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**Minimizing Vehicle Emissions through Transportation Road Network
Design Incorporating Demand Uncertainty**

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**Minimizing Vehicle Emissions through Transportation Road Network
Design Incorporating Demand Uncertainty**

by

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Dedication

To the generations faced with the challenge of living responsibly in a world with the allusion of unbridled wealth and endless resources. It is time to do more with less.

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Abstract

Minimizing Vehicle Emissions through Transportation Road Network Design Incorporating Demand Uncertainty

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Traditionally, transportation road networks have been designed for minimal congestion. Unfortunately, such approaches do not guarantee minimal vehicle emissions. Given the negative impacts of vehicle pollutants as well as tighter national air quality standards, it is critical for regions to be able to identify capacity modifications to road networks such that vehicle emissions are minimal. This ability combined with land use changes and opportunities for non-auto travel are paramount in helping regions improve air quality. However, network design research has yet to directly address this topic.

To fill this apparent gap in network design research, an emissions network design problem and solution method are proposed in this thesis. Three air pollutants are considered: hydrocarbons, nitrogen oxides, and carbon monoxide. The proposed model is applied to two road networks: Sioux Falls, ND and Anaheim, CA. The model is a bi-level optimization problem solved using a genetic algorithm and incorporates the influence of demand uncertainty. Findings indicate designing for minimal congestion tends to increase emissions of criteria air pollutants. However, not adding capacity to a road network also increases emissions of pollutants. Therefore, an optimization problem and solution method, such as the model presented here, is useful for identifying capacity additions that reduce vehicle emissions. It is also useful for understanding the tradeoffs between designing a network for minimal congestion versus minimal vehicle emissions.

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Chapter 1: Background and Literature Review

INTRODUCTION

The purpose of this research is to develop a methodology for incorporating emissions into road network design and to present information useful to practitioners and decision-makers faced with planning road network improvements under air quality constraints. The three objectives of this paper are: 1) demonstrate the need to incorporate air quality considerations into network design problems; 2) present and apply a method for incorporating vehicle emissions into network design problems; and 3) present results from exploring the differences and similarities between designing a network for minimal congestion (i.e., total travel time) versus minimal total vehicle emissions. The following sub-sections discuss the connection between air quality and transportation, approaches for managing transportation's impact on air quality, and air quality as it relates to road network design.

The Connection between Air Quality and Transportation

Transportation is a significant source of air pollution in the United States. One-third of greenhouse gas emissions in the U.S. come from transportation, which makes it the largest single source and the fastest growing source of greenhouse gas (Winkelman et al., 2009). In U.S. urban areas, 95 percent of carbon monoxide comes from vehicles (EPA, 2007b). Nationwide (urban and non-urban areas) vehicles account for over half of the carbon monoxide, hydrocarbons, and nitrogen oxides emissions in the air (EPA, 2007b; EPA, 2007c; EPA, 2007d). Carbon monoxide, hydrocarbons, nitrogen oxides, and fine particulate matter cause significant health and environmental damage on their own as well as produce other harmful pollutants including cancer-causing air toxins and

greenhouse gases (e.g., ground-level ozone) (Wang et al., 2009; EPA, 2007a; Aneja et al., 2001; Ye et al., 1997; Bond, 1995; Melnick and Kohn, 1995).

Carbon monoxide, hydrocarbons, nitrogen oxides, particulate matter, and ground-level ozone have been linked to numerous health problems including reducing the body's ability to deliver oxygen to organs, causing lung cancer, inducing or aggravating asthma, reducing lung function, inflaming lung tissue, permanently scarring lung tissue, and causing premature death (Burnett et al., 1997; Burnett et al., 1998; EPA, 2007b; EPA, 2007c; EPA, 2009b; EPA, 2008b; EPA, 2007e; McClellan, 2002). In addition to health problems, these pollutants also damage the environment and ecosystems. In the U.S., ground-level ozone is responsible for approximately \$500 million in reduced crop production each year (EPA, 2008a). Carbon monoxide, hydrocarbons, nitrogen oxides, particulate matter and ground-level ozone are either indirectly or directly responsible for damaging soil, increasing plants' susceptibility to disease, insects, other pollutants, and competition, reducing forest growth, and ultimately negatively impacting plant and animal diversity in ecosystems (EPA, 2008b; Mauzerall et al., 2005).

Vehicles emit carbon monoxide, hydrocarbons, nitrogen oxides, and particulate matter through their fuel combustion processes. Carbon monoxide is formed when fuel does not burn completely (EPA, 2007b). Hydrocarbons are due to incomplete fuel combustion and fuel evaporation (EPA, 2007c). Nitrogen oxides are created when fuel burns at high temperatures as it does in automobiles (EPA, 2007d). Particulate matter is formed when nitrogen oxides react with ammonia, moisture and other compounds in the air (EPA, 2009b). Finally, greenhouse gases such as ozone and carbon dioxide are created when nitrogen oxides, hydrocarbons and carbon monoxide react in the presence of sunlight (EPA, 2009b). Due to the health and environmental impacts of these and

related air pollutants, the federal government created the Clean Air Act to legislate ambient air quality standards.

The Environmental Protection Agency (EPA) is the federal government entity responsible for recommending air quality standards to lawmakers and enforcing the resulting National Ambient Air Quality Standards (NAAQS) set by Congress under the Clean Air Act. The NAAQS are comprised of primary and secondary ambient air concentration limits for six pollutants; these pollutants are: 1) carbon monoxide; 2) nitrogen dioxide (a compound within the nitrogen oxides family); 3) ground-level ozone; 4) particulate matter; 5) lead (an air toxin) and 6) sulfur dioxide (primary sources are power plants and other industrial facilities) (EPA, 2009d). Primary standards (i.e., limits) are set to protect public health and secondary standards are set to protect public welfare including protecting crops, vegetation, and other animals (EPA, 2009d). Metropolitan areas are required to comply with the standards for the six criteria pollutants. If they do not comply with the standards, regions fall into non-attainment for whichever pollutant whose limit was exceeded.

Consequences of non-attainment can be burdensome to the metropolitan planning organizations (MPO), public transportation agencies, private developers, prospective employers, and residents in the non-attainment region. Falling into non-attainment results in: 1) a loss of federal highway and transit funding; 2) mandatory boutique fuels (i.e., cleaner burning, more expensive fuels); 3) restrictive permitting requirements; 4) mandatory emissions offsetting; and 5) loss of economic development opportunities (USCC, 2009). One of the more significant consequences for transportation agencies in non-attainment regions is the additional analysis and project screening work they must do to remain eligible for federal funds. Transportation agencies in non-attainment regions must be able to demonstrate a proposed project will not increase emissions to be eligible

for federal funds (USCC, 2009). As a result, regions at-risk for non-attainment or those already in non-attainment need planning tools and information to help them identify infrastructure improvements that do not increase system emissions relative to a do-nothing or no-build scenario.

Managing Transportation's Impact on Air Quality

Over the last several years, alternative fuel sources, rail transit, and denser, more pedestrian-friendly (i.e., walkable) growth have been identified as key approaches to reduce air pollution as well as congestion. Research studies have shown public transit reduces fuel consumption and emissions (Neff, 2008; Litman, 2009a). Research also indicates denser, walkable land use patterns are more sustainable than current sprawling land use patterns in terms of minimizing air pollutant emissions, reducing energy consumption, and reducing household expenditures on basic amenities (CTOD, 2009; Winkelman et al., 2009; Litman, 2009b). Clearly, metropolitan regions need to be moving toward improved transit systems and denser, mixed-use, pedestrian-friendly land use as a means to reduce the need for travel by automobile and in-turn reduce emissions.

However, many U.S. metropolitan areas are faced with a chicken and egg conundrum. They don't have the land use patterns to support a large transit system investment, but the transit system investment could help create the denser, more walkable mixed land use patterns, which in-turn will support the expanded transit system. Additionally, changing land use patterns or building robust transit systems in a traditionally auto-dominated region takes considerable time. Full or substantial market penetration of alternative fuel vehicles and the corresponding necessary infrastructure is also a long-term endeavor. What do regions facing potential non-attainment or are in non-attainment do in the mean time? What about regions with transportation options that are still experiencing increasing demand for travel by auto? Should regions ignore the

growing demand for automobile travel and let congestion worsen? What improvements to their road network are pertinent, reasonable, sound improvements – ones that will help serve the demand, but not exacerbate emissions? Are these improvements the same as those that minimize total system travel time? These and other related questions are the ones this research aims to address.

Air Quality and Road Network Design

We propose a methodology for incorporating emissions considerations into planning for road network improvements. More formally, we present a network design problem incorporating vehicle emissions. The proposed formulation is a bi-level optimization problem where the upper level minimizes system emissions of a specific pollutant and the lower level enforces user-equilibrium route choice. The problem is solved using a genetic algorithm. The resulting problem solutions are a set of capacity improvements to a given network, for a given demand, subject to user-specified budget constraints and resulting in minimal network emissions. We consider three key pollutants: carbon monoxide (CO), hydrocarbons also known as volatile organic compounds (VOC), and nitrogen oxides (NO_x). These three pollutants were chosen because of their respective and combined significant impacts on human health and the environment. Furthermore, CO, VOC, and NO_x in the presence of sunlight react to form detrimental air toxins and greenhouse gases.

The methodology presented in this paper is applied to two different road networks in the U.S. one relatively small network, Sioux Falls, ND and the other of moderate size, Anaheim, CA. We also investigate the influence of demand uncertainty on the type of improvements identified to obtain minimal road network emissions. The proposed methodology and application fill a current gap in research related to network design problems. Based on our literature review, there is minimal to no research investigating:

1) how capacity additions to a network, made to minimize total system travel time, influence system emissions; and 2) how striving to minimize system emissions influences the capacity additions made to a road network. Traditionally, road network design problems have focused on minimizing system travel time (or travel cost) rather than system emissions.

The following sections of this chapter discuss traditional road network design problems and how emissions have been integrated into those as well as other related network optimization problems (e.g., traffic assignment).

NETWORK DESIGN PROBLEMS IN THE LITERATURE

Identifying, designing, funding and constructing road network infrastructure improvements has been and continues to be a complex and critical component of transportation planning. Network design concepts can be used to inform this planning process by offering insight into which network improvements can offer the most benefit for a given budget. Traditionally, network design problems have focused on finding the optimal set of network improvements to minimize total system travel time or cost either through adding new links (discrete network design problems) or by increasing capacity on existing links (continuous network design problems) (see LeBlanc, 1975; Poorzahedy and Turnquist, 1982; LeBlanc and Boyce, 1986; Friesz et al., 1992, Suh and Kim, 1992; Solanki et al. 1998; Cho and Lo, 1999). Network design related research in the 1960's through the 1990's tended to explore ways to formulate network design problems to reasonably approximate practical planning applications as well as develop more efficient solution algorithms (see Magnanti and Wong, 1984; Yang and Bell, 1998). In the late 1990's and 2000's, researchers increased the complexity and robustness of network design problems by formulating them as multi-criteria and multimodal problems (see Cantarella and Vietta, 2006; Kim and Kim, 2006). However, throughout this evolution,

the primary focus of most network design problems has remained minimizing total system travel time (or cost) without a thorough understanding of what this means to total system emissions.

