to control the loadings considered in the moment calculation. Each change in loading corresponds to an additional axle entering or leaving the bridge. The number of potential loading patterns increases with the number of axles on a vehicle. For two-axle trucks, there are two potential loading patterns; the second axle either enters the bridge before or after the first leaves it. For three-axle trucks there are five, and for four-axle trucks there are 14 patterns. For five-axle trucks, there are 42 different potential loading patterns.

Since the maximum moment will occur in different locations for different trucks and bridge lengths, moments are also measured at incremental distances along the bridge (.1 ft for this study, which will allow for measurement at the critical points where each load is applied). Each moment calculating function uses dummy variable functions

to determined the correct formula for calculation of a moment due to its location relative to loads on the bridge. Figure A1 demonstrates how these variables identify the moment region for calculation for a 3 axle truck when all of its loads are on a bridge.

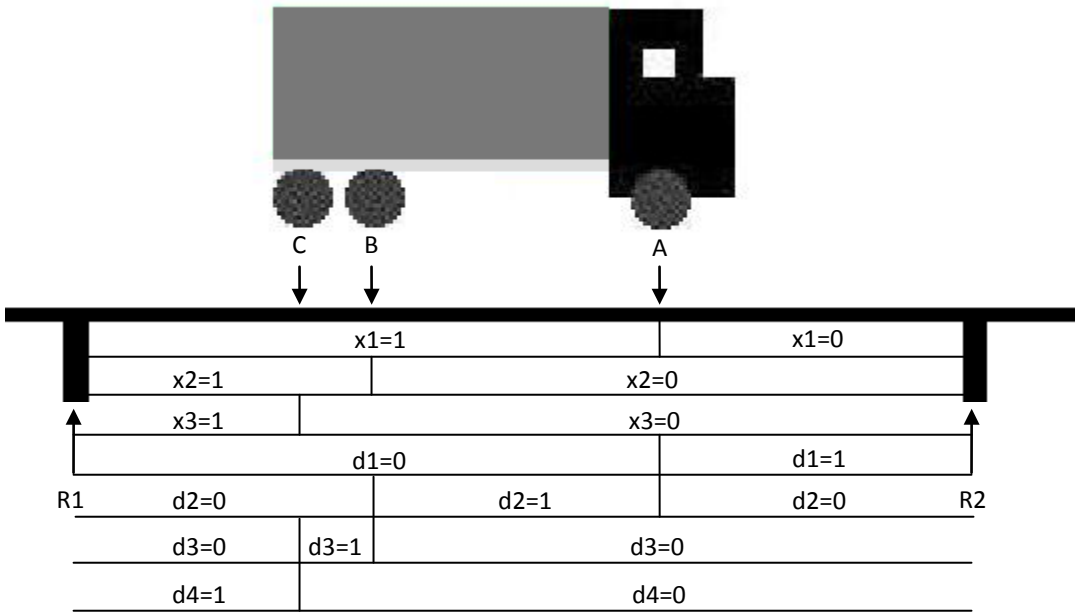

Figure A1. Dummy Variables for Moment Calculation

The following pages provide the source code for the program.

```
global.h
//  This file contains all the global input variables

//  Variables

float inc = .1;          // Increments (ft)
float  L  = 18;          // Bridge span length (ft)
int axlnum = 3 ;         //Number of axles on the truck class

ofstream fout;

int o = 1;               //O = Observation Number counter
int obs;
int MT;                  //MT = Moment Type - first num = #axles, 2nd
                         num = option

float A;                 //A = Load on Axle A
float B;                 //B = Load on Axle B
float C;                 //C = Load on Axle C
float D;                 //D = Load on Axle D
float E;                 //E = Load on Axle E

float AB;                //AB = Axle spacing from A to B
float BC;                //BC = Axle spacing from B to C
float CD;                //CD = Axle spacing from C to D
float DE;                //DE = Axle spacing from D to E

float MaxT;              //Location of Axle A when Max Moment Occurs
float MaxM;              //Maximum Moment
float MaxL;              //Location of Maximum Moment

float pM;                //Point where moment evaluated
float pX;                //Location of axle A
float pY;                //Location of axle B
float pZ;                //Location of axle C
float pU;                //Location of axle D
float pV;                //Location of axle E

float r1;                //Reaction at Left Girder
float r2;                //Reaction at Right Girder

float EL;                //Limit for single axle on two axle truck
                         entering bridge
float LL;                //Limit for single axle on two axle truck
                         leaving bridge
float UL;                // Upper Limit



//  Functions

void oneax(float pLoad, float Load );
void twoax(float pLoad_1, float pLoad_2, float Load_1, float Load_2);
```

```
void threeax(float pLoad_1, float pLoad_2, float pLoad_3, float Load_1,
float Load_2, float Load_3);
void fourax(float pLoad_1, float pLoad_2, float pLoad_3, float pLoad_4,
float Load_1, float Load_2, float Load_3, float Load_4);
void fiveax (float pLoad_1, float pLoad_2, float pLoad_3, float
pLoad_4, float pLoad_5, float Load_1, float Load_2, float Load_3, float
Load_4, float Load_5);
void position_increment();
void position_increment_2_axle();
void position_increment_3_axle();
void position_increment_4_axle();
void position_increment_5_axle();
void init_variables();



#include <iostream>
using std::ios;
using namespace std;
using std::ifstream;
#include <fstream>
#include <stdlib.h>
#include <time.h>
#include <math.h>
#include <iomanip>
#include <stdio.h>
#include "global.h"

int main()
{
 init_variables();
 cout <<endl<< "Thank you: Look for output in axle_load.txt";
 return 0;
}

//*********************************************************************
******************************
//function to initialize the variables
//*********************************************************************
*****************************

void init_variables()
{
    ifstream fin;
    switch(axlnum) {
          case 1:
          case 2:
             fin.open("2_input_loads.txt");
             if(fin.fail())
             {
                 cout<<endl<<" Cannot open input file 2_input_loads.txt
";
                 exit(-1);
```

```
            }
            while(!fin.eof()) {
                    fin >> A >> B >> AB ;
                    position_increment_2_axle();
                    }
            fin.close();
            break;
         case 3:
            fin.open("3_input_loads.txt");
            if(fin.fail())
            {
                cout<<endl<<" Cannot open input file 3_input_loads.txt
";
                exit(-1);
            }
            while(!fin.eof()) {
                    fin >> A >> B >> C >> AB >> BC;
                    position_increment_3_axle();
                    }
            fin.close();
            break;
         case 4:
            fin.open("4_input_loads.txt");
            if(fin.fail())
            {
                cout<<endl<<" Cannot open input file 4_input_loads.txt
";
                exit(-1);
            }
            while(!fin.eof()) {
                    fin >> A >> B >> C >> D >> AB >> BC >> CD;
                    position_increment_4_axle();
                    }
            fin.close();
            break;
         case 5:
            fin.open("5_input_loads.txt");
            if(fin.fail())
            {
                cout<<endl<<" Cannot open input file 5_input_loads.txt
";
                exit(-1);
            }
            while(!fin.eof()) {
                    fin >> obs >> A >> B >> C >> D >> E >> AB >> BC >>
CD >> DE;
                    position_increment_5_axle();
                    }
            fin.close();
            break;
         default:
            cout<<endl<<"Please ensure number of axles is less than
5";
```

```
     }

}



//*********************************************************************
******************************
//function to increment the position of the truck for 2 axle truck
//*********************************************************************
****************************

void position_increment_2_axle()
{
     fout.open("axle_load.txt", ios::app);
     if(AB < L )  //  if the distance between axles is less than the
span of the bridge
     {
           pX = 0;
               pY = 0;
               MT = 21;
               MaxT = 0;
               MaxM = 0;
               MaxL = 0;
           while(pX <= AB) {
                    oneax( pX, A );
                    pX = pX + inc;
                    }
               while(pX <=  L){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }
            while(pX <= (L + AB)){
                    oneax(pY, B);

                    pY = pY + inc;
                    pX = pX + inc;
                    }
     fout << endl << setw(10) << MaxM;
     }

     if( AB >= L )
     {
         pX = 0;
             pY = 0;
             MT = 22;
             MaxT = 0;
             MaxM = 0;
             MaxL = 0;
         while(pX <= L){
                    oneax( pX, A );
                    pX = pX + inc;
```

```
                    }
             while(pX <= AB ){
                    pX = pX + inc;
                    }

             while(pX <= (L + AB)){
                    oneax(pY, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }
       fout << endl << setw(10) << MaxM;
       }
     fout.close();

}

//*********************************************************************
******************************
//Function to increment the position of the truck for 3 axle truck.
//*********************************************************************
****************************

void position_increment_3_axle()
{
    fout.open("axle_load.txt", ios::app);

      if( (AB >= L) && (BC >= L) )
      {
             pX = 0;
             pY = 0;
             pZ = 0;
             MaxT = 0;
             MT = 31;
             MaxM = 0;
             MaxL = 0;
         while(pX < L){
                    oneax(pX, A);
                    pX = pX + inc;
                    }


             while(pX <  AB ){
                    pX = pX + inc;
                    }


             while(pX < (L + AB) ){
                    oneax(pY, B );
                    pX = pX + inc;
                    pY = pY + inc;
                    }
```

```
        while(pX < (AB + BC) ){
               pX = pX + inc;
               pY = pY + inc;
                         }

        while(pX < (L + AB + BC)){
               oneax(pZ, C );
               pX = pX + inc;
               pY = pY + inc;
               pZ = pZ + inc;
               }
fout << endl << setw(10) << MaxM;
  }

  if( (AB >= L) && (BC < L) )
  {
        pX = 0;
        pY = 0;
        pZ = 0;
        MaxT = 0;
        MT = 32;
        MaxM = 0;
        MaxL = 0;
     while(pX < L){
               oneax(pX, A);
               pX = pX + inc;
               }

        while(pX <  AB ){
               pX = pX + inc;
               }
        while(pX < (AB + BC) ){
               oneax(pY, B );
               pX = pX + inc;
               pY = pY + inc;
               }

        while(pX < (L + AB) ){
               twoax(pY, pZ, B, C);
               pX = pX + inc;
               pY = pY + inc;
               pZ = pZ + inc;
                         }

        while(pX < (L + AB + BC)){
               oneax(pZ, C );
                         pX = pX + inc;
                         pY = pY + inc;
                         pZ = pZ + inc;
               }
fout << endl << setw(10) << MaxM;
  }
  if( (AB < L) && (BC >= L) )
```

```
{
        pX = 0;
        pY = 0;
        pZ = 0;
        MaxT = 0;
        MT = 33;
        MaxM = 0;
        MaxL = 0;

        while(pX < AB){
                oneax(pX, A);
                pX = pX + inc;
                }

        while(pX < L ){
                twoax( pX , pY, A, B);
                pX = pX + inc;
                pY = pY + inc;
                }

        while(pX < (L + AB) ){
                oneax(pY, B );
                pX = pX + inc;
                pY = pY + inc;
                }


        while(pX < (AB + BC) ){
                pX = pX + inc;
                pY = pY + inc;
                }

       while(pX < (L + AB + BC)){
                oneax(pZ, C );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }
fout << endl << setw(10) << MaxM;
}

if( (AB < L) && (BC < L) && ( AB + BC >= L) ){
        pX = 0;
        pY = 0;
        pZ = 0;
        MaxT = 0;
        MT = 34;
        MaxM = 0;
        MaxL = 0;
        while(pX < AB){
                oneax(pX, A);
                pX = pX + inc;
                }
```

```
            while(pX < L ){
                   twoax( pX , pY, A, B);
                   pX = pX + inc;
                   pY = pY + inc;
                   }


            while(pX < (AB + BC) ){
                   oneax(pY, B );
                   pX = pX + inc;
                   pY = pY + inc;
                   }

            while(pX < (L + AB)){
                   twoax( pY, pZ, B, C);
                   pX = pX + inc;
                   pY = pY + inc;
                   pZ = pZ + inc;
                 }

       while(pX < (L + AB + BC)){
                   oneax( pZ, C);
                   pX = pX + inc;
                   pY = pY + inc;
                   pZ = pZ + inc;
                 }
fout << endl << setw(10) << MaxM;
   }

   if( (AB < L) && (BC < L) && ( AB + BC < L) ){
            pX = 0;
            pY = 0;
            pZ = 0;
            MaxT = 0;
            MT = 35;
            MaxM = 0;
            MaxL = 0;
       while(pX < AB){
                   oneax(pX, A);
                   pX = pX + inc;
                   }

       while(pX < (AB + BC) ){
                   twoax( pX , pY, A, B);
                   pX = pX + inc;
                   pY = pY + inc;
                   }

            while(pX < L ){
                   threeax(pX, pY, pZ, A, B, C);
                   pX = pX + inc;
```

```
                    pY = pY + inc;
                    pZ = pZ + inc;
                  }

         while(pX < (L + AB )){
                    twoax( pY , pZ, B, C);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                  }

         while(pX < (L + AB + BC )){
                    oneax( pZ, C);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                  }
         fout << endl << setw(10) << MaxM;
      }
      fout.close();


//*********************************************************************
******************************
//function to increment the position of the truck for 4 axle truck.