Consideration for emissions has been integrated into research regarding network topology and performance in the form of alternatives analyses, before and after empirical studies, and traffic signal timing considerations (see Lozano et al., 2008; O'Donoghue et al. 2007; Unal et al., 2003; Li et al., 2004; Yungpeng et al., 2008). In the specific context of network design, there have been some formulations focused on setting traffic signal timing along corridors to minimize emissions (see Medina et al., 2007; Stevanovic et al., 2009). Also, in some instances, the multi-criteria network design formulations create opportunities to incorporate emissions into a larger societal cost function (see Cantarella and Vietta, 2006; Kim and Kim, 2006). However, these formulations contain limitations in how they consider and calculate pollutant emissions. Examples of limitations in previous research include fixed pollutant emissions that do not vary with vehicle speed or vehicle type, restricting consideration to a single pollutant, and/or characterizing environmental impacts via an ill-defined monetary cost. Furthermore, the structure of the multi-criteria formulations make the models difficult to transfer to practical applications and challenging to infer informative trends related to emissions and system performance. For example, it is not clear how results from the multi-criteria objective problem differ compared to minimizing only total system travel time or only system emissions or another attribute of societal cost. Understanding these tradeoffs and trends are at the heart of the value models can provide to decision makers.

The proposed methodology and formulation in this paper incorporates emissions into a bi-level programming problem with the upper level minimizing total system emissions and the lower level enforcing user equilibrium route choice. This formulation

facilitates the comparison between network improvements to minimize total system travel time and total system emissions. Results from this methodology can be compared to assess the network performance tradeoffs when one chooses to design for minimal emissions versus minimal travel time. As noted above, this is valuable information for growing regions at risk for non-attainment (i.e., violating EPA's NAAQS) or in non-attainment. Network related research on traffic assignment and network pricing indicate models based on minimizing or reducing congestion or travel time do not guarantee minimal system emissions. Researchers in these areas have more thoroughly explored some of the effects route choice and pricing can have on network emissions. Results from this previous research indicate the need to and potential value in incorporating emissions into network design problems.

EMISSIONS WITHIN TRAFFIC ASSIGNMENT AND NETWORK PRICING LITERATURE

System emissions have been more thoroughly explored in traffic assignment and network pricing literature in contrast to the network design literature. Results from the traffic assignment and network pricing literature generally indicate that routing vehicles to minimize emissions on the network (either through information dissemination or pricing) tends to result in different link flows, higher total system travel time, higher individual travel time and lower system emissions than when vehicles are routed to minimize individual travel time or total system travel time (see Johansson, 1997; Rilett and Benedek, 1998; Yin and Lawphongpanich, 2006; Sugawara and Niemeier, 2002; Ahn and Rakha, 2008). Pertinent research incorporating emissions into traffic assignment and network pricing problems is discussed below.

Earlier research incorporating emissions into the traffic assignment problem includes work by Tzeng and Chen (1993), Rilett and Benedek (1994) and Benedek and Rilett (1998). These works tend to focus on developing a base methodology for

incorporating emissions by considering a single pollutant. Tzeng and Chen (1993) created a multiobjective traffic assignment method in which they incorporated carbon monoxide emissions through a fixed emission factor. Rilett and Benedek (1994) and Benedek and Rilett (1998) developed a formulation considering equitable traffic assignment with environmental cost functions. Initial findings indicated the objectives of minimizing total system travel time and system emissions via traffic assignment are conflicting (Rilett and Benedek, 1994). Subsequently, Benedek and Rilett (1998) found routing vehicles to minimize carbon monoxide emissions under congested conditions resulted in an approximately 7% emissions reduction compared to user equilibrium and system optimal assignment. Benedek and Rilett (1998) noted the potential benefit could increase for networks with more route choices (their test network was Edmonton University, which they noted had few alternative routes for the origin-destination pairs) and networks not at or near saturation (i.e., less congested networks). These two conditions, lower number of alternative routes and a congested network, restrict the number of route choices thereby reducing the potential variation in assignment.

More recent research by Sugawara and Niemeier (2002) thoroughly explored the relationship between traffic assignment and emissions providing additional insight into how route choice influences emissions on a system level. Sugawara and Niemeier (2002) formulated a trip assignment methodology to minimize emissions. Their emissions optimized (EO) assignment routes vehicles to minimize system carbon monoxide emissions; carbon monoxide emissions were modeled using a speed sensitive function developed from California Air Resources Board (CARB) emissions factors. The EO assignment was applied to a hypothetical network. Sugawara and Niemeier (2002) compared system travel time and emissions performance to system emissions experienced under user equilibrium (UE) and system optimal (SO) assignments.

Sugawara and Niemeier (2002) found the EO assignment effectively reduced emissions but did increase system travel time by 3.3% to 5% compared to the UE and SO assignments. They also found route assignment varied depending on the level of congestion in the network. At lower levels of congestion, EO assignment results in vehicles assigned to only surface streets rather than freeways and results in 23.9% to 26.0% reduction in carbon monoxide emissions compared to UE and SO assignment (Sugawara and Niemeier, 2002). As congestion increased, EO assignment still favored surface streets but inevitably became more similar to UE and SO assignments as route choices decreased; however, even under more congested conditions, EO assignment still provided 7% reduction in carbon monoxide emissions compared to UE and SO assignment (Sugawara and Niemeier, 2002). These findings support the results discovered by Benedek and Rilett (1998). Sugawara and Niemeier (2002) results are also consistent with those found by Yin and Lawphongpanich (2006) in their research on network pricing to reduce emissions as well as research by Ahn and Rakha (2008). Both of these research efforts are discussed in more detail below.

Yin and Lawphongpanich (2006) explore how different pricing schemes influence route choice and in-turn emissions. Other pricing related research by Johansson (1997), Nagurney (2000a), and Sakamoto (2006) also consider pricing schemes to reduce emissions. However, Yin and Lawphongpanich (2006) is most pertinent to this discussion as they compare system performance and route choice results between a congestion pricing scheme and emissions pricing scheme. Findings from Yin and Lawphongpanich (2006) indicate first-best congestion-pricing schemes do not guarantee reduced or minimal traffic emissions, which is supported by research by Rilett and Benedek (1995) as well as Johansson (1997). Yin and Lawphongpanich (2006) consider carbon monoxide emissions as a function of flow. Similar to Sugawara and Niemeier

(2002), they found total delay for the pricing scheme with minimal emissions is higher than the total delay experienced with system optimal (i.e., minimum congestion) pricing scheme (Yin and Lawphongpanich, 2006). These results indicate moderate speed facilities are better route choices, from an air quality perspective, than congested or uncongested higher speed facilities.

Ahn and Rakha (2008) consider the effect route choice has on vehicle energy consumption and emissions. Results found by Ahn and Rakha (2008) support the EO assignment findings from Sugawara and Niemeier (2002) and Yin and Lawphongpanich (2006) indicating higher speed routes, such as highways and freeways, are not guaranteed to minimize air pollution or energy consumption. Therefore, air quality improvements or minimal vehicle emissions tend to occur when motorists (and the system) experience additional travel time by choosing surface streets; this is reflected in findings from Sugawara and Niemeier (2002), Yin and Laphongpanich (2006), and Ahn and Rakha (2008). Finally, findings from Ahn and Rakha (2008) support the overall trend from Sugawara and Niemeier (2002) and Yin and Lawphongpanich (2006) that vehicle routing to minimize system emissions has the potential to create substantial air quality benefits compared to UE and SO assignment.

The research by Ahn and Rakha (2008) is particularly significant because they used more sophisticated emissions models able to consider changes in speed due to second by second changes in traffic flow. They also considered multiple pollutants: carbon monoxide, hydrocarbons, nitrogen oxides, and carbon dioxide. With these additional elements of sophistication, Ahn and Rakha (2008) results confirmed earlier research and highlighted the importance of using microscopic emissions models for analyzing traffic operations projects. Their results also illustrated the need to consider

multiple pollutants; Ahn and Rakha (2008) found minimizing one pollutant's emissions does not guarantee other pollutants will be minimized.

Findings from this literature review on traffic assignment and network pricing problems incorporating emissions indicate a consistent trend in results even with the varying levels of sophistication in modeling emissions. The more sophisticated emissions models (e.g., research considering multiple pollutants, allowing emission rates to vary with vehicle speed) provide more valuable and potentially useful information for policy and decision-making. However, the general results of the traffic assignment and pricing research consistently indicate operating a network to minimize total system travel time or individual user travel time does not guarantee minimal system emissions. This is a key reason for incorporating emissions into network design problems; it seems plausible that designing a network to minimize total system travel time does not guarantee minimal system emissions.

SUMMARY

The connection between air quality and transportation indicates the need to actively manage transportation's impact on air quality. Current techniques to manage transportation impacts on air quality include alternative fuels, travel demand management, increasing the number of modes available for travel, and modifying land use to support non-auto modes. Another key component is identifying road network design changes (e.g., changes to capacity, additional connections) that minimize additional system emissions. Identifying such changes to the road network is an important interim step in the gradual transition to full market penetration of alternative fuel vehicles, transit service improvements, and land use changes. Regions will continue to grow and will need to consider changes to their road network and as a result they need to be able to consider these changes in the context of minimizing total system emissions.

The methodology and numerical analysis presented in this paper illustrates how air quality can be integrated into road network design.

Subsequent chapters discuss the problem motivation, problem formulation and solution method, numerical analyses, and conclusions including future opportunities to expand this research.

Chapter 2: Problem Motivation and Problem Statement

PROBLEM MOTIVATION

Findings from previous research collectively demonstrate the need to incorporate emissions into network design for two compelling reasons. First, previous research has shown the impact of transportation system changes on total system vehicle emissions is a phenomenon that should be studied at the network level especially when the analyses are used to inform regional road infrastructure improvements. Changes to a road network that result in decreased local emissions may increase system-wide emissions. Second, previous research has shown operating road networks to minimize total system travel time does not guarantee minimal system emissions. Therefore, it is plausible designing a road network for minimal emissions is also different than designing a road network for minimal total system travel time. Finally, previous research related to demand uncertainty's influence on network design and other related network optimization problems illustrate the need to explore the influence demand uncertainty has on the proposed emissions network design problem.

The Broader Network Perspective

Research by Kaysi et al. (2004) and Noland and Quddus (2006) underscore the importance of considering road infrastructure and operational changes in the context of network performance and optimization as opposed to considering isolated pieces of a larger network. The research by Kaysi et al. (2004) and Noland and Quddus (2006) is discussed below.

Kaysi et al. (2004) evaluated the impact of incident management techniques on emissions. Different ITS travel information scenarios were used to prevent congestion at the site of the incident by giving alternative route information to motorists. Kaysi et al.

(2004) found the scenarios that decreased emissions the most for the entire network resulted in different routes for motorists than the scenarios that decreased emissions the most for the vicinity around the incident. This finding demonstrates the importance of considering the influence of changes to the road network on emissions from a broader network perspective. Reducing or adding capacity to various links in the network may decrease local emissions but increase region-wide emissions. Therefore, in planning for regional system improvements, the impacts of system changes on emissions should be considered at a network level.

Noland and Quddus (2006) looked at roadway improvements in isolation and the improvements' lasting impacts on reducing emissions. The research did not consider the broader network context. One scenario focused on a single freeway merge condition and the other scenario focused on traffic signal coordination on a single corridor (Noland and Quddus, 2006). In the research, traffic volumes appear to have been arbitrarily increased and assumed to be induced new trips due to reduced congestion. However, the research did not consider the likelihood that trips would be redirected from other potentially more congested portions of the network rather than being induced new trips. Therefore, results from Noland and Quddus (2006) indicate capacity improvements or traffic flow improvements make emissions worse due to induced demand. However, it appears these findings are naïve and potentially misleading because they do not consider the broader network context. Considering improvements in the context of network performance and optimization frames the problem such that analysts are considering which are the optimal locations and corridors (if any) to minimize total system emissions through capacity additions.