//*********************************************************************
****************************


void position_increment_4_axle()
{
      fout.open("axle_load.txt", ios::app);

      if( (AB >= L) && (BC >= L) && ( CD >= L)) {

             pX = 0;
             pY = 0;
             pZ = 0;
             pU = 0;
             MaxT = 0;
             MT = 41;
             MaxM = 0;
             MaxL = 0;
         while(pX <= L){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX <  AB ){
                    pX = pX + inc;
                    }

         while(pX <= (L + AB) ){
```

```
                oneax(pY, B );
                pX = pX + inc;
                pY = pY + inc;
                }

        while(pX < (AB + BC) ){
                pX = pX + inc;
                pY = pY + inc;
                          }

        while(pX <= (L + AB + BC)){
                oneax(pZ, C );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }

    while(pX < (AB + BC + CD) ){
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                          }

    while(pX <= (L + AB + BC +  CD)){
                oneax(pU, D );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }
fout << endl << setw(10) << MaxM;
}


if( (AB >= L) && (BC >= L) && ( CD < L)) {

        pX = 0;
        pY = 0;
        pZ = 0;
        pU = 0;
        MaxT = 0;
        MT = 42;
        MaxM = 0;
        MaxL = 0;
    while(pX <= L){
                oneax(pX, A);
                pX = pX + inc;
                }

    while(pX <  AB ){
                pX = pX + inc;
                }
```

```
      while(pX <= (L + AB) ){
                 oneax(pY, B );
                 pX = pX + inc;
                 pY = pY + inc;
                 }

         while(pX < (AB + BC) ){
                 pX = pX + inc;
                 pY = pY + inc;
                           }

         while(pX < (AB + BC + CD)){
                 oneax(pZ, C );
                 pX = pX + inc;
                 pY = pY + inc;
                 pZ = pZ + inc;
                 }

      while(pX <= (L + AB + BC ) ){
                 twoax(pZ, pU, C, D);
                 pX = pX + inc;
                 pY = pY + inc;
                 pU = pU + inc;
                 pZ = pZ + inc;
                 }

      while(pX <= (L + AB + BC +  CD)){
                 oneax(pU, D );
                 pX = pX + inc;
                 pY = pY + inc;
                 pZ = pZ + inc;
                 pU = pU + inc;
                 }
fout << endl << setw(10) << MaxM;
  }

  if( (AB >= L) && (BC < L) && ( CD >= L)) {


          pX = 0;
          pY = 0;
          pZ = 0;
          pU = 0;
          MaxT = 0;
          MT = 43;
          MaxM = 0;
          MaxL = 0;
      while(pX <= L){
                 oneax(pX, A);
                 pX = pX + inc;
                 }

      while(pX <  AB ){
```

```
                pX = pX + inc;
                }

   while(pX < (AB + BC) ){
                oneax(pY, B );
                pX = pX + inc;
                pY = pY + inc;
                }
      while(pX < (L + AB ) ){
                twoax(pY, pZ, B, C );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }

      while(pX <= (L + AB + BC)){
                oneax(pZ, C );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }

   while(pX < (AB + BC + CD) ){
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }

   while(pX <= (L + AB + BC +  CD)){
                oneax(pU, D );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }

fout << endl << setw(10) << MaxM;
}


if( (AB >= L) && (BC < L) && ( CD <  L) && ((BC + CD) >= L ) )
{
       pX = 0;
       pY = 0;
       pZ = 0;
       pU = 0;
       MaxT = 0;
       MT = 44;
       MaxM = 0;
       MaxL = 0;
   while(pX <= L){
                oneax(pX, A);
                pX = pX + inc;
```

```
            }

   while(pX <  AB ){
            pX = pX + inc;
            }
   while(pX < (AB + BC) ){
            pX = pX + inc;
            pY = pY + inc;
            }
      while(pX < (L + AB ) ){
            twoax(pY, pZ, B, C );
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            }

      while(pX < (AB + BC + CD ) ){
            oneax(pZ, C );
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
                     }

   while(pX <= (L + AB + BC ) ){
            twoax(pZ, pU, C, D);
            pX = pX + inc;
            pY = pY + inc;
            pU = pU + inc;
            pZ = pZ + inc;
                     }

   while(pX <= (L + AB + BC +  CD)){
            oneax(pU, D );
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            }
fout << endl << setw(10) << MaxM;
}

if( (AB >= L) && (BC < L) && ( CD <  L) && ((BC + CD) < L ) )
{

      pX = 0;
      pY = 0;
      pZ = 0;
      pU = 0;
      MaxT = 0;
      MT = 45;
      MaxM = 0;
      MaxL = 0;
   while(pX <= L){
```

```
                oneax(pX, A);
                pX = pX + inc;
                }

        while(pX <  AB ){
                pX = pX + inc;
                }

        while(pX < (AB + BC) ){
                oneax(pY, B );
                pX = pX + inc;
                pY = pY + inc;
                }

            while(pX < (AB + BC + CD) ){
                twoax(pY, pZ, B, C );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }
            while(pX <= (L + AB ) ){
                threeax(pY, pZ, pU, B, C, D);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
            }

            while(pX <= (L + AB + BC ) ){
                twoax(pZ, pU, C, D);
                pX = pX + inc;
                pY = pY + inc;
                pU = pU + inc;
                pZ = pZ + inc;
            }

            while(pX <= (L + AB + BC + CD ) ){
                oneax( pU, D);
                pX = pX + inc;
                pY = pY + inc;
                pU = pU + inc;
                pZ = pZ + inc;
            }

      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD <  L) && ((AB + BC) >= L )&&
((BC + CD) >= L ) )
      {
            pX = 0;
            pY = 0;
            pZ = 0;
```

```
        pU = 0;
        MaxT = 0;
        MT = 46;
        MaxM = 0;
        MaxL = 0;
        while(pX < AB){
                oneax(pX, A);
                pX = pX + inc;
                }

        while(pX <= L){
                twoax(pX, pY, A, B);
                pX = pX + inc;
                pY = pY + inc;
                }


       while(pX < (AB+ BC)){
                oneax(pY, B);
                pX = pX + inc;
                pY = pY + inc;
                }

       while(pX <= (L + AB)){
                twoax(pY, pZ, B, C);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }

        while(pX < (AB + BC + CD)){
                oneax(pZ, C);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }

        while(pX <= (L + AB + BC )){
                twoax(pZ, pU, C, D);
                pX = pX + inc;
                pY = pY + inc;
                pU = pU + inc;
                pZ = pZ + inc;
                }

        while(pX <= (L + AB + BC + CD )){
                oneax(pU, D);
                pX = pX + inc;
                pY = pY + inc;
                pU = pU + inc;
                pZ = pZ + inc;
                        }
fout << endl << setw(10) << MaxM;
```

```
      }

      if( (AB < L) && (BC < L) && ( CD <  L) && ((AB + BC) >= L )&&
((BC + CD) < L ) )
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            MaxT = 0;
            MT = 47;
            MaxM = 0;
            MaxL = 0;
         while(pX < AB){
                     oneax(pX, A);
                     pX = pX + inc;
                     }

         while(pX <= L){
                     twoax(pX, pY, A, B);
                     pX = pX + inc;
                     pY = pY + inc;
                     }

         while(pX < (AB+ BC)){
                     oneax(pY, B);
                     pX = pX + inc;
                     pY = pY + inc;
                     }

             while(pX < (AB+ BC + CD)){
                     twoax(pY, pZ, B, C);
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
             }

             while(pX <= (L + AB)){
                     threeax(pY, pZ, pU, B, C, D);
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                     pU = pU + inc;
             }

             while(pX <= (L + AB + BC)){
                     twoax(pZ, pU, C, D);
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                     pU = pU + inc;
             }
```

```
            while(pX <= (L + AB + BC + CD)){
                    oneax( pU,  D);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
            }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD <  L) && ((AB + BC) < L )&& ((BC
+ CD) >= L ) )
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            MaxT = 0;
            MT = 48;
            MaxM = 0;
            MaxL = 0;
         while(pX < AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

            while(pX < (AB + BC)){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }

            while(pX <= L){
                    threeax(pX, pY, pZ, A, B, C);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }

            while(pX <= (L + AB)){
                    twoax(pY, pZ, B, C);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }

            while(pX < ( AB + BC + CD)){
                    oneax(pZ, C);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }
```

```
            while(pX <= (L + AB + BC)){
                    twoax(pZ, pU, C, D);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }

           while(pX <= (L + AB + BC + CD)){
                    oneax(pU, D);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD <  L) && ((AB + BC) < L )&& ((BC
+ CD) < L ) && ((AB + BC + CD) >=L) )
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            MaxT = 0;
            MT = 49;
            MaxM = 0;
            MaxL = 0;
         while(pX < AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

            while(pX < (AB + BC)){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }

            while(pX <= L){
                    threeax(pX, pY, pZ, A, B, C);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }

            while(pX < (AB + BC + CD)){
                    twoax(pY, pZ, B, C);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }
```

```
            while(pX <= (L + AB)){
                    threeax(pY, pZ, pU, B, C, D);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }

           while(pX <= (L + AB + BC)){
                    twoax(pZ, pU, C, D);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }

           while(pX <= (L + AB + BC + CD)){
                    oneax(pU, D);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD <  L) && ((AB + BC) < L )&& ((BC
+ CD) < L ) && ((AB + BC + CD) < L) )
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            MaxT = 0;
            MT = 410;
            MaxM = 0;
            MaxL = 0;
         while(pX < AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

            while(pX < (AB + BC)){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }

            while(pX < (AB + BC + CD)){
                    threeax(pX, pY, pZ, A, B, C);
                    pX = pX + inc;
                    pY = pY + inc;
```

```
                pZ = pZ + inc;
                }

        while(pX <= L){
                fourax(pX, pY, pZ, pU, A, B, C, D);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }

        while(pX <= (L + AB)){
                threeax(pY, pZ, pU, B, C, D);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }

       while(pX <= (L + AB + BC)){
                twoax(pZ, pU, C, D);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }

       while(pX <= (L + AB + BC + CD)){
                oneax(pU, D);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }
fout << endl << setw(10) << MaxM;
}
if( (AB < L) && (BC < L) && ( CD >=  L) && ((AB + BC) >= L) )
{

        pX = 0;
        pY = 0;
        pZ = 0;
        pU = 0;
        MaxT = 0;
        MT = 411;
        MaxM = 0;
        MaxL = 0;
   while(pX < AB){
                oneax(pX, A);
                pX = pX + inc;
                }

   while(pX <= L){
```

```
                twoax(pX, pY, A, B);
                pX = pX + inc;
                pY = pY + inc;
                }


    while(pX < (AB+ BC)){
                oneax(pY, B);
                pX = pX + inc;
                pY = pY + inc;
                }

    while(pX <= (L + AB)){
                twoax(pY, pZ, B, C);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }

       while(pX <= (L + AB + BC)){