Operating and Designing a Network for Minimal Emissions

Based on research results from the literature regarding traffic assignment and network pricing incorporating emissions, it is evident operating a network efficiently from a travel time or congestion perspective does not guarantee the network is operating efficiently from an emissions perspective (see Sugawara and Niemeier, 2002; Yin and Lawphongpanich, 2006; Rilett and Benedek, 1994; Yin and Lu, 1999; Ahn and Rakha, 2008). Furthermore, network alternatives analysis conducted by Lozano et al. (2008) demonstrate the “preferred” set of network improvements varies depending on whether the analyst chooses to reduce total system travel time or total system emissions of a specific pollutant. This indicates a well-designed network in terms of emissions is likely to be different than a well-designed network in terms of congestion. Furthermore, Nagurney’s emissions paradox indicates the influence of network changes on emissions is not necessarily intuitive and deserves specific study.

Nagurney (2000b) demonstrates the emissions paradox using three simple network examples and a constant emissions factor. The three examples illustrate: 1) adding a road to a network may result in an increase in total emissions and no change in demand; 2) total emissions may increase with a decrease in travel demand; and 3) improving a road in terms of travel cost (e.g., adding link capacity, reducing travel time) may result in an increase in total emissions without a change in travel demand (Nagurney, 2000b). These results are a key indication emissions should be explicitly considered in network design. The methodology and numerical analysis presented in this paper explore Nagurney’s second and third phenomena noted above.

Travel Time and Average Vehicle Speed versus Emissions and Average Vehicle Speed

The research findings in related fields, discussed in Chapter 1 as well as research by Lozano et al. (2008) and Nagurney's emissions paradox noted above, indicate there is a different relationship between travel time and traffic flow characteristics compared to the relationship between emissions and traffic flow characteristics. In this research, average vehicle speed is the most accessible traffic flow characteristic to observe. Average vehicle speed is most accessible because the network design problem is formulated as a static network being analyzed at the macroscopic level. From the static and macroscopic model perspective, previous research findings indicate as travel time decreases on the system, emissions is not guaranteed to also decrease. More specifically, as travel time decreases on the system average vehicle speeds are increasing; however, decreasing system emissions does not necessarily correspond to reducing average vehicle speeds.

The set of figures below illustrate the different relationships between travel time and average vehicle speed versus emissions and average vehicle speed. The shape of the curves in Figures 1 through 4 illustrate fundamental differences between travel time and emissions that influence why operating and designing a network to minimize total system travel time is often different than operating and designing a network to minimize system emissions.

Figure 1 illustrates the relationship between travel time and average vehicle speed.

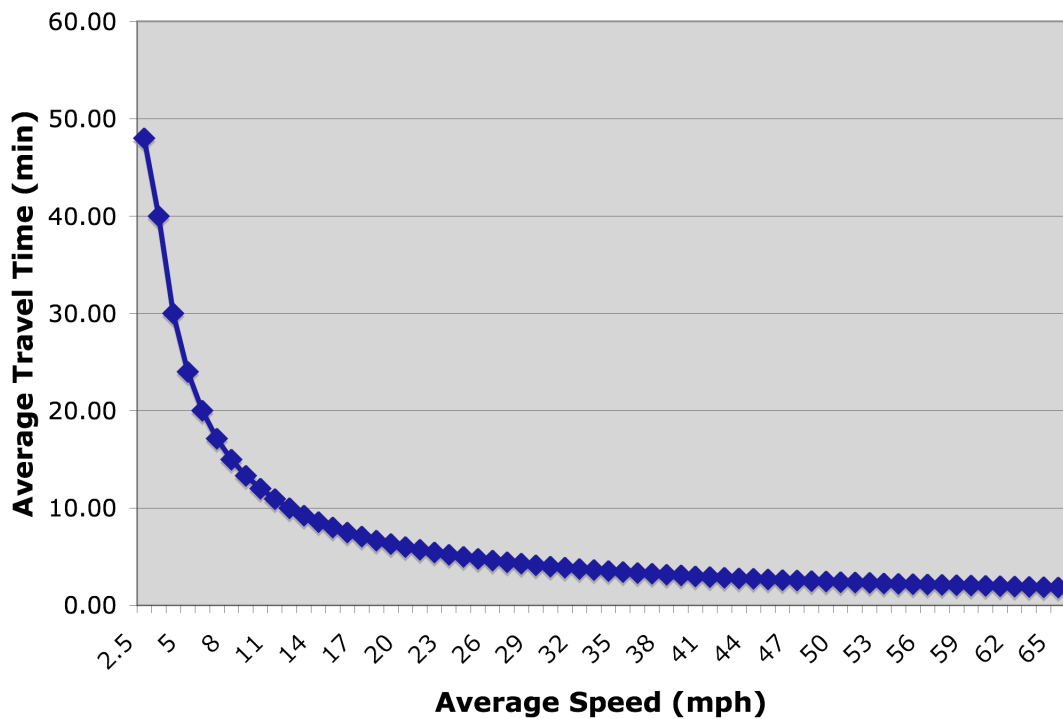


Figure 1. Relationship between average travel time and average vehicle speed.

Travel time above is modeled by the Bureau of Public Roads link performance function (the formulation for this function is provided in Chapter 3 Problem Formulation and Solution Method). As shown in Figure 1, travel time decreases monotonically as average vehicle speed increases. From a network design perspective and at an elementary level, this means one would design the network such that all vehicles are traveling as fast as possible to reach each motorist's destination.

Figure 2 illustrates the relationship between hydrocarbons emissions rate (grams/mile/vehicle) and average vehicle speed. The curve is specific to arterial facilities located in Anaheim, CA in July; the Emissions Calculations sub-section in Chapter 3 discusses how the emissions curves for the test networks were developed.

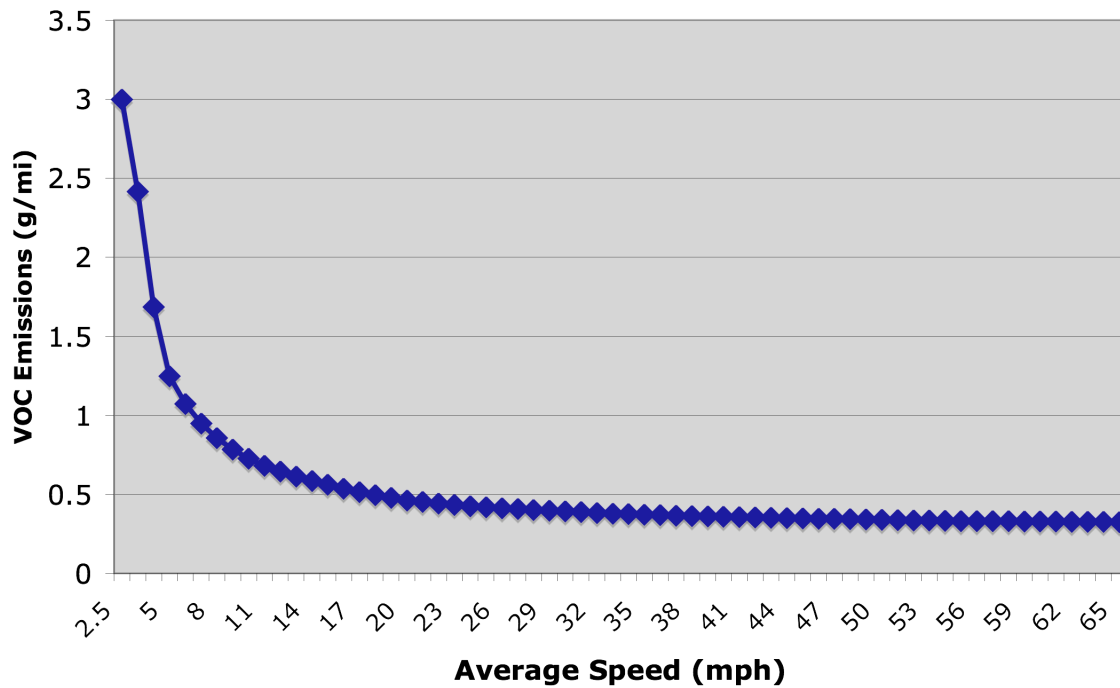


Figure 2. Relationship between hydrocarbons emissions and average vehicle speed.

The hydrocarbons curve above is plotted using values generated by MOBILE6.2 (EPA's mobile source emissions model). The plot indicates a similar shape to travel time as average vehicle speed increases. Therefore, it is reasonable to expect hydrocarbons to be near their minimal amount when system travel time is minimized.

Figure 3 illustrates the relationship between carbon monoxide emissions rate (grams/mile/vehicle) and average vehicle speed; the curve is specific to arterial roadways in Anaheim, CA in July.

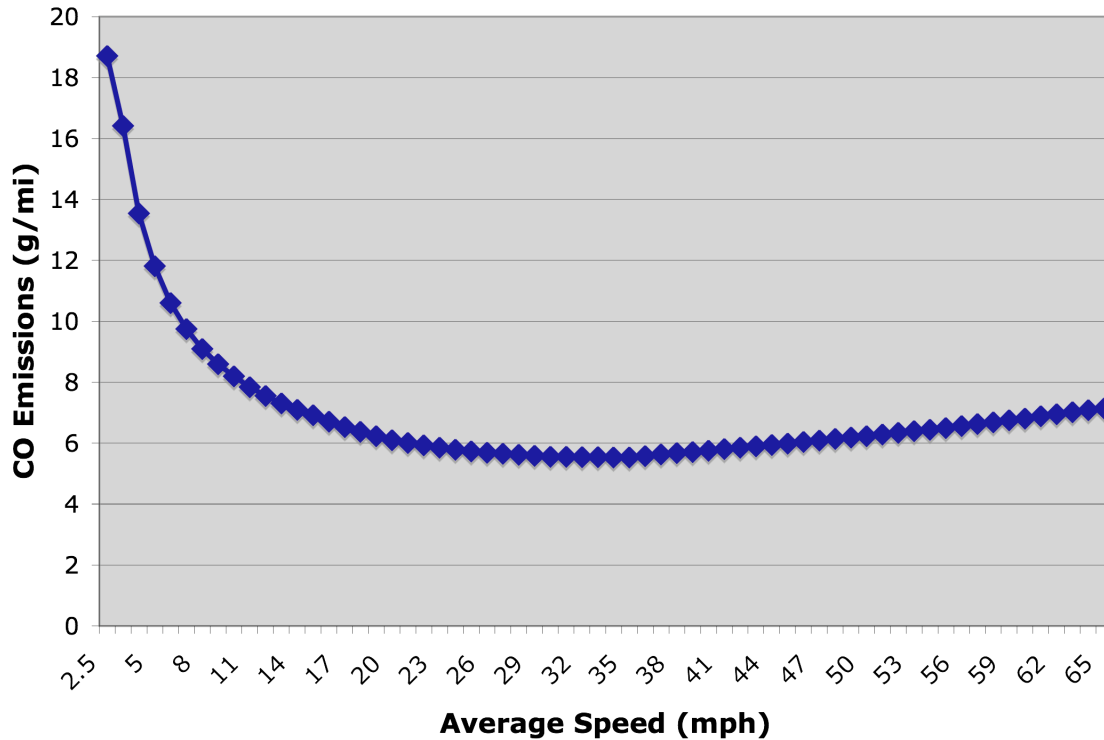


Figure 3. Relationship between carbon monoxide emissions and average vehicle speed.

The carbon monoxide curve was also plotted using EPA’s MOBILE6.2 software program. The curve is a convex, bowl-shape where the lowest emission rate tends to occur around 33 mph. This shape compared to the average travel time curve supports the findings from the traffic assignment and network pricing with emissions research: travel time and emissions have different relationships to traffic flow characteristics such as average vehicle speed. From a network design perspective, to minimize carbon monoxide emissions one would not want to design the network such that vehicles are traveling as fast as possible to their destinations. Instead a certain amount of congestion or slower speed facilities appear desirable to minimize carbon monoxide emissions.

Figure 4 illustrates the relationship between the emissions rate for nitrogen oxides and average vehicle speed. The curve is specific to arterial roadways in Anaheim, CA in July.

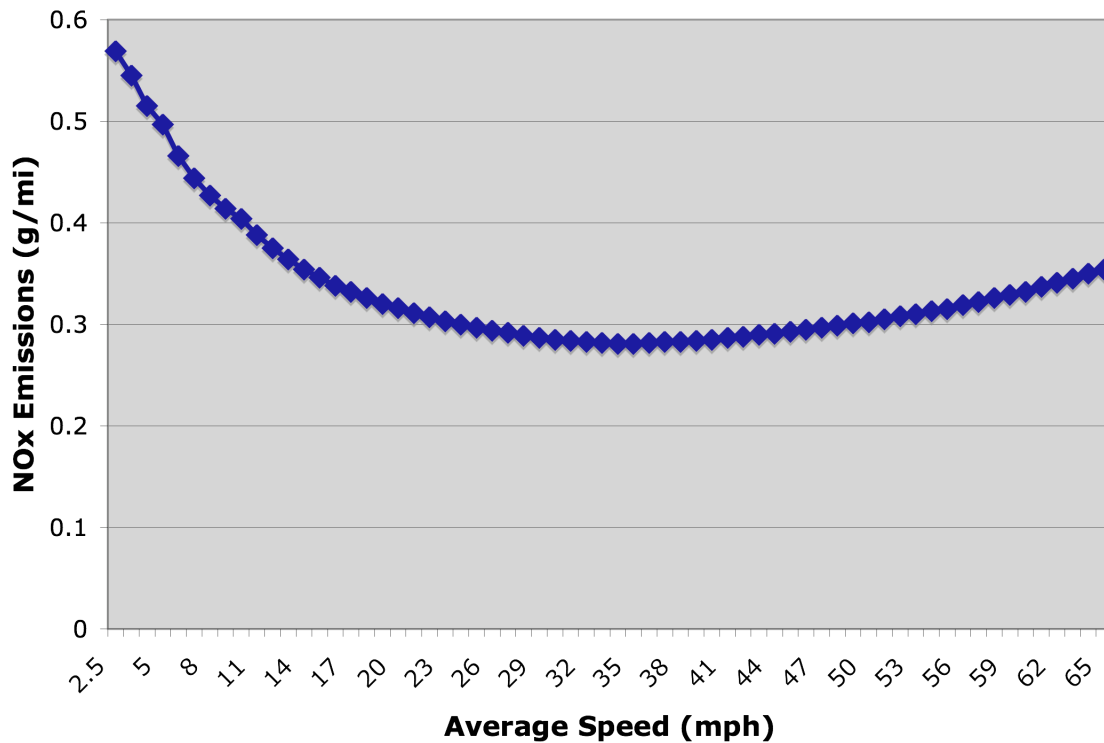


Figure 4. Relationship between nitrogen oxides emissions and average vehicle speed.

The nitrogen oxides curve was also plotted using values from EPA's MOBLIE6.2 software program. Similar to carbon monoxide, the plot is a convex, bowl-shape, where the lowest emissions rate tends to occur around 37 mph. Also similar to carbon monoxide, the plot supports the findings in the traffic assignment and network pricing research with emissions: travel time and emissions have different relationships to traffic flow characteristics such as average vehicle speed. Again similar to carbon monoxide,

from a network design perspective, a certain amount of congestion and/or slower speed facilities appear desirable to minimize nitrogen oxides emissions.

Demand Uncertainty

In practice and frequently in research, travel demand forecasts are treated as a fixed, known quantity, when in reality they are not. This is particularly true when dealing with travel demand forecasts produced for 10, 20, 30 or more years into the future. Travel demand depends on many future attributes and conditions that cannot be predicted perfectly, such as, land use patterns, rates of development, population growth, spatial distribution of the population, economic conditions, and political conditions. As a result, travel demand forecasts should be considered uncertain rather than fixed, precise numbers when planning for transportation system changes (see Asakura and Sasaki, 1990; Lam and Tam, 1998; Waller et al., 2001; Duthie et al., 2009). Results from previous research, which illustrate the influence of demand uncertainty on network design solutions (when total system travel time or system cost is minimized), is the primary motivation for incorporating long-term demand uncertainty into the proposed emissions network design problem.

Research by Waller et al. (2001) and Lam and Tam (1998) illustrate accounting for demand uncertainty in network design problems can significantly influence problem solutions. Waller et al. (2001) found network system performance was overestimated when demand was fixed, which creates the potential for selecting system changes that do not improve (and may degrade) system performance in reality. This is consistent with findings by Lam and Tam (1998). Results from Waller et al. (2001), and other related research noted above, demonstrate that accounting for demand uncertainty in transportation planning is a more sound, far-sighted approach (compared to assuming fixed demand) because the system modifications selected result in a network capable of

performing well under a variety of feasible future scenarios rather than a single fixed scenario.

Based on demand uncertainty's influence on network design problems when system travel time or system cost is minimized, it seems prudent to also consider demand uncertainty's influence on the proposed emissions network design problem. Therefore, demand uncertainty is incorporated into the proposed emissions network design problem and applied to one of the test networks. It should be noted that some researchers argue for incorporating demand elasticity to account for the variability in demand due to changes in system performance (see Yang and Bell, 1998). Demand elasticity is formulated such that demand increases or decreases depending on system performance. However, applying demand elasticity is not appropriate when minimizing total system cost (or total emissions) is the upper-level objective because total emissions (or travel time or cost) can be reduced by simply eliminating demand. This characteristic may lead to unreasonable results by potentially lowering demand below a known or practical base level. Therefore, in the proposed emissions network design model, the impact of demand elasticity is not considered; instead the focus of this work is to isolate the effect of uncertainty without confounding it by the effect of elasticity. To a limited degree, the effect of elasticity can be incorporated in the probability distributions chosen for travel demand. The effect of uncertainty on the emissions network design model is discussed in Chapter 4: Numerical Analyses.

Developing a Problem Statement and Research Plan

The findings from previous research and the relationship between emissions and average vehicle speed were used to develop a problem statement focused on incorporating emissions into the network design problem. In this process, a research plan also evolved focused on answering supporting questions related to identifying the

differences and similarities between designing to minimize system travel time versus system emissions. The following section discusses the problem statement and research plan in more detail.

PROBLEM STATEMENT AND RESEARCH PLAN

As noted in the Chapter 1: Introduction, the primary purpose of this research is to develop and apply a method for identifying network road improvements to accommodate automobile demand such that system emissions are minimized. The intent is to assist planners and decision-makers, who are working under air quality constraints and must determine which road network improvements, if any, should be made. In addition to the proposed method, there are also supporting questions developed and explored as part of this research with the goal extracting consistent trends useful in the transportation planning process. For example, a useful trend to know could be that networks composed of a grid of arterials tends to produce fewer emissions of a certain pollutant than a network comprised of a higher percentage of freeways. Another example of a useful trend could be that designing to minimize emissions tends to result in a certain percentage increase in total system travel time. These are general trends planners and practitioners could use to screen projects and choose which system projects are selected for further detailed analyses.

The supporting questions developed for this research are: 1) how is designing networks for minimal emissions different than designing for minimal travel time; 2) do network design improvements vary depending on the pollutant being considered; 3) are trends in designing to minimize emissions consistent across different regions in the U.S.; and 4) to what degree does demand uncertainty alter how one designs a road network for minimal emissions? These questions formed the basis for the research plan. The

research plan was developed to provide a framework for applying the proposed new method and answering the questions above.

To address the questions above, the emissions network design problem method was applied to two urban road networks. The method was applied to the Sioux Falls, ND and Anaheim, CA road networks. These two cities were selected because they provided some variety in road network size and geographic location. Also, network data (i.e., network topology and origin-destination demand tables) were available. Applying the proposed method to two network sizes with different network topologies provides the opportunity to explore the effectiveness and efficiency of the proposed formulation and solution method. Applying the proposed method in two different geographic areas in the U.S. provides the opportunity to consider the degree to which the environmental context such as temperature and humidity influence the trends in designing to minimize emissions. Finally, demand uncertainty was explored on the Sioux Falls, ND network to begin to understand how demand uncertainty influences the network design problem and any previous trends established using fixed demand.

SUMMARY

The motivation for integrating emissions into network design is based on previous findings in traffic assignment and network pricing research that incorporates emissions. Research by Kaysi et al. (2004), Noland and Quddus (2006), network alternatives analysis by Lozano et al. (2008), and Nagurney's emissions paradox further illustrate the importance of considering the impact road infrastructure modifications have on emissions at a network level rather than an isolated, local level. The fundamental differences in how emission rates of key pollutants change with vehicle speed compared to how travel time changes with vehicle speed also serves as motivation for exploring an emissions network design problem. The research problem statement and plan are formulated to

enable exploring a number of supporting questions whose answers are potentially useful in the transportation planning environment.

The following chapter presents the mathematical formulation, emission factor development and solution method that form the emissions network design problem.

Chapter 3: Problem Formulation and Solution Methodology

PROBLEM FORMULATION

To be able to identify the optimal capacity or link additions to a road network, one needs to be able to formulate the problem as a mathematical optimization problem. In general, optimization problems have an objective function and set of constraints. In traditional road network design problems, the objective function calculates total system travel time and the objective is to minimize that value. The constraints typically define a budget limit, network user behavior, and enforce traffic flow conservation. Formulating transportation network design problems as optimization problems is challenging because there are two levels of decision-makers influencing network performance. One level of decision-makers is the system managers and the second level is made up of system users. It is difficult to capture or approximate these two-levels in a single-level optimization problem. An alternative approach is use a bi-level problem formulation that more accurately models the two-levels of behavior influencing network performance. The draw-back is bi-level optimization problems are more difficult to solve. Despite this draw-back, the proposed emissions network design problem is formulated a bi-level optimization problem. The following sections discuss the evolution of network design problem formulations, the emissions network design formulation used in this research, and how emissions was accounted for within the problem formulation.

Evolution of Network Design Formulations

Originally, network design problems were formulated as single-level optimization problems. Discrete network design problems tended to be formulated as mixed-integer programming problems and continuous network design problems were formulated as nonlinear optimization problems (Abdulaal and LeBlanc, 1979; Magnanti and Wong,

1984). In both instances, the problems were formulated with a single objective function and a set of constraints. An early challenge in formulating, applying and solving these single-level network design problems was modeling network user behavior (e.g., route choice). In formulating the objective function, researchers either chose: 1) system optimal network design in which total system travel time was minimized and system optimal route choice behavior was assumed (i.e., users choose routes to minimize total system travel time rather than their own person travel time); or 2) user optimal network design in which individual travel time was minimized and user-equilibrium route choice behavior assumed (i.e., users choose routes to minimize personal travel time) (Abdulaal and LeBlanc, 1979). Both of these approaches had significant limitations, which led to the network design bi-level programming formulation.