                oneax(pZ, C );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }

    while(pX < (AB + BC + CD) ){
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }

    while(pX <= (L + AB + BC +  CD)){
                oneax(pU, D );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }
fout << endl << setw(10) << MaxM;
}

if( (AB < L) && (BC < L) && ( CD >=  L) && ((AB + BC) < L) )
{

        pX = 0;
        pY = 0;
        pZ = 0;
        pU = 0;
        MaxT = 0;
        MT = 412;
        MaxM = 0;
        MaxL = 0;
```

```
   while(pX < AB){
              pX = pX + inc;
              }

       while(pX < (AB + BC)){
              twoax(pX, pY, A, B);
              pX = pX + inc;
              pY = pY + inc;
              }

       while(pX <= L){
              threeax(pX, pY, pZ, A, B, C);
              pX = pX + inc;
              pY = pY + inc;
              pZ = pZ + inc;
              }

       while(pX <= (L + AB)){
              twoax(pY, pZ, B, C);
              pX = pX + inc;
              pY = pY + inc;
              pZ = pZ + inc;
              }

      while(pX <= (L + AB + BC)){
              oneax(pZ, C );
              pX = pX + inc;
              pY = pY + inc;
              pZ = pZ + inc;
              }

   while(pX < (AB + BC + CD) ){
              pX = pX + inc;
              pY = pY + inc;
              pZ = pZ + inc;
              }

   while(pX <= (L + AB + BC +  CD)){
              oneax(pU, D );
              pX = pX + inc;
              pY = pY + inc;
              pZ = pZ + inc;
              pU = pU + inc;
              }
fout << endl << setw(10) << MaxM;
}
if( (AB < L) && (BC >= L) && ( CD < L))
{
       pX = 0;
       pY = 0;
       pZ = 0;
       pU = 0;
       MaxT = 0;
```

```
        MT = 413;
        MaxM = 0;
        MaxL = 0;
   while(pX < AB){
              oneax(pX, A);
              pX = pX + inc;
              }

   while(pX <= L){
              twoax(pX, pY, A, B);
              pX = pX + inc;
              pY = pY + inc;
              }


   while(pX <= (L + AB) ){
              oneax(pY, B );
              pX = pX + inc;
              pY = pY + inc;
              }

      while(pX < (AB + BC) ){
              pX = pX + inc;
              pY = pY + inc;
              }

      while(pX < (AB + BC + CD)){
              oneax(pZ, C );
              pX = pX + inc;
              pY = pY + inc;
              pZ = pZ + inc;
              }

   while(pX <= (L + AB + BC ) ){
              twoax(pZ, pU, C, D);
              pX = pX + inc;
              pY = pY + inc;
              pU = pU + inc;
              pZ = pZ + inc;
              }
   while(pX <= (L + AB + BC +  CD)){
              oneax(pU, D );
                        pX = pX + inc;
                        pY = pY + inc;
                        pZ = pZ + inc;
                        pU = pU + inc;
              }
fout << endl << setw(10) << MaxM;
}

if( (AB < L) && (BC >= L) && ( CD >= L))
{
       pX = 0;
```

```
            pY = 0;
            pZ = 0;
            pU = 0;
            MaxT = 0;
            MT = 414;
            MaxM = 0;
            MaxL = 0;
        while(pX < AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

        while(pX <= L){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }

           while(pX <= (L + AB) ){
                    oneax(pY, B );
                    pX = pX + inc;
                    pY = pY + inc;
                    }

           while(pX < (AB + BC) ){
                    pX = pX + inc;
                    pY = pY + inc;
                              }

           while(pX <= (L + AB + BC)){
                    oneax(pZ, C );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }

        while(pX < (AB + BC + CD) ){
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }

        while(pX <= (L + AB + BC +  CD)){
                    oneax(pU, D );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }
      fout << endl << setw(10) << MaxM;
      }
           fout.close();
}
```

```
//*********************************************************************
******************************
//Function to increment the position of the truck for 5 axle truck.
//*********************************************************************
****************************

void position_increment_5_axle()
{
      fout.open("axle_load.txt", ios::app);
      if( (AB >= L) && (BC >= L) && ( CD >= L) && ( DE >= L))     //
Option 1
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 51;
            MaxM = 0;
            MaxL = 0;
          while(pX < L){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

            while(pX <  AB ){
                    pX = pX + inc;
                    }

            while(pX < (L + AB) ){
                    oneax(pY, B );
                    pX = pX + inc;
                    pY = pY + inc;
                    }

            while(pX < (AB + BC) ){
                    pX = pX + inc;
                    pY = pY + inc;
                              }

            while(pX < (L + AB + BC)){
                    oneax(pZ, C );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }

            while(pX < (AB + BC + CD) ){
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                              }
```

```
            while(pX < (L + AB + BC +  CD)){
                    oneax(pU, D );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }

            while(pX < (AB + BC + CD + DE) ){
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                              }

       while(pX <= (L + AB + BC +  CD + DE)){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }
      fout << endl << setw(10) << MaxM:
      }

      if( (AB >= L) && (BC >= L) && ( CD >= L) && ( DE < L))       //
Option 2
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 52;
            MaxM = 0;
            MaxL = 0;
          while(pX < L){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

            while(pX <  AB ){
                    pX = pX + inc;
                    }

            while(pX < (L + AB) ){
                    oneax(pY, B );
                    pX = pX + inc;
                    pY = pY + inc;
                    }
```

```
            while(pX < (AB + BC) ){
                   pX = pX + inc;
                   pY = pY + inc;
                              }

            while(pX < (L + AB + BC)){
                    oneax(pZ, C );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }

            while(pX < (AB + BC + CD) ){
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                              }

         while(pX < (AB + BC +  CD + DE)){
                    oneax(pU, D );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }

        while(pX < (L + AB + BC + CD ) ){
                    twoax( pU, pV, pU, pV);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }

       while(pX <= (L + AB + BC +  CD + DE)){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }
      fout << endl << setw(10) << MaxM:
      }

      if( (AB >= L) && (BC >= L) && ( CD < L) && ( DE >= L))
// Option 3
      {
            pX = 0;
            pY = 0;
            pZ = 0;
```

```
    pU = 0;
    pV = 0;
    MaxT = 0;
    MT = 53;
    MaxM = 0;
    MaxL = 0;
  while(pX < L){
            oneax(pX, A);
            pX = pX + inc;
            }

    while(pX <  AB ){
            pX = pX + inc;
            }

    while(pX < (L + AB) ){
            oneax(pY, B );
            pX = pX + inc;
                      pY = pY + inc;
            }

    while(pX < (AB + BC) ){
            pX = pX + inc;
            pY = pY + inc;
                      }

    while(pX < (AB + BC + CD)){
            oneax(pZ, C );
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            }

 while(pX < (L + AB + BC ) ){
            twoax(pZ, pU, C, D);
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            }

 while(pX < (L + AB + BC +  CD)){
            oneax(pU, D );
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            }

while(pX < (AB + BC + CD + DE) ){
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
```

```
                    pU = pU + inc;
                              }

        while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                              }
fout << endl << setw(10) << MaxM:   }

      if( (AB >= L) && (BC < L) && ( CD >= L) && ( DE >= L))
// Option 4
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 54;
             MaxM = 0;
             MaxL = 0;
         while(pX <= L){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX <  AB ){
                    pX = pX + inc;
                    }

         while(pX < (AB + BC) ){
                    oneax(pY, B );
                    pX = pX + inc;
                    pY = pY + inc;
                    }

            while(pX < (L + AB ) ){
                          twoax(pY, pZ, B, C );
                    pX= pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                              }

            while(pX <= (L + AB + BC)){
                    oneax(pZ, C );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }
```

```
        while(pX < (AB + BC + CD) ){
                   pX = pX + inc;
                   pY = pY + inc;
                   pZ = pZ + inc;
                             }

        while(pX < (L + AB + BC +  CD)){
                   oneax(pU, D );
                   pY = pY + inc;
                   pZ = pZ + inc;
                   pU = pU + inc;
                   }

       while(pX < (AB + BC + CD + DE) ){
                   pX = pX + inc;
                   pY = pY + inc;
                   pZ = pZ + inc;
                   pU = pU + inc;
                             }

       while(pX <= (L + AB + BC + CD + DE) ){
                   oneax(pV, E );
                   pX = pX + inc;
                   pY = pY + inc;
                   pZ = pZ + inc;
                   pU = pU + inc;
                   pV = pV + inc;
                             }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB >= L) && (BC >= L) && ( CD < L) && ( DE < L) && ( (CD +
DE) >= L))     //Option 5
      {

            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 55;
             MaxM = 0;
             MaxL = 0;
        while(pX <= L){
                   oneax(pX, A);
                   pX = pX + inc;
                   }

        while(pX <  AB ){
                  pX = pX + inc;
                   }
```

```
    while(pX < (L + AB) ){
               oneax(pY, B );
               pX = pX + inc;
               pY = pY + inc;
               }

       while(pX < (AB + BC) ){
               pX = pX + inc;
               pY = pY + inc;
                         }

       while(pX < (AB + BC + CD)){
               oneax(pZ, C );
               pX = pX + inc;
               pY = pY + inc;
               pZ = pZ + inc;
               }

    while(pX < (L + AB + BC ) ){
               twoax(pZ, pU, C, D);
               pX = pX + inc;
                 pY = pY + inc;
                 pU = pU + inc;
                 pZ = pZ + inc;
                         }

    while(pX < (AB + BC +  CD + DE)){
               oneax(pU, D );
               pX = pX + inc;
               pY = pY + inc;
               pU = pU + inc;
               pZ = pZ + inc;
                 }

    while(pX < (L+ AB + BC +  CD)){
               twoax(pU, pV, D, E );
               pX = pX + inc;
               pY = pY + inc;
               pU = pU + inc;
               pZ = pZ + inc;
               pV = pV + inc;
               }

   while(pX <= (L + AB + BC +  CD + DE)){
               oneax(pV, E );
               pX = pX + inc;
               pY = pY + inc;
               pZ = pZ + inc;
               pU = pU + inc;
               pV = pV + inc;
               }
fout << endl << setw(10) << MaxM;
```

```
      }

      if( (AB >= L) && (BC >= L) && ( CD < L) && ( DE < L) && ( (CD +
DE) < L))    //Option 6
      {

            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 56;
             MaxM = 0;
             MaxL = 0;
         while(pX <= L){
                     oneax(pX, A);
                     pX = pX + inc;
                     }

         while(pX <  AB ){
                     pX = pX + inc;
                     }

         while(pX < (L + AB) ){
                     oneax(pY, B );
                     pX = pX + inc;
                     pY = pY + inc;
                     }

         while(pX < (AB + BC) ){
                     pX = pX + inc;
                     pY = pY + inc;
                     }

         while(pX < (AB + BC + CD)){