The primary limitation of the single-level system optimal network design was the assumption that users would act to minimize total system travel time or cost rather than their own, which is unrealistic. System optimal network design found improvements to minimize total system congestion but due to the user behavior assumption (users choose routes to minimize total system travel time rather than their own) the resulting minimal system congestion is not practical relative to how motorists actually behave (Abdulaal and LeBlanc, 1979; Leblanc and Abdulaal, 1984; Magananti and Wong, 1984). The primary limitation of the single-level user optimal network design formulation was the solutions (i.e., network improvements) did not minimize system congestion. The user optimal network design formulation identifies improvements such that user-optimum flows on the network would experience the lowest cost (i.e., travel time or cost for each user is minimized); however, congestion on the network would not necessarily be minimal (LeBlanc and Abdulaal, 1984). The user optimal network design formulation more realistically represents user behavior but does not meet the needs of practitioners

trying to minimize congestion on their systems. Furthermore, the single-level user optimal network design formulation is difficult to solve, particularly in the discrete formulation; as a result, researchers or practitioners tended to solve the system optimal formulation and then check system congestion with user optimum flows (LeBlanc and Abdulaal, 1984; Magnanti and Wong, 1984).

In the mid-1980's, LeBlanc and Boyce (1986) presented a bi-level programming formulation for the continuous network design problem along with an exact solution method for smaller networks and techniques to accurately estimate solutions for larger networks. The bi-level formulation addresses the issue of having two levels of decision makers. One level, the upper level, is the system manager or decision-makers determining how to change or modify the network. The second level, the lower level, is the system users or motorists reacting to the network modifications. In road network design and performance, these two levels act independently. System managers do not have absolute control over the route choices users make; system managers can only influence them through network changes or modifications. Network users do not have control over changes made to the network; motorists are only able to react to changes made. The bi-level programming problem captures this leader-follower behavior.

Emissions Network Design Problem Formulation

Network design formulations since the mid-1980's tend to appear as bi-level formulations where the upper level is used to minimize total system travel time or cost, while the lower level enforces individual traveler behavior (often user-equilibrium route choice) (Yang and Bell, 1998). The emissions network design problem presented in this paper is also formulated as a bi-level programming problem; however, the upper level minimizes total system emissions as opposed to total system travel time (or cost) and the lower level enforces user-equilibrium route choice.

In this research, the more traditional network design problem (i.e., minimizing total system travel time) is solved along side of the emissions network design problem. Therefore, each is applied to the same test networks, under the same conditions and solved simultaneously using the same solution method. More specifically, four upper-level objectives are solved simultaneously within the bi-level problem: one upper-level objective is minimizing total system travel time, another upper-level objective is minimizing volatile organic compound (VOC) emissions, another upper level objective is minimizing carbon monoxide (CO) emissions, and the fourth is minimizing nitrogen oxides (NOx) emissions. The purpose of this approach is to compare and contrast the results of designing for minimal system travel time versus designing to minimize each of the three air pollutants (e.g., results facilitate creating pareto-optimal curves comparing total travel time to total emissions of each pollutant). The differences and similarities found from this comparison are discussed in Chapter 4: Numerical Analyses. The formulation for the entire problem is presented below.

As noted above, the primary difference between the emissions network design problem and more traditional network design problems is the upper level objective function. The traditional general form of the upper level objective function when system congestion is minimized (i.e., total system travel time) is shown in equation (1).

$$\text{Minimize } f_{TSTT}(v, y) = \sum_{i \in \mathcal{I}} v_i t_i(v_i, y_i) \quad (1)$$

Where, v is vehicle flow per link, t is travel time as a function of flow and added capacity, y , and i is the link index.

The general form of the upper level objective function for minimizing system emissions is equation (2). Each pollutant (i.e., VOC, NOx, and CO) has its own specific case of equation (2) because the emissions factors per pollutant have different relationships with average vehicle speed (see Figures 2 through 4 in Chapter 2). System

emissions for each pollutant is calculated by multiplying the vehicle flow on each link by the length of the link and an emissions factor per link (the emissions factor is specific to a pollutant and varies with average vehicle speed) and then summing across links in the network.

$$\text{Minimize } f_{SE,a}(v, y) = \sum_{i \in I} v_i l_i k_{a,i}(s_i) \quad (2)$$

Where, v is link flow (vehicles per hour), l is link length (miles), k is the emissions factor (grams per mile) that varies with average link speed, s , (average link speed is a function of link flow, v , and added practical capacity, y), a is the index specific to an air pollutant, and i is the link index.

The emissions factor is a function of the average vehicle speed, s , on each link, which depends on link flow, v , and added practical capacity y . The emission factor function is a stepwise function defined by equation (3i) through equation (3iii).

$$k_{a,i}(s) = \sum_{b \in B} \sum_{r \in R} \gamma_{r,b} S_r(s_i) L_b(i) \quad (3i)$$

$$S_r(s_i) = \{1 \text{ if } s_i \in r, 0 \text{ if } s_i \notin r\} \quad (3ii)$$

$$L_b(i) = \{1 \text{ if } type(i) = b, 0 \text{ if } type(i) \neq b\} \quad (3iii)$$

Where, s is average vehicle speed (miles per hour), a is the index specific to an air pollutant, i is the index specific to a link, γ is an emission factor corresponding to speed r , and facility type b , S_r is the indicator function for the stepwise function, R is a set of speed increments, $L_b(i)$ is the indicator function for whether or not link i is of type b (i.e., $type(i) = b$), and B is the set of all link types.

Equation (4) illustrates the relationship between average speed, s , vehicle flow, v , and added practical capacity, y .

$$s_i(v_i, y_i) = \left\{ \frac{l_i}{t_i^0 \left[1 + \alpha_i \left(\frac{v_i}{c_i + y_i} \right)^{\beta_i} \right]} \right\} \quad (4)$$

Where, s is average vehicle speed (miles per hour), l is link length (miles), t^0 is free flow travel time (minutes), c is original practical capacity (vehicles per hour), y is added capacity (vehicles per hour), α and β are link specific parameters that can vary based on facility type, and i is the link index.

Equations (3) and (4) connect the upper level objective function with the lower level objective function through the travel time on each link, which is determined by link flow and added capacity per link. Travel time is defined by the U.S. Bureau of Public Roads link performance function shown as equation (5) below.

$$t_i(v_i, y_i) = t_i^0 \left[1 + \alpha_i \left(\frac{v_i}{c_i + y_i} \right)^{\beta_i} \right] \quad (5)$$

Where, t is travel time (minutes), t^0 is free flow travel time (minutes), c is original practical capacity (vehicles per hour), y is added capacity (vehicles per hour), α and β are link specific parameters that can vary based on facility type, and i is the link index. We assume adding practical capacity to a link will influence the travel time on the link, but will not influence the link's free flow travel time.

The lower level objective function is shown in equation (6). It enforces user-equilibrium route choice. User-equilibrium was first stated by Wardrop (1952) and is paraphrased in the following two sentences. User-equilibrium route choice assigns vehicles to routes such that users experience minimal and equivalent travel time per origin-destination pair. As a result, no user can unilaterally switch routes and reduce his or her travel time.

$$\text{Minimize } f_{UE}(v, y) = \sum_{i \in I} \int_{x=0}^{v_i} t_i(x, y_i) dx \quad (6)$$

Where, t is travel time (minutes), v is vehicle flow (vehicles per hour), y is added practical capacity (vehicles per hour), and i is the link index.

The constraints on the upper level objective function are shown in equation (7) and (8). One of the problem constraints is a budget constraint. The budget constraint limits the amount of capacity (vehicles per hour) that can be added to the network. This constraint can be modified and additional related constraints can be added to reflect more complex fiscal constraints depending on an agency's needs. The budget constraint used in this research is shown in equation (7).

$$\sum_{i \in I} y_i \leq \psi \quad (7)$$

Where, y is the practical capacity added, ψ is the available capacity budget, and i is the link index.

Equation (8) is the non-negativity constraint to ensure added practical capacity, y , is either zero or a positive value for each link.

$$y_i \geq 0 \quad \forall i \in I \quad (8)$$

Where, y is the added practical capacity and i is the link index.

The constraints on the lower level objective function are shown in equation (9). Equation (9) illustrates the flow conservation between vehicle link flows, vehicle path flows, and the origin-destination demand. The flow conservation constraints ensure vehicles are not randomly created or lost within the network. Equation (9) also illustrates the non-negativity constraint for vehicle flow.

$$V = \{v \mid v = Ph, d = Gh, v \geq 0\} \quad (9)$$

Where, V is the set of feasible vectors of vehicle flows, v is the vector of vehicle flows on each link, P is a link-path incidence matrix, h is the vector of vehicle flow per path, and G is an origin destination trip-path incidence matrix.

Demand uncertainty was incorporated into the problem by modifying the upper-level objective function to minimize the expected value of total system travel time, VOC system emissions, NOx system emissions, and CO system emissions. The expected value is created through external, random samples of demand values over the range of a pre-specified uncertainty (e.g., +/- 15%). The sample demand values are used to solve the lower level objective function (i.e., user-equilibrium) and then calculate the network performance measures (i.e., total travel time, total VOC emissions, total NOx emissions and total CO emissions). Over the course of a pre-specified number of samples (i.e., realizations), this creates an approximation of expected total travel time, expected total VOC emissions, expected total NOx emissions and expected total CO emissions.

The expected value for total travel time is defined in equation (10).

$$Ef_{TSTT}(y, \tilde{d}) = \overline{f_{TSTT}}(y) + \varepsilon \quad (10)$$

Where, $Ef_{TSTT}(y, \tilde{d})$ is the expected value of total system travel time, $\overline{f_{TSTT}}(y)$ is the sample average, $\tilde{d}$ is a matrix of uncertain demands, y is added practical capacity, and ε is sampling error.

The general form of the expected value for total VOC, NOx, and CO system emissions is defined in equation (11).

$$Ef_{SE,a}(y, \tilde{d}) = \overline{f_{SE,a}}(y) + \varepsilon \quad (11)$$

Where, $Ef_{SE,a}(y, \tilde{d})$ is the expected value of total system emissions for pollutant a , $\overline{f_{SE,a}}(y)$ is the sample average for pollutant a , $\tilde{d}$ is a matrix of uncertain demands, y is added practical capacity, and ε is sampling error.

Therefore, when incorporating demand uncertainty and designing for minimal system travel time, the upper-level objective function is to minimize equation (10). Similarly, when incorporating demand uncertainty and designing for a minimal air pollutant, the upper-level objective function is to minimize equation (11). In this research, the distribution function of $\tilde{d}$, $\Phi \tilde{d}$, is a uniform distribution.

To apply the above formulations it is necessary to have an origin-destination demand table (or a distribution of an origin-destination table) as well as information on the road network topology and characteristics including link length, free flow travel time (or free flow speed), original practical capacity per link, and α and β parameters per link. Emissions factors as a function of speed are also needed. The development of these factors is discussed in the following sub-section.

Emissions Calculations

As discussed above as well as, in chapters 1 and 2, three pollutants are considered within this research. These pollutants are hydrocarbons also known as volatile organic compounds (VOC), nitrogen oxides (NO_x), and carbon monoxide (CO). The pollutants are incorporated in the problem formulation in the upper level objective function as a step-wise emission function that varies based on average vehicle speed per link. Each pollutant has its own unique step-wise function. These functions were created from emissions factors developed using the Environmental Protection Agency's (EPA) software program MOBILE6.2. Figures 2 through 4 in Chapter 2 illustrate how the emissions factors developed for arterial roadways in Anaheim, California change with average vehicle speed. The following sub-sections discuss: 1) MOBILE6.2, specifically what it is, how it is used, and why it was chosen as the emissions model; and 2) the specific inputs used to develop the emissions factors for this research.