                     oneax(pZ, C );
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                     }

         while(pX < (AB + BC + CD + DE)){
                     twoax(pZ, pU, C, D );
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                     pU = pU + inc;
                     }

            while(pX < (L + AB + BC )){
                     threeax(pZ, pU, pV, C, D, E );
                     pX = pX + inc;
```

```
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }

         while(pX < (L+ AB + BC +  CD)){
                    twoax(pU, pV, D, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                      }

        while(pX <= (L + AB + BC +  CD + DE)){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB >= L) && (BC < L) && ( CD < L) && ( DE >= L) && ( (BC +
CD)>= L))         //Option 7
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 57;
             MaxM = 0;
             MaxL = 0;
         while(pX < L){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX <  AB ){
                    pX = pX + inc;
                    }

         while(pX < (AB + BC) ){
                    pX = pX + inc;
                    pY = pY + inc;
                    }

            while(pX < (L + AB ) ){
```

```
                twoax(pY, pZ, B, C );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                          }


        while(pX < (AB + BC + CD ) ){
                oneax(pZ, C );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                          }

        while(pX < (L  + AB + BC ) ){
                twoax(pZ, pU, C, D );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }

        while(pX < (L + AB + BC + CD ) ){
                oneax(pU, D );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                          }

      while(pX < (AB + BC + CD + DE) ){
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                          }

      while(pX <= (L + AB + BC + CD + DE) ){
                oneax(pV, E );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }
    fout << endl << setw(10) << MaxM;
    }

    if( (AB >= L) && (BC < L) && ( CD < L) && ( DE >= L) && ( (BC +
CD) < L))        // Option 8
    {
          pX = 0;
          pY = 0;
```

```
   pZ = 0;
   pU = 0;
   pV = 0;
   MaxT = 0;
   MT = 58;
    MaxM = 0;
    MaxL = 0;
while(pX < L){
           oneax(pX, A);
           pX = pX + inc;
           }

while(pX <  AB ){
           pX = pX + inc;
           }


while(pX < (AB + BC) ){
           oneax(pY, B );
           pX = pX + inc;
           pY = pY + inc;
           }

   while(pX < (AB + BC + CD ) ){
           twoax(pY, pZ, B, C );
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
                     }

   while(pX < (L + AB ) ){
           threeax(pY, pZ, pU, B, C, D );
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           pU = pU + inc;
           }


   while(pX < (L  + AB + BC ) ){
           twoax(pZ, pU, C, D );
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           pU = pU + inc;
           }

   while(pX < (L + AB + BC + CD ) ){
           oneax(pU, D );
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           pU = pU + inc;
```

```
                    }

          while(pX < (AB + BC + CD + DE) ){
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }

          while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                              }
      fout << endl << setw(10) << MaxM;
      }
      if( (AB >= L) && (BC < L) && ( CD >= L) && ( DE < L) )
//Option 9
      {

            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 59;
             MaxM = 0;
             MaxL = 0;
         while(pX < L){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX <  AB ){
                    pX = pX + inc;
                    }

         while(pX < (AB + BC) ){
                    oneax(pY, B );
                    pX = pX + inc;
                    pY = pY + inc;
                    }

         while(pX < (L + AB ) ){
                    twoax(pY, pZ, B, C );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }
```

```
          while(pX < (L + AB + BC ) ){
                    oneax(pZ, C );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }


            while(pX < (AB + BC + CD ) ){
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }

            while(pX < (AB + BC + CD + DE ) ){
                    oneax(pU, D );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }

           while(pX < (L + AB + BC + CD ) ){
                    twoax(pU, pV, D, E);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pV = pV + inc;
                    pU = pU + inc;
                              }

           while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pV = pV + inc;
                    pU = pU + inc;
                              }
      fout << endl << setw(10) << MaxM;
      }
      if( (AB >= L) && (BC < L) && ( CD < L) && ( DE < L) && ((CD + DE)
>= L) && ( (BC + CD)>= L))
                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                
```

```
                                                                    1
                                                                    0
{

      pX = 0;
      pY = 0;
      pZ = 0;
      pU = 0;
      pV = 0;
      MaxT = 0;
      MT = 510;
       MaxM = 0;
       MaxL = 0;
   while(pX < L){
              oneax(pX, A);
              pX = pX + inc;
              }

   while(pX <  AB ){
              pX = pX + inc;
              }

   while(pX < (AB + BC) ){
              oneax(pY, B );
              pX = pX + inc;
              pY = pY + inc;
              }

   while(pX < (L + AB ) ){
              twoax(pY, pZ, B, C );
              pX = pX + inc;
              pY = pY + inc;
              pZ = pZ + inc;
              }

      while(pX < (AB + BC + CD ) ){
              oneax(pZ, C );
              pX = pX + inc;
              pY = pY + inc;
              pZ = pZ + inc;
                        }

      while(pX < (L  + AB + BC ) ){
              twoax(pZ, pU, C, D );
              pX = pX + inc;
              pY = pY + inc;
              pZ = pZ + inc;
              pU = pU + inc;
                        }


      while(pX < (AB + BC + CD + DE ) ){
              oneax(pU, D );
```

```
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }

          while(pX < (L + AB + BC + CD ) ){
                    twoax(pU, pV, D, E);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }

          while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB >= L) && (BC < L) && ( CD < L) && ( DE < L) && ((CD + DE)
< L) && ( (BC + CD)>= L))   //Option 11
      {

            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 511;
            MaxM = 0;
            MaxL = 0;
         while(pX < L){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX <  AB ){
            pX = pX + inc;
                    }

         while(pX < (AB + BC) ){                    // Only axle B is
on the bridge
                    oneax(pY, B );
                    pX = pX + inc;
                    pY = pY + inc;
```

```
                }

        while(pX < (L + AB ) ){
                twoax(pY, pZ, B, C );
                pX = pX + inc;
                pY = pY + inc;
                          }

        while(pX < (AB + BC + CD ) ){
                oneax(pZ, C );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                          }

        while(pX < (AB + BC + CD + DE ) ){
                twoax(pZ, pU, C, D );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                          }

        while(pX < (L + AB + BC ) ){
                threeax(pZ, pU, pV, C, D, E );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                          }


      while(pX < (L + AB + BC + CD ) ){
                twoax(pU, pV, D, E);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }

      while(pX <= (L + AB + BC + CD + DE) ){
                oneax(pV, E );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }
fout << endl << setw(10) << MaxM;
}
```

```
      if( (AB >= L) && (BC < L) && ( CD < L) && ( DE < L) && ((CD + DE)
>= L) && ( (BC + CD) < L))
```

/Option 12

```
      {

            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 512;
             MaxM = 0;
             MaxL = 0;
         while(pX < L){
                     oneax(pX, A);
                     pX = pX + inc;
                     }

         while(pX <  AB ){
                     pX = pX + inc;
                     }

         while(pX < (AB + BC) ){
                     oneax(pY, B );
                     pX = pX + inc;
                     pY = pY + inc;
                     }

            while(pX < (AB + BC + CD ) ){
                     twoax(pY, pZ, B, C );
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                     }

            while(pX < (L + AB ) ){
                     threeax(pY, pZ, pU, B, C, D );
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                     pU = pU + inc;
                     }
```

```
            while(pX < (L  + AB + BC ) ){
                    twoax(pZ, pU, C, D );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }


            while(pX < (AB + BC + CD + DE ) ){
                    oneax(pU, D );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }

          while(pX < (L + AB + BC + CD ) ){
                    twoax(pU, pV, D, E);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pV = pV + inc;
                    pU = pU + inc;
                    }

          while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pV = pV + inc;
                    pU = pU + inc;
                              }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB >= L) && (BC < L) && ( CD < L) && ( DE < L) && ((CD + DE)
< L) && ( (BC + CD) < L) && ( (BC + CD + DE) >= L))
                                                //Option 13
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 513;
             MaxM = 0;
             MaxL = 0;
         while(pX < L){
                    oneax(pX, A);
```

```
            pX = pX + inc;
            }

while(pX <  AB ){
            pX = pX + inc;
            }

while(pX < (AB + BC) ){
            oneax(pY, B );
            pX = pX + inc;
            pY = pY + inc;
            }

   while(pX < (AB + BC + CD ) ){
            twoax(pY, pZ, B, C );
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            }

   while(pX < (L + AB ) ){
            threeax(pY, pZ, pU, B, C, D );
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            }


   while(pX < (AB + BC + CD + DE ) ){
            twoax(pZ, pU, C, D );
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            }

   while(pX < (L + AB + BC ) ){
            threeax(pZ, pU, pV, C, D, E );
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            pV = pV + inc;
            }

   while(pX < (L + AB + BC + CD ) ){
            twoax(pU, pV, D, E);
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            pV = pV + inc;
```

```
                                }

            while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                                }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB >= L) && (BC < L) && ( CD < L) && ( DE < L) && ((CD + DE)
< L) && ( (BC + CD) < L) && ( (BC + CD + DE) < L))
                                                  //Option 14
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 514;
             MaxM = 0;
             MaxL = 0;
         while(pX < L){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX <  AB ){
                    pX = pX + inc;
                    }

         while(pX < (AB + BC) ){
                    oneax(pY, B );
                    pX = pX + inc;
                                pY = pY + inc;
                    }

            while(pX < (AB + BC + CD ) ){
                    twoax(pY, pZ, B, C );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }

            while(pX < (AB + BC + CD + DE ) ){
                    threeax(pY, pZ, pU, B, C, D );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
```

```
                pU = pU + inc;
                }

        while(pX < (L + AB ) ){
                fourax(pY, pZ, pU, pV, B, C, D, E );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }

        while(pX < (L + AB + BC ) ){
                threeax(pZ, pU, pV, C, D, E );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }


      while(pX < (L + AB + BC + CD ) ){
                twoax(pU, pV, D, E);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }

      while(pX <= (L + AB + BC + CD + DE) ){
                oneax(pV, E );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                          }
    fout << endl << setw(10) << MaxM;
    }

    if( (AB < L) && (BC < L) && ( CD < L) && ( DE < L) && ((CD + DE)
>= L) && ( (BC + CD) >= L) && ( (AB + BC) >= L))
                                                //Option 15
    {
          pX = 0;
          pY = 0;
          pZ = 0;
          pU = 0;
          pV = 0;
          MaxT = 0;
          MT = 515;
```

```
    MaxM = 0;
    MaxL = 0;
while(pX < AB){
           oneax(pX, A);
           pX = pX + inc;
           }

while(pX < L){
           twoax(pX, pY, A, B);
           pX = pX + inc;
           pY = pY + inc;
           }


while(pX < (AB+ BC)){
           oneax(pY, B);
           pX = pX + inc;
           pY = pY + inc;
           }

while(pX < (L + AB)){
           twoax(pY, pZ, B, C);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           }

    while(pX < (AB + BC + CD)){
           oneax(pZ, C);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           }

    while(pX < (L + AB + BC )){
           twoax(pZ, pU, C, D);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           pU = pU + inc;
           }

    while(pX < (AB + BC + CD + DE ) ){
           oneax(pU, D );
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           pU = pU + inc;
           }

 while(pX < (L + AB + BC + CD ) ){
           twoax(pU, pV, D, E);
           pX = pX + inc;
```

```
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }

         while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }
      fout << endl << setw(10) << MaxM;
      }
      if( (AB < L) && (BC < L) && ( CD < L) && ( DE < L) && ((CD + DE)
< L) && ( (BC + CD) >= L) && ( (AB + BC) >= L))
                                                  //Option 16
      {

            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 516;
             MaxM = 0;
             MaxL = 0;
         while(pX < AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX < L){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }


         while(pX < (AB+ BC)){
                    oneax(pY, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }

         while(pX < (L + AB)){
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }
```

```
            while(pX < (AB + BC + CD)){
                   oneax(pZ, C);
                   pX = pX + inc;
                   pY = pY + inc;
                   pZ = pZ + inc;
                   }

            while(pX < (AB + BC + CD + DE)){
                   twoax(pZ, pU, C, D);
                   pX = pX + inc;
                   pY = pY + inc;
                   pZ = pZ + inc;
                   pU = pU + inc;
                   }

            while(pX < (L + AB + BC) ){
                   threeax(pZ, pU, pV, C, D, E );
                   pX = pX + inc;
                   pY = pY + inc;
                   pZ = pZ + inc;
                   pU = pU + inc;
                   pV = pV + inc;
                   }


        while(pX < (L + AB + BC + CD ) ){
                   twoax(pU, pV, D, E);
                   pX = pX + inc;
                   pY = pY + inc;
                   pZ = pZ + inc;
                   pV = pV + inc;
                   pU = pU + inc;
                   }

        while(pX <= (L + AB + BC + CD + DE) ){
                   oneax(pV, E );
                   pX = pX + inc;
                   pY = pY + inc;
                   pZ = pZ + inc;
                   pV = pV + inc;
                   pU = pU + inc;
                   }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD < L) && ( DE < L) && ((CD + DE)
>= L) && ( (BC + CD) < L) && ( (AB + BC) >= L))
                                                  //Option 17
      {
            pX = 0;
            pY = 0;
            pZ = 0;
```

```
   pU = 0;
   pV = 0;
   MaxT = 0;
   MT = 517;
   MaxM = 0;
   MaxL = 0;
while(pX < AB){
           oneax(pX, A);
           pX = pX + inc;
           }

while(pX < L){
           twoax(pX, pY, A, B);
           pX = pX + inc;
           pY = pY + inc;
           }


while(pX < (AB+ BC)){
           oneax(pY, B);
           pX = pX + inc;
           pY = pY + inc;
           }

while(pX < (AB + BC + CD)){
           twoax(pY, pZ, B, C);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           }

    while(pX < (L + AB)){
           threeax(pY, pZ, pU, B, C, D);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           pU = pU + inc;
           }


    while(pX < (L + AB + BC)){
           twoax(pZ, pU, C, D);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           pU = pU + inc;
           }


    while(pX < (AB + BC + CD + DE) ){
           oneax(pV, D );
           pX = pX + inc;
           pY = pY + inc;
```

```
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }

          while(pX < (L + AB + BC + CD ) ){
                    twoax(pU, pV, D, E);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }

          while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD < L) && ( DE < L) && ((CD + DE)
< L) && ( (BC + CD) < L) && ( (AB + BC) >= L) && ( (BC + CD + DE) >= L)
)                                                  //Option 18
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 518;
             MaxM = 0;
             MaxL = 0;
         while(pX < AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX < L){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }


         while(pX < (AB+ BC)){
                    oneax(pY, B);
                    pX = pX + inc;
                    pY = pY + inc;
```

```
            }

while(pX < (AB + BC + CD)){
            twoax(pY, pZ, B, C);
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            }

    while(pX < (L + AB)){
            threeax(pY, pZ, pU, B, C, D);
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            }


    while(pX < (AB + BC + CD + DE)){
            twoax(pZ, pU, C, D);
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            }

    while(pX < (L + AB + BC) ){
            threeax(pZ, pU, pV, C, D, E );
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            pV = pV + inc;
            }


 while(pX < (L + AB + BC + CD ) ){
            twoax(pU, pV, D, E);
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            pV = pV + inc;
            }

 while(pX <= (L + AB + BC + CD + DE) ){
            oneax(pV, E );
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            pV = pV + inc;
                      }
```

```
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD < L) && ( DE < L) && ((CD + DE)
< L) && ( (BC + CD) < L) && ( (AB + BC) >= L) && ( (BC + CD + DE) < L)
)                                                   //Option 19
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 519;
             MaxM = 0;
             MaxL = 0;
         while(pX < AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX < L){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }

             while(pX < (AB+ BC)){
                    oneax(pY, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }

         while(pX < (AB + BC + CD)){
                    twoax(pY, pZ, B, C);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }

             while(pX < (AB + BC + CD + DE)){
                    threeax( pY, pZ, pU, B, C, D);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }

             while(pX < (L + AB )){
                    fourax(pY , pZ, pU, pV, B, C, D, E);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
```

```
                    pU = pU + inc;
                    pV = pV + inc;
                    }


            while(pX < (L + AB + BC) ){
                    threeax(pZ, pU, pV, C, D, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }


         while(pX < (L + AB + BC + CD ) ){
                    twoax(pU, pV, D, E);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }

         while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                              }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD < L) && ( DE < L) && ((CD + DE)
< L) && ( (BC + CD) < L) && ( (AB + BC) < L) && ( (BC + CD + DE) >= L)
&& ( (AB + BC + CD) >= L) )                      //Option 20
      {

            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 520;
             MaxM = 0;
             MaxL = 0;
         while(pX < AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }
```

```
while(pX < (AB + BC)){
           twoax(pX, pY, A, B);
           pX = pX + inc;
           pY = pY + inc;
           }

    while(pX < L ){
           threeax(pX, pY, pZ, A, B, C);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           }


while(pX < (AB + BC + CD )){
           twoax( pY, pZ, B, C);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           }

    while(pX < (L + AB )){
           threeax( pY, pZ, pU, B, C, D);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           pU = pU + inc;
           }


    while(pX < (AB + BC + CD + DE )){
           twoax( pZ, pU, C, D);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           pU = pU + inc;
           }

    while(pX < (L + AB + BC) ){
           threeax(pZ, pU, pV, C, D, E );
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           pU = pU + inc;
           pV = pV + inc;
                     }


 while(pX < (L + AB + BC + CD ) ){
           twoax(pU, pV, D, E);
           pX = pX + inc;
           pY = pY + inc;
```

```
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }

          while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                              }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD < L) && ( DE < L) && ((CD + DE)
< L) && ( (BC + CD) < L) && ( (AB + BC) < L) && ( (BC + CD + DE) < L)
&& ( (AB + BC + CD) >= L) )                        //Option 21
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 521;
             MaxM = 0;
             MaxL = 0;
         while(pX < AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX < (AB + BC)){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }

             while(pX < L ){
                    threeax(pX, pY, pZ, A, B, C);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }


         while(pX < (AB + BC + CD )){
                    twoax( pY, pZ, B, C);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
```

```
                }

            while(pX < (AB + BC + CD + DE)){
                threeax( pY, pZ, pU, B, C, D);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }

            while(pX < (L + AB )){
                fourax(pY , pZ, pU, pV, B, C, D, E);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }


            while(pX < (L + AB + BC) ){
                threeax(pZ, pU, pV, C, D, E );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }


        while(pX < (L + AB + BC + CD ) ){
                twoax(pU, pV, D, E);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }

        while(pX <= (L + AB + BC + CD + DE) ){
                oneax(pV, E );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                          }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD < L) && ( DE < L) && ((CD + DE)
< L) && ( (BC + CD) < L) && ( (AB + BC) < L) && ( (BC + CD + DE) >= L)
&& ( (AB + BC + CD) < L) )                              //Option 22
```

```
{
      pX = 0;
      pY = 0;
      pZ = 0;
      pU = 0;
      pV = 0;
      MaxT = 0;
      MT = 522;
      MaxM = 0;
      MaxL = 0;
   while(pX < AB){
              oneax(pX, A);
              pX = pX + inc;
              }

   while(pX < (AB + BC)){
              twoax(pX, pY, A, B);
              pX = pX + inc;
              pY = pY + inc;
              }

       while(pX < (AB + BC + CD) ){
              threeax(pX, pY, pZ, A, B, C);
              pX = pX + inc;
              pY = pY + inc;
              pZ = pZ + inc;
              }

       while(pX < L ){
              fourax(pX, pY , pZ, pU, A, B, C, D);
              pX = pX + inc;
              pY = pY + inc;
              pU = pU + inc;
              pZ = pZ + inc;
              }


       while(pX < (L + AB )){
              threeax( pY, pZ, pU, B, C, D);
              pX = pX + inc;
              pY = pY + inc;
              pZ = pZ + inc;
              pU = pU + inc;
              }


       while(pX < (AB + BC + CD + DE )){
              twoax(pZ, pU, D, E);
              pX = pX + inc;
              pY = pY + inc;
              pZ = pZ + inc;
              pU = pU + inc;
              }
```

```