MOBILE6.2: What, How and Why?

MOBILE6.2 is a software program produced by the EPA; it estimates emission factors as grams per mile per vehicle for fuel and diesel highway vehicles. MOBILE6.2 has been used widely in practice and research for such things as EPA's evaluation of mobile emissions source control strategies and state, local, and metropolitan planning organization (MPO) - level planning to control or reduce vehicle emissions for a region (EPA, 2003). The program has the ability to calculate emissions rates for 28 different types of vehicles that span the calendar year from 1952 forward to 2050. MOBILE6.2 calculates emissions factors for the following air pollutants: volatile organic compounds, carbon monoxide, nitrogen oxides, particulate matter, sulfur dioxide, ammonia, six hazardous air toxins, and carbon dioxide. As noted in Chapter 1, in this research, VOC, NO_x, and CO were selected to incorporate into the problem formulation, because of the severe health and environmental implications associated with them, as well as their classification as criteria pollutants under the Clean Air Act, and/or their contribution to creating criteria pollutants listed under the Clear Air Act.

To calculate emissions factors for the various pollutants listed above, the MOBILE6.2 works from a basic emission rate and applies correction factors determined by analysts' inputs regarding vehicle operating conditions. The basic emissions rates and the correction factors are based on research conducted by the EPA (see the technical papers posted at <http://www.epa.gov/otaq/models.htm> for the specific calculation procedures embedded within MOBILE6.2). Basic emission rates are developed from emissions tests conducted under a standard set of conditions with regards to temperature, fuel, driving cycle, and other related operating conditions. Correction factors are applied when conditions differ from the standard set under which the basic emissions rates were developed.

There are 27 different input parameters for which analysts are responsible for providing data or values (in the absence of data, default values are used; default values are based on EPA's national data). The input parameters address context specific characteristics (e.g., calendar year, month, minimum and maximum temperature, altitude), vehicle or vehicle fleet related characteristics (e.g., fuel type, vehicle type, vehicle inspection/maintenance programs), and operating characteristics (e.g., average vehicle speed, road facility type). Adjustments to the basic emission factors are made depending on which (if any) of the characteristics vary from the standard testing conditions. For the research presented in this research, the most significant of these characteristics are average vehicle speed, facility type, temperature, and humidity. For more in-depth information on MOBILE6.2's structure and how to use it please refer to the EPA's *User's Guide to MOBILE6.1 and MOBILE6.2* (see EPA, 2003).

As noted above, MOBILE6.2 has been widely used by the EPA, state transportation departments, metropolitan planning organizations, local agencies, and research institutions. This is one of the primary reasons it was selected as the tool to use to develop emissions factors for this research. The other substantial reason MOBILE6.2 was selected to serve as the emissions model is, at the time the emissions factors for this research were developed (early fall of 2009), it was the most current, EPA approved software for vehicle emissions modeling. There was a draft version of EPA's update to MOBILE6.2 that had been under development since 2004; however, that version was still under going testing. The updated version was officially released for use in January 2010; it is called MOVES2010 (Motor Vehicle Emission Simulator 2010) (EPA, 2010).

The most substantial differences between MOBILE6.2 and MOVES2010 do not influence the methodology presented in this paper nor do they influence the results and trends discussed in chapters 4 and 5. The methodology, results, and trends discussed in

this paper remain valid. The most significant gain made with MOVES2010 software in modeling emissions (as compared to MOBILE6.2) is the ability to use acceleration and deceleration data to calculate emissions more precisely (as opposed to using average vehicle speed) (EPA, 2009e). However, the research presented here is at the macroscopic model level, therefore the most refined speed data available is average speed, so MOBILE6.2 remains an appropriate emissions modeling tool. The ability of MOVES2010 to model the effects of acceleration and deceleration on emissions will be beneficial for future planned research expanding the emissions network design problem discussed in this paper to a dynamic context (see Chapter 5 for further discussion of future work).

Specific Inputs for Developing the Emissions Factors for the Test Networks

Emissions factors were developed for the two test network cities: Sioux Falls, ND and Anaheim, CA. Data was not available regarding vehicle or vehicle fleet characteristics specific to these two cities, therefore the EPA default values based on national data were used for inputs such as fuel type, vehicle fleet mix, and inspection/maintenance programs. Data and information was available to provide context (i.e., environment) and operating characteristics specific to each city. Table 1 summarizes the characteristics modified to fit each city and the corresponding input values used.

Table 1. Key Inputs Used to Develop Emissions Factors

Input Parameter	Sioux Falls	Anaheim
Calendar Year	2030	2030
Month	July	July
Minimum Temperature (°F)	60	62
Maximum Temperature (°F)	86	84
Absolute Humidity (grains water/lb of dry air)	95	114
Altitude (Low or High)	Low	Low

Using the inputs in Table 1, emissions factors were calculated for average vehicle speed of 2.5 mph up to 65 mph (these are the limits of MOBILE6.2) at 1 mph increments for vehicles operating on arterial roadways and freeways. The resulting composite vehicle emissions factors form the functions used in the upper-level objective function to capture system emissions. One set of these factors is plotted in Figures 2 through 4 (see Chapter 2). There are two sets of functions, one for arterial roadways and one for freeways, for each pollutant type (six functions per city). The calendar year was set to 2030 to mirror a 20-year planning horizon (this influences the vehicle fleet mix MOBILE6.2 uses in its calculations). The minimum and maximum temperatures per city and absolute humidity values are based on historic averages for each city in the month of July; such information is available online at: <http://www.weather.com>.

SOLUTION METHODOLOGY

Network design problems are complex and have consistently been computationally challenging to solve since such problems entered transportation research (Yang and Bell, 1998; Magnanti and Wong, 1984). Early solution methods included a variety of tried and proven network optimization techniques (e.g., branch and bound algorithms), simplifying assumptions to reduce problem complexity, and heuristic algorithms. As research related to transportation network design problems progressed, heuristic algorithms and meta-heuristics solution methods became more prominent; particularly as, additional complexities like bi-level formulations and incorporating demand uncertainty began to be applied. The proposed emissions network design problem discussed in this paper is solved using a genetic algorithm, which is a meta-heuristic algorithm. The following sub-sections discuss the evolution of solution methods used to solve network design problems, the methods considered for the problem

presented in this paper, and the actual solution method used to solve the proposed emissions network design problem.

Evolution of Network Design Problem Solution Methods

Solution methods for single-level network design problems tend to fall into one of three general categories: 1) tried and proven techniques from related optimization problems; 2) simplifying assumptions to form linear, mixed integer or other related problem formations; and 3) heuristic algorithms. The use of Benders decomposition algorithm, branch and bound algorithms, and branch and backtrack algorithms are cited as solution methods in a number of papers in the late 1960's through 1970's (Abdulaal and LeBlanc, 1979; Magnanti and Wong, 1984). Some researchers used simplifying assumptions such as the absence of congestion, which enabled cost functions (i.e., travel time) to be modeled as linear functions. Approximating the cost functions as linear made it feasible to solve the problems using the Frank-Wolfe algorithm (LeBlanc and Abdulaal, 1984). Other assumptions related to directed versus undirected arcs, demand, and number of origins were used to modify network design problems to appear similar to other related network optimization problems (e.g., traveling salesman problem or vehicle routing) (Magnanti and Wong, 1984). Such assumptions were found advantageous in offering more efficient solution methodologies. Heuristic solution methods were also emerging in the 1960's and 1970's; these tended to be iterative solution processes in which network capacity values were temporarily fixed with a feedback loop calculating the resulting system optimal flows (Abdulaal and LeBlanc, 1979; Magnanti and Wong, 1984).

Formulating the network design problem as a bi-level programming problem added more complexity to solving the problem efficiently. In general, network design problems that are formulated as a bi-level programming problems and account for

network congestion are non-convex, which makes it difficult to find a globally optimal solution (Yang and Bell, 1998). Three heuristic algorithms commonly cited in the late 1980's and in the 1990's are Iterative-Optimization-Assignment (IOA) algorithm, Link Usage Proportion-Based (LUPB) algorithm, and Sensitivity Analysis-Based (SAB) algorithm (Yang and Bell, 1998). Each of these algorithms takes an iterative approach to solving the bi-level program by solving the upper level problem, solving the lower level problem, adjusting the solution found by an influence factor and repeating. This basic approach is also seen in the meta-heuristics apparent in recent research related to network design problems; this includes the meta-heuristic used to solve the proposed emissions network design problem.

Solution Methods Considered to Solve Emissions Network Design Problem

Meta-heuristics such as random search (RS), simulated annealing (SA), and genetic algorithms (GA) are appropriate for NP-hard, non-convex optimization problems, such as bi-level network design problems. These three meta-heuristics tend to be desirable solution methods to consider for bi-level network design problems that have multiple origins and destinations and will be applied to relatively large networks. The reason for this is because each of the above meta-heuristics is capable of producing solutions beyond local optima making it possible to achieve solutions more closely approximating the globally optimal solution (Karoonsoontawong and Waller, 2006). These three meta-heuristics are reasonable potential solution methods for the proposed emissions network design problem, because the emissions network design problem is a bi-level problem that will be applied to relatively large networks with multiple origins and destinations.

The genetic algorithm (GA) was chosen to solve the proposed emissions network design problem; this decision was based on three related factors. First, GA takes

advantage of existing neighborhood effects when searching for a solution, which in this problem means considering link improvements (i.e., capacity additions) similar to those that have been shown to perform well in previous iterations. Second, findings by Karoonsoontawong and Waller (2006) found GA to outperform SA and RS solution algorithms in solving continuous network design problems. GA outperformed SA and RS in terms of solution quality, convergence, speed and process time (Karoonsoontawong and Waller, 2006). Finally, there are plans to expand this research to consider the emissions network design problem in a dynamic context, which is the context in which Karoonsoontawong and Waller (2006) conducted their research.

Solution Method Used to Solve Emissions Network Design Problem

The concept behind GA is Darwin's theory of evolution: survival of the fittest. The basic components of GA are chromosomes, populations, generations, fitness values, selection, mutation, and crossover. Chromosomes are binary number strings representing problem solutions. In the instance of the emissions network design problem, chromosomes represent the amount of capacity (if any) to add to each network link eligible for improvement. Within a single chromosome are sub-strings, each sub-string represents a link in the network that is eligible to receive additional capacity. A population is a set of chromosomes within the same generation. Therefore, for a single generation you have a set of possible solutions (the set is the "population", the solutions within that set are "chromosomes"). The fitness value is equivalent to the objective function value for a given solution; therefore, a fitness value is calculated for each chromosome string (i.e., problem solution). Selection is the process in which the "best-fitting" chromosomes (or solutions) from each population are selected to serve as a "parent" for the following generation. Crossover is the step in which the "parent" chromosomes from the previous generation are paired and combined to create two new

“child” chromosomes. Mutation is when each gene (i.e., sub-string) within each chromosome is mutated; this facilitates the search for finding similar well-fitting solutions (i.e., accounts for neighborhood effects). See Holland (1975) and Goldberg (1989) for a comprehensive discussion of GA.

Below are the steps of the GA as applied to solve the emissions network design problem formulation previously presented in the sub-section titled Emissions Network Design Problem Formulation.

Step 1: Initialize population: Set the index for the current generation to $n=1$. Randomly set each gene in each of the chromosomes to zero or one. This first set of chromosomes represents the initial population, pop_1 .

Step 2: Demand sampling (to account for demand uncertainty): Randomly sample demand values based on a specified uncertainty. Solve user-equilibrium and calculate performance measures (i.e., total system travel time, VOC system emissions, NOx system emissions, and CO system emissions) for each chromosome and each realization of demand.

Step 3: Calculate objective functions: Calculate the expected value per performance measure for each chromosome in pop_n . Check for convergence (i.e., if $n=n_{max}$). If convergence is not reached, go to Step 4.

Step 4: S-tournament selection: For each group (i.e., tournament) of s chromosomes, keep the best chromosome as a parent for generation $n+1$.

Step 5: Crossover: Let $n=n+1$. Generate K uniform(0,1) random numbers for each pair of “parent” chromosomes. If the kth random number is less than the probability of crossover, p_c , perform a uniform crossover operation on the kth sub-strings in the pair to create two new “child” chromosomes. The set of children chromosomes is pop_n .

Step 6: Mutation: Mutate each gene of each chromosome in pop_n with probability P_m .

Step 7: Convergence: Check for convergence. If convergence is not reached, go to Step 2.

One parameter within GA was varied when the solution method was applied to the emissions network design problem. This parameter is the number of generations. The specific values used for each of the GA parameters when solving the emissions network design problem are discussed in Chapter 4: Numerical Analyses.

SUMMARY

The emissions network design problem is formulated as a bi-level optimization problem solved using a genetic algorithm. The bi-level formulation captures the leader-follower behavior present in transportation system management and performance. The genetic algorithm solution method is most suitable due to the complexity of the problem (e.g., multiple origin – destination pairs, incorporating demand uncertainty). The genetic algorithm also has the ability to find solutions beyond local optima, account for neighborhood effects, and out performs its peer solution methods. Pollutant emissions are accounted for by integrating a step-wise function into the upper-level objective function. The pollutant functions are based on emissions factors that vary with average speed and operating conditions (e.g., temperature, humidity). EPA's MOBILE6.2 software program was used to generate the emission factor functions.

The following chapter presents and discusses the numerical results of applying the proposed formulation and solution method to two test networks: Sioux Falls, ND and Anaheim, CA.

Chapter 4: Numerical Analyses

CONTEXT FOR ANALYSES

The proposed emissions network design model was applied to two test networks (i.e., Sioux Falls, ND and Anaheim, CA) to demonstrate the model and explore the differences between designing for minimal total travel time and minimal system vehicle emissions. The emissions network design model was applied to both networks with fixed demand; the model was then applied to the Sioux Falls network incorporating demand uncertainty. The numerical analyses considered the potential effects of adding smaller versus larger increments of capacity to road network links eligible for improvement. The analyses also included applying the model to the test networks under congested and uncongested conditions. The budget constraint was also varied to look at the effect of increasing the available budget on the solutions produced by the model. Finally, the influence of increasing demand uncertainty was explored.

Results from the numerical analyses indicate designing to minimize network congestion (i.e., total travel time) does not guarantee the design minimizes VOC, NO_x or CO system emissions. Furthermore, designing to minimize emissions of one air pollutant does not guarantee emissions of other air pollutants are minimal. It's also demonstrated that demand uncertainty significantly influences system performance with respect to total travel time and system emissions of each pollutant. Solutions found in this analysis also indicate increasing the available budget and spending more resources does not guarantee proportional decreases in the objectives (e.g., total travel time, NO_x system emissions). Finally, analysis results indicate there are differences in the types of improvements selected to minimize total travel time versus the types of improvements selected to minimize certain air pollutants. The following sections present the analysis scenarios,

solution method parameters used in the analysis scenarios and the corresponding effectiveness of the solution method, the analysis results, and a chapter summary.

ANALYSIS SCENARIOS

As noted, a number of analysis scenarios were run to investigate the influence of: 1) adding smaller increments of capacity versus larger increments of capacity to a network; 2) increasing demand (i.e., congestion) on the network; 3) increasing the available budget; 4) increasing the number of road links eligible for improvement; and 5) increasing demand uncertainty. The scenarios tested on the Sioux Falls network are summarized in Table 2. The scenarios tested on the Anaheim network are summarized in Table 3.

Table 2. Analysis Scenarios Tested on the Sioux Falls Network

Scenario Attributes		Sioux Falls with Fixed Demand			Sioux Falls with Demand Uncertainty
		Fixed Congestion, Vary Budget	Fixed Congestion, Vary Budget	Fixed Budget, Vary Congestion	Fixed Base Congestion, Fixed Budget, Vary Uncertainty
% of OD Table on Network (Base Congestion)		100%	100%	25%, 50%, 75%, 100%, 125%, 150%, 175%, 200%	100%
Budget Constraint (1,000 veh/hr)		3.6, 9, 18, 27, 36	3.6, 9, 18, 27, 36	18	18
Capacity Increments Added To	Arterial Roadways (veh/hr)	300	1800	1800	1800
	Freeways (veh/hr)	1800	1800	1800	1800
% Network Eligible for Improvement		94.7%	94.7%	94.7%	94.7%
Demand Uncertainty		0.00%	0.00%	0.00%	10%, 15%, 20%, 25%, 30%, 35%, 40%

Table 3. Analysis Scenarios Tested on the Anaheim Network

Scenario Attributes	Anaheim with Fixed Demand		
	Fixed Congestion, Vary Budget	Fixed Budget, Vary Congestion	Increase Eligible Links
% of OD Table on Network (Base Congestion)	200%	150%, 175%, 200%, 225%, 250%, 275%	200%
Budget Constraint (1,000 veh/hr)	18, 36, 54, 72	72	72
Capacity Increments Added to Arterial Roadways (veh/hr)	1800	1800	1800
Capacity Increments Added to Freeways (veh/hr)	1800	1800	1800
% Network Eligible for Improvement	4.36%	4.36%	10.92%
Demand Uncertainty	0.00%	0.00%	0.00%

In total, eighteen analysis scenarios were run for the Sioux Falls network with fixed demand, eleven analysis scenarios were run for the Anaheim network with fixed demand, and seven analysis scenarios were run for the Sioux Falls network with demand uncertainty. The following paragraphs discuss the reasoning for the attribute (e.g., budget, eligible links) values that define the scenarios in Table 2 and Table 3.

The ranges for the percent of the origin-destination (OD) demand table loaded on the network were determined based on the percent of network links with volume-to-capacity ratios greater than or equal to 1.00 in the “do-nothing” analysis scenario. Therefore, the ranges for the percent of the OD demand table loaded on the network creates a full range of uncongested through congested base network conditions. The percentage values for the OD demand loaded on the Anaheim network are higher than the Sioux Falls network, because the original base OD demand table for Anaheim has a lower level of congestion than the Sioux Falls base OD demand table.

The budget ranges were established such that each range creates analysis runs in which very few improvements can be made and extends to analysis runs in which nearly all eligible links could be improved. The purpose of developing the budget range in this manner is to identify the influence of additional budget on the model's ability to further optimize system performance measures (e.g., NO_x system emissions).

The percent of links in the network eligible for improvement are based primarily on network size and corresponding run time to execute the solution method. Larger networks such as Anaheim take considerably longer to run due to the increased number of possible solutions; therefore, the percent of eligible links was kept smaller to keep the run time manageable.

The effect of adding smaller increments of capacity was explored using increments of 300 vehicles/hour for arterial roadways; this value was selected as a means to approximate additional capacity due to improved signal timing. The larger increment of capacity (1800 vehicles/hour) is a conservative value for approximating the capacity gained by adding a travel lane to a road link. The purpose of this analysis was to consider if adding smaller increments of capacity enabled the model to better optimize system performance measures than adding larger increments of capacity. For example, it considers the question: is it more advantageous to add smaller amounts of capacity throughout many links on the network or add larger amounts of capacity to only a few links on the network?

The following section discusses the solution method parameter values used and the corresponding effectiveness of the solution method in evaluating the analysis scenarios above. The subsequent section presents key analysis results.

SOLUTION METHOD PARAMETER VALUES USED AND EFFECTIVENESS

As discussed in Chapter 3, a genetic algorithm (GA) was used to solve the emissions network design problem. GA was applied because of its past performance effectively solving bi-level optimization problems with multiple origins and destinations. There are a number of GA parameters that need to be set when applying it to solve an optimization problem. In applying GA to solve the emission network design problem, many of the parameter values remained fixed with one that varied depending on the analysis scenario. The GA parameters that remained fixed or consistent across all analysis scenarios within this research are: 1) the cross-over probability; 2) the type of cross-over; 3) the mutation probability; 4) GA population size, and 5) number of realizations (when demand uncertainty is considered). In applying GA to solve the emissions network design model, the cross-over probability was set to 0.8, the cross-over type was uniform cross-over, the mutation probability was 0.01, the GA population was set to 100, and the number of realizations used was 50. The only parameter varied based on the analysis scenario was the number of generations. In applying the emissions network design model, the number of generations used for the analysis scenarios with fixed demand was 35, 40, 45 or 60 generations. The number of generations used for the scenarios including demand uncertainty was 30 generations.

The number of generations used for the scenarios with fixed demand changed based on the scenario's attributes and the corresponding convergence of the fitness values (i.e., objective values). A sufficient level of convergence was defined as when the change in each objective value over the last 10 generations is less than 0.25%. Analysis scenarios that were run with more generations were those at the higher end of the available budget range, the higher end of the demand range (i.e., base congestion range) and/or had a higher number of links eligible for improvement. This was done to ensure

solution convergence for scenarios likely to encounter more feasible solutions due to relaxed constraints (e.g., increasing the available budget, increasing number of links eligible for improvement). The following figures and paragraphs illustrate and discuss the solution convergence for each air pollutant objective in a sampling of analysis scenarios. In general, the objectives for each scenario tended to converge in 20 to 45 generations.

Figures 5, 6, and 7 illustrate the convergence of system VOC emissions, system NOx emissions, and system CO emissions for the Sioux Falls moderately congested network with fixed demand, a budget constraint of 18,000 vehicles/hour, and 94.7% of network links eligible for improvement.