            while(pX < (L + AB + BC) ){
                    threeax(pZ, pU, pV, C, D, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }


          while(pX < (L + AB + BC + CD ) ){
                    twoax(pU, pV, D, E);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }

          while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                   pV = pV + inc;
                              }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD < L) && ( DE < L) && ((CD + DE)
< L) && ( (BC + CD) < L) && ( (AB + BC) < L) && ( (BC + CD + DE) < L)
&& ( (AB + BC + CD) < L) && ( (AB + BC + CD + DE) >= L) )
//Option 23
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 523;
             MaxM = 0;
             MaxL = 0;
         while(pX < AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX < (AB + BC)){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
```

```
        pY = pY + inc;
        }

    while(pX < (AB + BC + CD) ){
        threeax(pX, pY, pZ, A, B, C);
        pX = pX + inc;
        pY = pY + inc;
        pZ = pZ + inc;
        }

    while(pX < L){
        fourax(pX, pY , pZ, pU, A, B, C, D);
        pX = pX + inc;
        pY = pY + inc;
        pZ = pZ + inc;
        pU = pU + inc;
        }


    while(pX < (AB + BC + CD + DE)){
        threeax( pY, pZ, pU , B, C, D);
        pX = pX + inc;
        pY = pY + inc;
        pZ = pZ + inc;
        pU = pU + inc;
                }

    while(pX < (L + AB )){
        fourax(pY , pZ, pU, pV, B, C, D, E);
        pX = pX + inc;
        pY = pY + inc;
        pZ = pZ + inc;
        pU = pU + inc;
        pV = pV + inc;
        }


    while(pX < (L + AB + BC) ){
        threeax(pZ, pU, pV, C, D, E );
        pX = pX + inc;
        pY = pY + inc;
        pZ = pZ + inc;
        pU = pU + inc;
        pV = pV + inc;
        }


while(pX < (L + AB + BC + CD ) ){
        twoax(pU, pV, D, E);
        pX = pX + inc;
        pY = pY + inc;
        pZ = pZ + inc;
        pU = pU + inc;
```

```
                    pV = pV + inc;
                    }

          while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                              }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD < L) && ( DE < L) && ((CD + DE)
< L) && ( (BC + CD) < L) && ( (AB + BC) < L) && ( (BC + CD + DE) < L)
&& ( (AB + BC + CD) < L) && ( (AB + BC + CD + DE) < L) )
// Option 24
      {

            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 524;
             MaxM = 0;
             MaxL = 0;
         while(pX <= AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX <= (AB + BC)){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }

             while(pX <= (AB + BC + CD) ){
                    threeax(pX, pY, pZ, A, B, C);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }

             while(pX <= (AB + BC + CD + DE) ){
                    fourax(pX, pY , pZ, pU, A, B, C, D);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
```

```
                }

        while(pX <= L){
                fiveax( pX, pY, pZ, pU, pV, A, B, C, D, E);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }


        while(pX <= (L + AB )){
                fourax(pY , pZ, pU, pV, B, C, D, E);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }


        while(pX <= (L + AB + BC) ){
                threeax(pZ, pU, pV, C, D, E );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
              }

    while(pX <= (L + AB + BC + CD ) ){
                twoax(pU, pV, D, E);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }

    while(pX <= (L + AB + BC + CD + DE) ){
                oneax(pV, E );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
               pV = pV + inc;
                           }
fout << endl << setw(10) << MaxM;
}

if( (AB < L) && (BC < L) && ( CD < L) && ( DE >= L) && ( (BC +
CD) >= L) && ( (AB + BC) >= L) )
```

```
//Option 25
      {
      pX = 0;
      pY = 0;
      pZ = 0;
      pU = 0;
      pV = 0;
      MaxT = 0;
      MT = 525;
      MaxM = 0;
      MaxL = 0;
   while(pX < AB){
              oneax(pX, A);
              pX = pX + inc;
              }

   while(pX < L){
              twoax(pX, pY, A, B);
              pX = pX + inc;
              pY = pY + inc;
              }

    while(pX < (AB + BC) ){
              oneax(pY, B);
              pX = pX + inc;
              pY = pY + inc;
                        }

       while(pX < (L+AB) ){
              twoax(pY , pZ, B, C);
              pX = pX + inc;
              pY = pY + inc;
              pZ = pZ + inc;
                }

        while(pX < (AB + BC + CD)){
              oneax( pZ, C);
              pX = pX + inc;
              pY = pY + inc;
              pZ = pZ + inc;
                        }

       while(pX < (L + AB + BC )){
              twoax(pZ, pU, C, D);
              pX = pX + inc;
              pY = pY + inc;
              pZ = pZ + inc;
              pU = pU + inc;
              }


       while(pX < (L + AB + BC + CD) ){
              oneax(pU, D );
```

```
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }

          while(pX < (AB + BC + CD + DE ) ){
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }

          while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD < L) && ( DE >= L) && ( (BC +
CD) < L) && ( (AB + BC) >= L) )
//Option 26
      {

            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 526;
             MaxM = 0;
             MaxL = 0;
         while(pX < AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX < L){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }

          while(pX < (AB + BC) ){
                    oneax(pY, B);
                    pX = pX + inc;
                    pY = pY + inc;
```

```
                }

        while(pX < (AB + BC + CD) ){
                twoax(pY , pZ, B, C);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }

         while(pX < (L + AB)){
                threeax( pY, pZ, pU, B, C, D);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }


        while(pX < (L + AB + BC )){
                twoax(pZ, pU, C, D);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }

        while(pX < (L + AB + BC + CD) ){
                oneax(pU, D );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }

       while(pX < (AB + BC + CD + DE ) ){
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }

    while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                          }
fout << endl << setw(10) << MaxM;
}
```

```
      if( (AB < L) && (BC < L) && ( CD < L) && ( DE >= L) && ( (BC +
CD) >= L) && ( (AB + BC) < L) )
//Option 27
      {

            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 527;
             MaxM = 0;
             MaxL = 0;
         while(pX < AB){
                     oneax(pX, A);
                     pX = pX + inc;
                     }

         while(pX < (AB + BC) ){
                     twoax(pX, pY, A, B);
                     pX = pX + inc;
                     pY = pY + inc;
                     }

          while(pX < L ){
                     threeax(pX, pY, pZ, A, B, C);
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                               }

          while(pX < (L + AB) ){
                     twoax(pY , pZ, B, C);
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                     }


          while(pX < (AB + BC + CD)){
                     oneax( pZ, C);
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                     }

             while(pX < (L + AB + BC )){
                     twoax(pZ, pU, C, D);
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                     pU = pU + inc;
```

```
                    }


            while(pX < (L + AB + BC + CD) ){
                    oneax(pU, D );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }


          while(pX < (AB + BC + CD + DE ) ){
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }

          while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }
fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD < L) && ( DE >= L) && ( (BC +
CD) < L) && ( (AB + BC) < L) && ( (AB + BC + CD) >= L)  )
                                                  //Option 28
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 528;
             MaxM = 0;
             MaxL = 0;
         while(pX < AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX < (AB + BC)){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }
```

```
while(pX < L ){
          threeax(pX, pY, pZ, A, B, C);
          pX = pX + inc;
          pY = pY + inc;
          pZ = pZ + inc;
          }


   while(pX < (AB + BC + CD) ){
          twoax(pY , pZ, B, C);
          pX = pX + inc;
          pY = pY + inc;
          pZ = pZ + inc;
          }

    while(pX < (L + AB)){
          threeax( pY, pZ, pU, B, C, D);
          pX = pX + inc;
          pY = pY + inc;
          pZ = pZ + inc;
          pU = pU + inc;
          }


   while(pX < (L + AB + BC )){
          twoax(pZ, pU, C, D);
          pX = pX + inc;
          pY = pY + inc;
          pZ = pZ + inc;
          pU = pU + inc;
          }


   while(pX < (L + AB + BC + CD) ){
                 oneax(pU, D );
          pX = pX + inc;
          pY = pY + inc;
          pZ = pZ + inc;
          pU = pU + inc;
          }


while(pX < (AB + BC + CD + DE ) ){
          pX = pX + inc;
          pY = pY + inc;
          pZ = pZ + inc;
          pU = pU + inc;
          }

while(pX <= (L + AB + BC + CD + DE) ){
          oneax(pV, E );
          pX = pX + inc;
```

```
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD < L) && ( DE >= L) && ( (BC +
CD) < L) && ( (AB + BC) < L) && ( (AB + BC + CD) < L)  )
                                                  //Option 29
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 529;
             MaxM = 0;
             MaxL = 0;
         while(pX < AB){
                oneax(pX, A);
                pX = pX + inc;
                }

         while(pX < (AB + BC)){
                twoax(pX, pY, A, B);
                pX = pX + inc;
                pY = pY + inc;
                }

             while(pX < (AB + BC + CD) ){
                threeax(pX, pY, pZ, A, B, C);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }

             while(pX < L){
                fourax(pX, pY , pZ, pU, A, B, C, D);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                  }

             while(pX < (L + AB)){
                threeax( pY, pZ, pU, B, C, D);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
```

```
                        }

            while(pX < (L + AB + BC )){
                   twoax(pZ, pU, C, D);
                   pX = pX + inc;
                   pY = pY + inc;
                   pZ = pZ + inc;
                   pU = pU + inc;
                   }


            while(pX < (L + AB + BC + CD) ){
                   oneax(pU, D );
                   pX = pX + inc;
                   pY = pY + inc;
                   pZ = pZ + inc;
                   pU = pU + inc;
                   }


        while(pX < (AB + BC + CD + DE ) ){
                   pX = pX + inc;
                   pY = pY + inc;
                   pZ = pZ + inc;
                   pU = pU + inc;
                   }

        while(pX <= (L + AB + BC + CD + DE) ){
                   oneax(pV, E );
                   pX = pX + inc;
                   pY = pY + inc;
                   pZ = pZ + inc;
                   pU = pU + inc;
                   pV = pV + inc;
                             }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD >= L) && ( DE < L) && ( (AB +
BC) >= L)  )   // Option 30
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 530;
             MaxM = 0;
             MaxL = 0;
         while(pX < AB){
                   oneax(pX, A);
```

```
            pX = pX + inc;
            }

 while(pX < L){
            twoax(pX, pY, A, B);
            pX = pX + inc;
            pY = pY + inc;
            }


 while(pX < (AB+ BC)){
            oneax(pY, B);
            pX = pX + inc;
            pY = pY + inc;
            }

 while(pX < (L + AB)){
            twoax(pY, pZ, B, C);
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            }

while(pX < (L + AB + BC)){
            oneax(pZ , C);
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            }

while(pX < (AB + BC + CD)){
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            }

while(pX < (AB + BC + CD + DE)){
            oneax(pU , D);
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            }

     while(pX < (L + AB + BC + CD )){
            twoax(pU , pV, D, E);
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            pV = pV + inc;
            }
```

```
            while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD >= L) && ( DE < L) && ( (AB +
BC) < L)  )
//Option 31
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 531;
             MaxM = 0;
             MaxL = 0;
         while(pX < AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX < (AB + BC) ){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }

          while(pX < L ){
                    threeax(pX, pY, pZ, A, B, C);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }

            while(pX < (L + AB)){
                    twoax(pY, pZ, B, C);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }

            while(pX < (L + AB + BC)){
                    oneax(pZ , C);
                    pX = pX + inc;
                    pY = pY + inc;
```

```
                pZ = pZ + inc;
                }

        while(pX < (AB + BC + CD)){
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }

        while(pX < (AB + BC + CD + DE)){
                oneax(pU , D);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }

        while(pX < (L + AB + BC + CD )){
                twoax(pU , pV, D, E);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }

        while(pX <= (L + AB + BC + CD + DE) ){
                oneax(pV, E );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }
    fout << endl << setw(10) << MaxM;
    }

    if( (AB < L) && (BC >= L) && ( CD < L) && ( DE < L) && ( (CD +
DE) >= L)  )    //Option 32
    {
          pX = 0;
          pY = 0;
          pZ = 0;
          pU = 0;
          pV = 0;
          MaxT = 0;
          MT = 532;
           MaxM = 0;
           MaxL = 0;
       while(pX < AB){
                oneax(pX, A);
                pX = pX + inc;
                }
```

```
while(pX < L ){
           twoax(pX, pY, A, B);
           pX = pX + inc;
           pY = pY + inc;
           }

 while(pX < (L + AB) ){
           oneax(pY, B);
           pX = pX + inc;
           pY = pY + inc;
                     }

   while(pX < (AB + BC)){
           pX = pX + inc;
           pY = pY + inc;
           }

while(pX < (AB + BC + CD)){
           oneax(pZ, C);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           }

    while(pX < (L + AB + BC)){
           twoax(pZ, pU, C, D);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           pU = pU + inc;
           }

    while(pX < (AB + BC + CD + DE)){
           oneax(pU , D);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           pU = pU + inc;
           }

    while(pX < (L + AB + BC + CD )){
           twoax(pU , pV, D, E);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           pU = pU + inc;
           pV = pV + inc;
           }

    while(pX <= (L + AB + BC + CD + DE) ){
           pX = pX + inc;
           pY = pY + inc;
```

```
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC >= L) && ( CD < L) && ( DE < L) && ( (CD +
DE) < L)  )       //Option 33
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 533;
             MaxM = 0;
             MaxL = 0;
         while(pX < AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX < L ){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }

          while(pX < (L + AB) ){
                    oneax(pY, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }

            while(pX < (AB + BC)){
                    pX = pX + inc;
                    pY = pY + inc;
                    }

         while(pX < (AB + BC + CD)){
                    oneax(pZ, C);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }

             while(pX < (AB + BC + CD + DE)){
                    twoax(pZ, pU, C, D);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
```

```
                pU = pU + inc;
                }

        while(pX < (L + AB + BC )){
                threeax(pZ, pU, pV, C, D, E);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }

        while(pX < (L + AB + BC + CD )){
                twoax(pU , pV, D, E);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }

        while(pX <= (L + AB + BC + CD + DE) ){
                oneax(pV, E );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                          }
    fout << endl << setw(10) << MaxM;
    }

    if( (AB < L) && (BC < L) && ( CD >= L) && ( DE >= L) && ( (AB +
BC) >= L)  )   //Option 34
    {
          pX = 0;
          pY = 0;
          pZ = 0;
          pU = 0;
          pV = 0;
          MaxT = 0;
          MT = 534;
          MaxM = 0;
          MaxL = 0;
      while(pX < AB){
                oneax(pX, A);
                pX = pX + inc;
                }

       while(pX < L ){
                twoax(pX, pY, A, B);
                pX = pX + inc;
                pY = pY + inc;
```

```
                }

    while(pX < (AB + BC) ){
                oneax(pY, B);
                pX = pX + inc;
                pY = pY + inc;
                          }

      while(pX < (L + AB )){
                twoax(pY, pZ, B, C);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }

      while(pX < (L+ AB + BC)){
                oneax(pZ, C);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }


       while(pX < (AB + BC + CD )){
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }

       while(pX < (L + AB + BC + CD )){
                oneax(pU, D);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }

       while(pX < (AB + BC + CD + DE )){
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
             }

       while(pX <= (L + AB + BC + CD + DE) ){
                oneax(pV, E );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }
fout << endl << setw(10) << MaxM;
```

```
      }

      if( (AB < L) && (BC < L) && ( CD >= L) && ( DE >= L) && ( (AB +
BC) < L)  )     //Option 35
      {
            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 535;
            MaxM = 0;
            MaxL = 0;
         while(pX < AB){
                     oneax(pX, A);
                     pX = pX + inc;
                     }

         while(pX < (AB + BC) ){
                     twoax(pX, pY, A, B);
                     pX = pX + inc;
                     pY = pY + inc;
                     }

          while(pX < L ){
                     threeax(pX, pY, pZ, A, B, C);
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                     }

             while(pX < (L + AB) ){
                     twoax(pY , pZ, B, C);
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                     }

             while(pX < (L + AB + BC )){
                     oneax(pZ, C);
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                     }

             while(pX < (AB + BC + CD )){
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                     }

             while(pX < (L + AB + BC + CD )){
```

```
                oneax(pU, D);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }

        while(pX < (AB + BC + CD + DE )){
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }

        while(pX <= (L + AB + BC + CD + DE) ){
                oneax(pV, E );
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                          }
fout << endl << setw(10) << MaxM;
}

if( (AB < L) && (BC >= L) && ( CD < L) && ( DE >= L) )
      // Option 36
{

      pX = 0;
      pY = 0;
      pZ = 0;
      pU = 0;
      pV = 0;
      MaxT = 0;
      MT = 536;
       MaxM = 0;
       MaxL = 0;
   while(pX < AB){
                oneax(pX, A);
                pX = pX + inc;
                }

   while(pX < L ){
                twoax(pX, pY, A, B);
                pX = pX + inc;
                pY = pY + inc;
                }

    while(pX < (L + AB) ){
                oneax(pY, B);
                pX = pX + inc;
                pY = pY + inc;
```

```
                        }

            while(pX < (AB + BC)){
                    pX = pX + inc;
                    pY = pY + inc;
                    }

         while(pX < (AB + BC + CD)){
                    oneax(pZ, C);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }

             while(pX < (L + AB + BC)){
                    twoax(pZ, pU, C, D);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }

             while(pX < (L + AB + BC + CD )){
                    oneax(pU , D);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }


             while(pX < (AB + BC + CD + DE )){
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    }

             while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                        }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC >= L) && ( CD >= L) && ( DE < L) )
//Option 37
      {
            pX = 0;
            pY = 0;
```

```
   pZ = 0;
   pU = 0;
   pV = 0;
   MaxT = 0;
   MT = 537;
    MaxM = 0;
    MaxL = 0;
while(pX < AB){
           oneax(pX, A);
           pX = pX + inc;
           }

while(pX < L ){
           twoax(pX, pY, A, B);
           pX = pX + inc;
           pY = pY + inc;
           }

 while(pX < (L + AB) ){
           oneax(pY, B);
           pX = pX + inc;
           pY = pY + inc;
           }

   while(pX < (AB + BC)){
           pX = pX + inc;
           pY = pY + inc;
           }

while(pX < (L + AB + BC )){
           oneax(pZ, C);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           }


    while(pX < (AB + BC + CD)){
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           }

    while(pX < (AB + BC + CD + DE )){
           oneax(pU , D);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           pU = pU + inc;
           }

    while(pX < (L + AB + BC + CD )){
           twoax(pU, pV, D, E);
```

```
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }

          while(pX <= (L + AB + BC + CD + DE) ){
                    oneax(pV, E );
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                              }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC >= L) && ( CD >= L) && ( DE >= L) )
//Option 38
      {

            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 538;
            MaxM = 0;
            MaxL = 0;
         while(pX < AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX < L ){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }

          while(pX < (L + AB) ){
                    oneax(pY, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }

            while(pX < (AB + BC)){
                    pX = pX + inc;
                    pY = pY + inc;
                    }
```

```
        while(pX < (L + AB + BC )){
                  oneax(pZ, C);
                  pX = pX + inc;
                  pY = pY + inc;
                  pZ = pZ + inc;
                  }


           while(pX < (AB + BC + CD)){
                  pX = pX + inc;
                  pY = pY + inc;
                  pZ = pZ + inc;
                  }

           while(pX < (L + AB + BC + CD )){
                  oneax(pU , D);
                  pX = pX + inc;
                  pY = pY + inc;
                  pZ = pZ + inc;
                  pU = pU + inc;
                  }


         while(pX < (AB + BC + CD + DE) ){
                  pX = pX + inc;
                  pY = pY + inc;
                  pZ = pZ + inc;
                  pU = pU + inc;
                 }

           while(pX < (L + AB + BC + CD + DE )){
                  oneax(pV, E);
                  pX = pX + inc;
                  pY = pY + inc;
                  pZ = pZ + inc;
                  pU = pU + inc;
                  pV = pV + inc;
                  }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD < L) && ( DE < L) && ((AB + BC)
< L) && ((BC + CD) >= L) && ((CD+DE) >= L)  )
                                                  //Option 39
      {

            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 539;
```

```
   MaxM = 0;
   MaxL = 0;
while(pX < AB){
           oneax(pX, A);
           pX = pX + inc;
           }

while(pX < (AB +BC) ){
           twoax(pX, pY, A, B);
           pX = pX + inc;
           pY = pY + inc;
           }

 while(pX < L ){
           threeax(pX,pY,pZ,A,B,C);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
                     }

   while(pX < (L + AB)){
           twoax(pY,pZ,B,C);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           }

while(pX < (AB + BC + CD)){
           oneax(pZ,C);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           }


    while(pX < (L + AB + BC)){
           twoax(pZ,pU,C,D);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           pU = pU + inc;
           }

    while(pX < (AB + BC + CD + DE)){
           oneax(pU , D);
           pX = pX + inc;
           pY = pY + inc;
           pZ = pZ + inc;
           pU = pU + inc;
           }
```

```
          while(pX < (L + AB + BC + CD) ){
                    twoax(pU,pV,D,E);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                    }

             while(pX < (L + AB + BC + CD + DE )){
                    oneax(pV, E);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                              }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD < L) && ( DE < L) && ((AB + BC)
< L) && ((BC + CD) >= L) && ((CD+DE) < L)  )
                                                        //Option 40
      {

            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 540;
            MaxM = 0;
            MaxL = 0;
         while(pX < AB){
                    oneax(pX, A);
                    pX = pX + inc;
                    }

         while(pX < (AB +BC) ){
                    twoax(pX, pY, A, B);
                    pX = pX + inc;
                    pY = pY + inc;
                    }

         while(pX < L ){
                    threeax(pX,pY,pZ,A,B,C);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    }

         while(pX < (L + AB)){
```

```
                twoax(pY,pZ,B,C);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }

    while(pX < (AB + BC + CD)){
                oneax(pZ,C);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                }


    while(pX < (AB + BC + CD + DE)){
               twoax(pZ,pU,C,D);
               pX = pX + inc;
               pY = pY + inc;
               pZ = pZ + inc;
               pU = pU + inc;
               }

    while(pX < (L + AB + BC)){
                threeax(pZ, pU, pV, C, D, E);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }

     while(pX < (L + AB + BC + CD) ){
                twoax(pU,pV,D,E);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }

        while(pX < (L + AB + BC + CD + DE )){
                oneax(pV, E);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }
fout << endl << setw(10) << MaxM;
}
```

```
      if( (AB < L) && (BC < L) && ( CD < L) && ( DE < L) && ((AB + BC)
< L) && ((BC + CD) < L) && ((CD + DE) >= L) && ((AB + BC + CD) >= L))
                                                  //Option 41
      {

            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 541;
            MaxM = 0;
            MaxL = 0;
         while(pX < AB){
                     oneax(pX, A);
                     pX = pX + inc;
                     }

         while(pX < (AB + BC) ){
                     twoax(pX, pY, A, B);
                     pX = pX + inc;
                     pY = pY + inc;
                     }

          while(pX < L ){
                     threeax(pX,pY,pZ,A,B,C);
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                               }

            while(pX < (AB + BC + CD)){
                     twoax(pY,pZ,B,C);
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                     }

         while(pX < (L + AB)){
                     threeax(pY,pZ,pU,B,C,D);
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
                     pU = pU + inc;
                     }


             while(pX < (L + AB + BC)){
                     twoax(pZ,pU,C,D);
                     pX = pX + inc;
                     pY = pY + inc;
                     pZ = pZ + inc;
```

```
                pU = pU + inc;
                }

            while(pX < (AB + BC + CD + DE)){
                oneax(pU, D);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                }

         while(pX < (L + AB + BC + CD) ){
                twoax(pU,pV,D,E);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }

            while(pX < (L + AB + BC + CD + DE )){
                oneax(pV, E);
                pX = pX + inc;
                pY = pY + inc;
                pZ = pZ + inc;
                pU = pU + inc;
                pV = pV + inc;
                }
      fout << endl << setw(10) << MaxM;
      }

      if( (AB < L) && (BC < L) && ( CD < L) && ( DE < L) && ((AB + BC)
< L) && ((BC + CD) < L) && ((CD + DE) >= L)  && ((AB + BC + CD) < L))
//Option 42
      {

            pX = 0;
            pY = 0;
            pZ = 0;
            pU = 0;
            pV = 0;
            MaxT = 0;
            MT = 542;
            MaxM = 0;
            MaxL = 0;
         while(pX < AB){
                oneax(pX, A);
                pX = pX + inc;
                }

         while(pX < (AB + BC) ){
                twoax(pX, pY, A, B);
                pX = pX + inc;
```

```
            pY = pY + inc;
            }

 while(pX < (AB + BC + CD) ){
            threeax(pX,pY,pZ,A,B,C);
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
                      }

   while(pX < L){
            fourax(pX,pY,pZ,pU,A,B,C,D);
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            }

while(pX < (L + AB)){
            threeax(pY,pZ,pU,B,C,D);
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            }


while(pX < (L + AB + BC)){
            twoax(pZ,pU,C,D);
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            }

while(pX < (AB + BC + CD + DE)){
            oneax(pU, D);
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            }

while(pX < (L + AB + BC + CD) ){
            twoax(pU,pV,D,E);
            pX = pX + inc;
            pY = pY + inc;
            pZ = pZ + inc;
            pU = pU + inc;
            pV = pV + inc;
            }

    while(pX < (L + AB + BC + CD + DE )){
```

```
                    oneax(pV, E);
                    pX = pX + inc;
                    pY = pY + inc;
                    pZ = pZ + inc;
                    pU = pU + inc;
                    pV = pV + inc;
                                }
      fout << endl << setw(10) << MaxM;
      }

            fout.close();
}



//*********************************************************************
//Function to calculate the maximum moment when one axle is on the
bridge.
//*********************************************************************
******************************


void oneax(float pLoad, float Load )
{
      float Ma, AbsMa;
      pM = 0;
      AbsMa = 0;

      while (pM < L){
            r2 = (pLoad*Load)/L;
            r1 = Load - r2;
            if (pLoad <= pM){
                  Ma = r2*(L-pM);
                  AbsMa = fabs (Ma);
                  }
            else {
                  Ma = -r1*(pM);
                  AbsMa = fabs (Ma);
                  }
            if (AbsMa>MaxM){
                  MaxT = pX;
                  MaxM = AbsMa;
                  MaxL = pM;
                  }
            pM = pM + inc;
            }
}
```

```
//*********************************************************************
******************************
//Function to calculate the maximum moment when two axles are on the
bridge.
//*********************************************************************
******************************


void twoax (float pLoad_1, float pLoad_2, float Load_1, float Load_2)
{
      int x1, x2;
      int d1, d2, d3;
      float Ma, AbsMa;
      pM = 0;
      AbsMa = 0;

      while (pM < L){
            r2 = (pLoad_1*Load_1 + pLoad_2*Load_2)/L;
            r1 = Load_1 + Load_2 - r2;
            x1 = x2 = 0;
            d1 = d2 = d3 = 0;
            if (pLoad_1 >= pM) { x1 = 1;  }
            if (pLoad_2 >= pM) { x2 = 1;  }
            d1 = 1 - x1;
            d2 = x1 * (1 - x2);
            d3 = x1 * x2;
            Ma = d1*r2*(L-pM) +
                 d2*(r2*(L-pM)-(pLoad_1-pM)*Load_1) –
                 d3*r1*pM;
            AbsMa = fabs (Ma);
            if (AbsMa > MaxM){
                  MaxT = pX;
                  MaxM = AbsMa;
                  MaxL = pM;
                  }
            pM = pM + inc;
            }
}
```

```
//*********************************************************************
******************************
//Function to calculate the maximum moment when three axles are on the
bridge.
//*********************************************************************
******************************
void threeax(float pLoad_1, float pLoad_2, float pLoad_3, float Load_1,
float Load_2, float Load_3)
{
```

```
      int x1, x2, x3;
      int d1, d2, d3, d4;
      float Ma, AbsMa;
      pM = 0;
      AbsMa = 0;

      while (pM < L){
            r2 = (pLoad_1*Load_1 + pLoad_2*Load_2 + pLoad_3*Load_3)/L;
            r1 =  Load_1 + Load_2 + Load_3 -r2;
            x1 = x2 = x3 = 0;
            d1 = d2 = d3 = d4 = 0;

        if (pLoad_1 >=  pM) { x1 = 1; }
            if (pLoad_2 >=  pM) { x2 = 1; }
            if (pLoad_3 >=  pM) { x3 = 1; }

            d1 = 1- x1;
            d2 = x1 * (1 - x2);
            d3 = x1 * x2 * (1 - x3);
            d4 = x1 * x2 * x3;

        Ma = d1*r2*(L-pM) +  d2*(r2*(L-pM)-(pLoad_1-pM)*Load_1)+
             d3*(-r1*pM+(pM-pLoad_3)*Load_3) +
             d4*(-r1*pM);
            AbsMa = fabs (Ma);

        if (AbsMa>MaxM){
                  MaxT = pX;
                  MaxM = AbsMa;
                  MaxL = pM;
                  }
            pM = pM + inc;
            }
}

//*********************************************************************
******************************
//Function to calculate the maximum moment when four axles are on the
bridge.
//*********************************************************************
******************************

void fourax (float pLoad_1, float pLoad_2, float pLoad_3, float
pLoad_4, float Load_1, float Load_2, float Load_3, float Load_4)
{
      int x1, x2, x3, x4;
      int d1, d2, d3, d4, d5;
      float Ma, AbsMa;
      pM = 0;
      AbsMa = 0;

      while (pM < L){
```

```
            r2 = (pLoad_1*Load_1 + pLoad_2*Load_2 + pLoad_3*Load_3 +
pLoad_4*Load_4)/L;
            r1 = Load_1 + Load_2 + Load_3 + Load_4 - r2;
            x1 = x2 = x3 = x4 = 0;
            d1 = d2 = d3 = d4 = d5 = 0;

            if (pX >= pM) { x1 = 1;  }
            if (pY >= pM) { x2 = 1;       }
            if (pZ >= pM) { x3 = 1;       }
            if (pU >= pM) { x4 = 1;  }

            d1 = 1- x1;
            d2 = x1 * (1 - x2);
            d3 = x1 * x2 * (1 - x3);
            d4 = x1 * x2 * x3 * (1 - x4);
            d5 = x1 * x2 * x3 * x4;

            Ma = d1*r2*(L-pM) + d2*(r2*(L-pM)-(pLoad_1-pM)*Load_1) +
                 d3*(r2*(L-pM)-(pLoad_1-pM)*Load_1 -(pLoad_2-
                  pM)*Load_2) +
                 d4*(-r1*pM+(pM-pLoad_4)*Load_4) + d5*(-r1*pM);

            AbsMa = fabs (Ma);
            if (AbsMa > MaxM){
                  MaxT = pX;
                  MaxM = AbsMa;
                  MaxL = pM;
                  }
            pM = pM + inc;
            }
}

//*********************************************************************
******************************
//Function to calculate the maximum moment when five axles are on the
bridge.
//*********************************************************************
******************************



void fiveax (float pLoad_1, float pLoad_2, float pLoad_3, float
pLoad_4, float pLoad_5, float Load_1, float Load_2, float Load_3, float
Load_4, float Load_5)
{
      int x1, x2, x3, x4, x5;
      int d1, d2, d3, d4, d5, d6;
      float Ma, AbsMa;
      pM = 0;
      AbsMa = 0;

      while (pM < L){
```

```
        r2 = (pLoad_1*Load_1 + pLoad_2*Load_2 + pLoad_3*Load_3 +
        pLoad_4*Load_4 + pLoad_5*Load_5)/L;
        r1 = Load_1 + Load_2 + Load_3 + Load_4 + Load_5 - r2;
        x1 = x2 = x3 = x4 = x5 = x6 = x7 = x8 = x9 = x10 = 0;
        d1 = d2 = d3 = d4 = d5 = d6 = d7 = d8 = d9 = d10 = d11 = 0;

        if (pX >= pM) {   x1 = 1;     }
        if (pY >= pM) {   x2 = 1;     }
        if (pZ >= pM) {   x3 = 1;     }
        if (pU >= pM) {   x4 = 1;     }
        if (pV >= pM) {   x5 = 1;     }

        d1 = 1- x1;
        d2 = x1 * (1 - x2);
        d3 = x1 * x2 * (1 - x3);
        d4 = x1 * x2 * x3 * (1 - x4);
        d5 = x1 * x2 * x3 * x4 * (1-x5);
        d6 = x1 * x2 * x3 * x4 * x5;

        Ma = d1*r2*(L-pM) + d2*(r2*(L-pM)-(pLoad_1-pM)*Load_1) +
             d3*(r2*(L-pM)-(pLoad_1-pM)*Load_1-(pLoad_2-pM)*Load_2)
              +
             d4*(-r1*pM + (pM-pLoad_4)*Load_4 +(pM-pLoad_5)*Load_5)
              +
             d5*(-r1*pM+(pM-pLoad_5)*Load_5) + d6*(-r1*pM);
        AbsMa = fabs (Ma);
        if (AbsMa>MaxM){
              MaxT = pX;
              MaxM = AbsMa;
              MaxL = pM;
              }
        pM = pM + inc;
        }
}
```

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