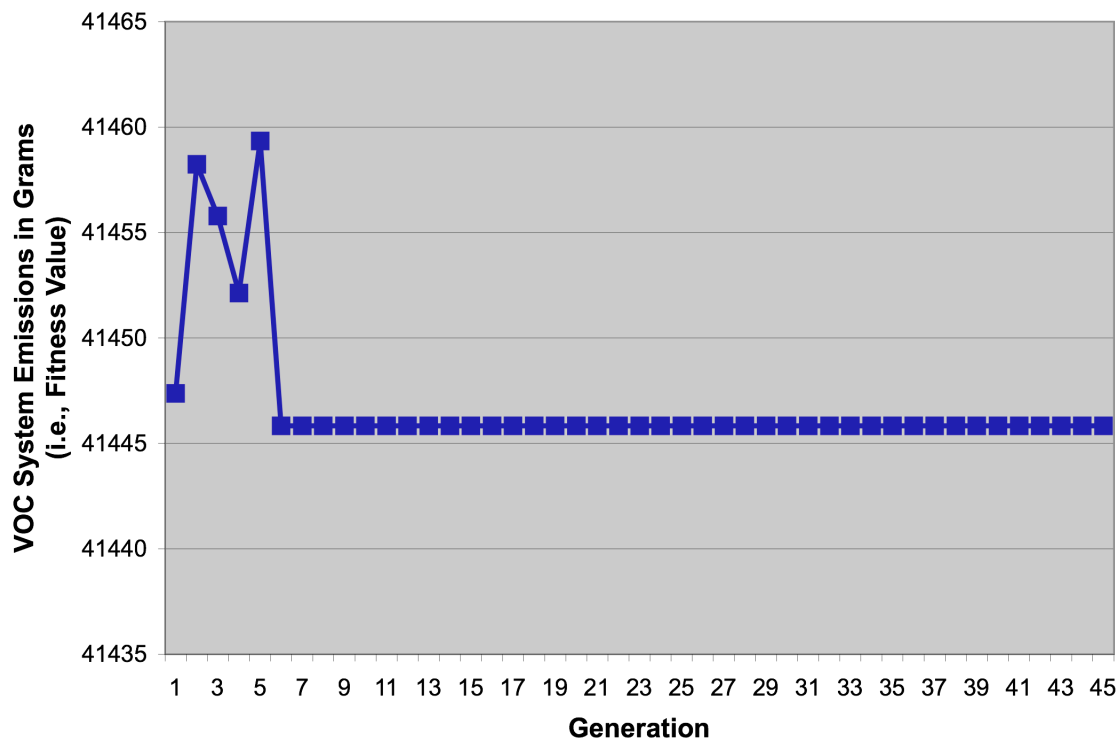


Figure 5. VOC System Emissions Convergence for Sioux Falls network with Fixed Demand

As can be seen in Figure 5, VOC system emissions appears to converge after approximately six generations for the fixed demand scenario on the Sioux Falls network. The relatively quick convergence for VOC system emissions tends to be consistent across the analysis scenarios for the Sioux Falls and Anaheim networks. Exceptions where convergence of the VOC system emissions objective took slightly longer tended to be scenarios with larger budgets, increased demand or demand uncertainty.

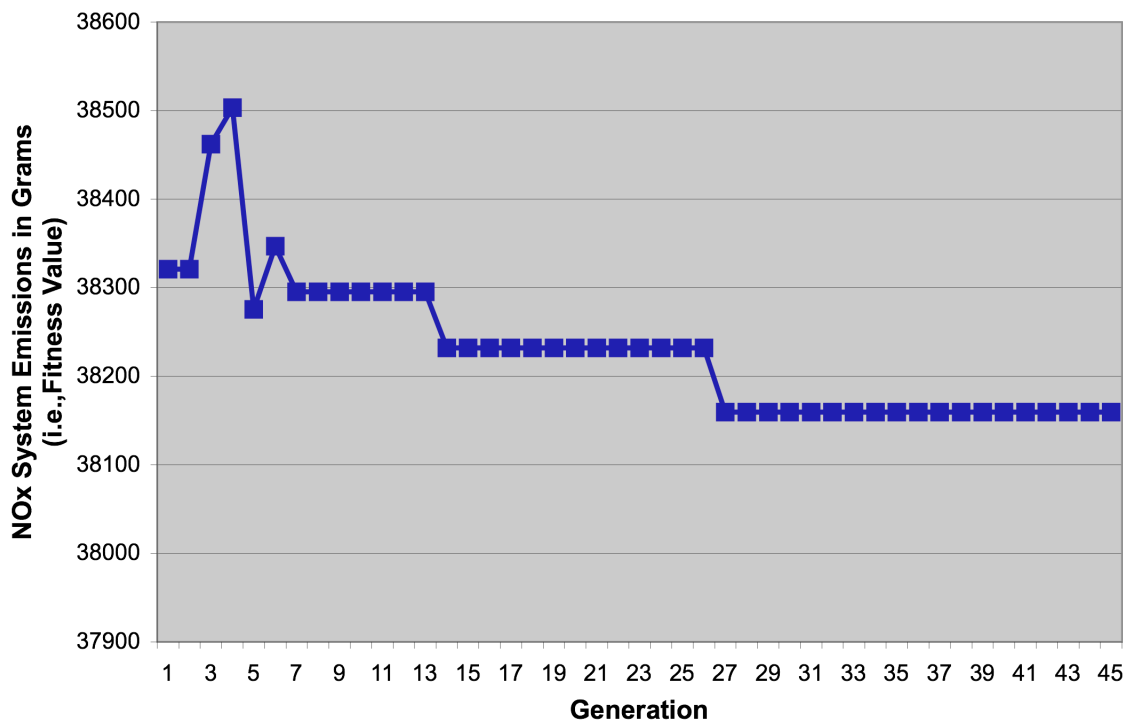


Figure 6. NOx System Emissions Convergence for Sioux Falls Network with Fixed Demand

As can be seen in Figure 6, NOx system emissions appears to converge after approximately 26 generations for the fixed demand scenario on the Sioux Falls network. Convergence for NOx system emissions tends to be 25 to 30 generations consistently across the analysis scenarios for the Sioux Falls and Anaheim networks.

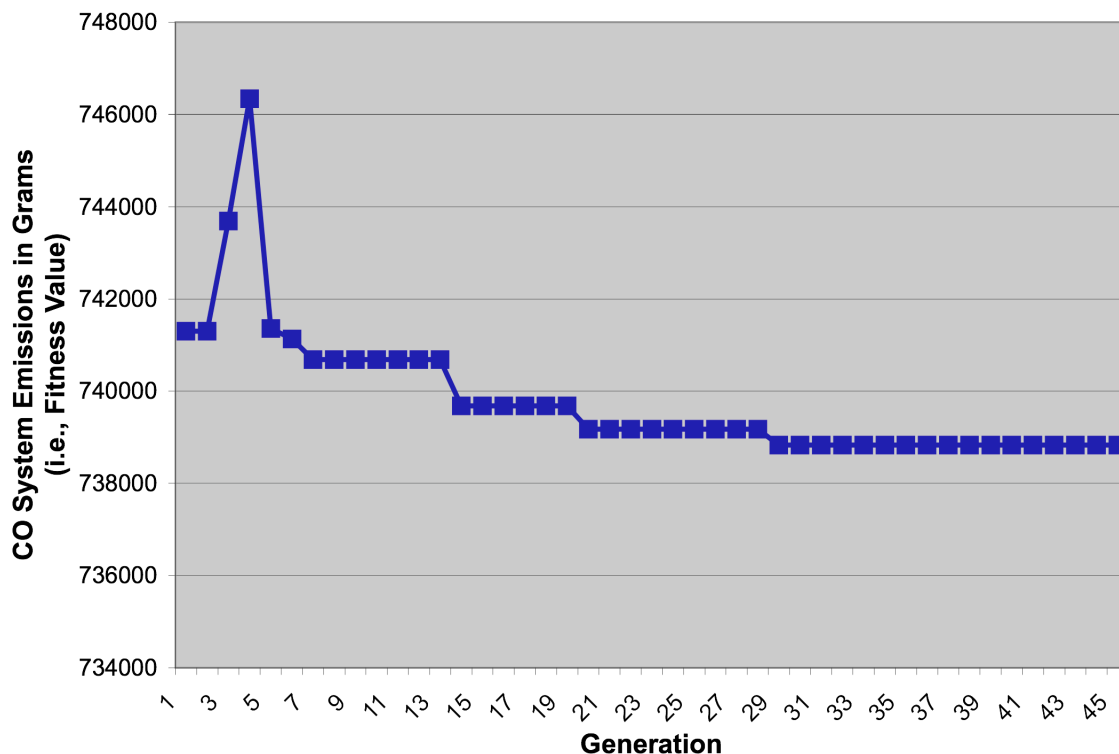


Figure 7. CO System Emissions Convergence for Sioux Falls Network with Fixed Demand

Figure 7 illustrates CO system emissions appears to converge after approximately 30 generations for the fixed demand scenario on the Sioux Falls network. Similar to NOx system emissions, convergence for CO system emissions tends to be 25 to 30 generations consistently across the analysis scenarios for the Sioux Falls and Anaheim networks.

Figures 5 through 7 illustrate system emissions for each air pollutant changes minimally or not at all after generation 30. This is consistent across each of the Sioux Falls network analysis scenarios with fixed demand even as base congestion on the network and the available budget increase.

Figures 8, 9, and 10 illustrate the convergence of system VOC emissions, system NOx emissions, and system CO emissions for the Anaheim moderately congested

network with fixed demand, a budget of 72,000 vehicles/hour, and 4.36% of network links eligible for improvement.

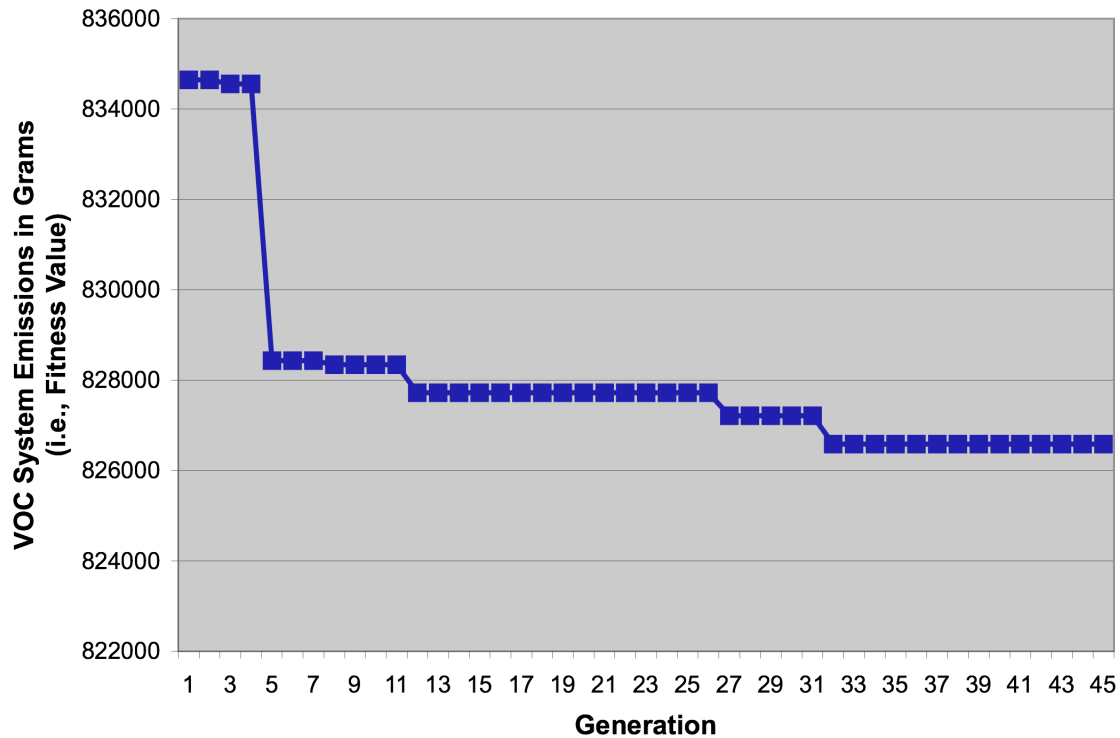


Figure 8. VOC System Emissions Convergence for Anaheim Network with Fixed Demand

Figure 8 illustrates VOC system emissions converges at approximately 32 generations for the fixed demand scenario on the Anaheim network. The time to convergence for VOC system emissions on the Anaheim network tended to be longer compared to Sioux Falls network. This is likely due to the fact the Anaheim network is larger with 916 links compared to Sioux Falls at 76 links.

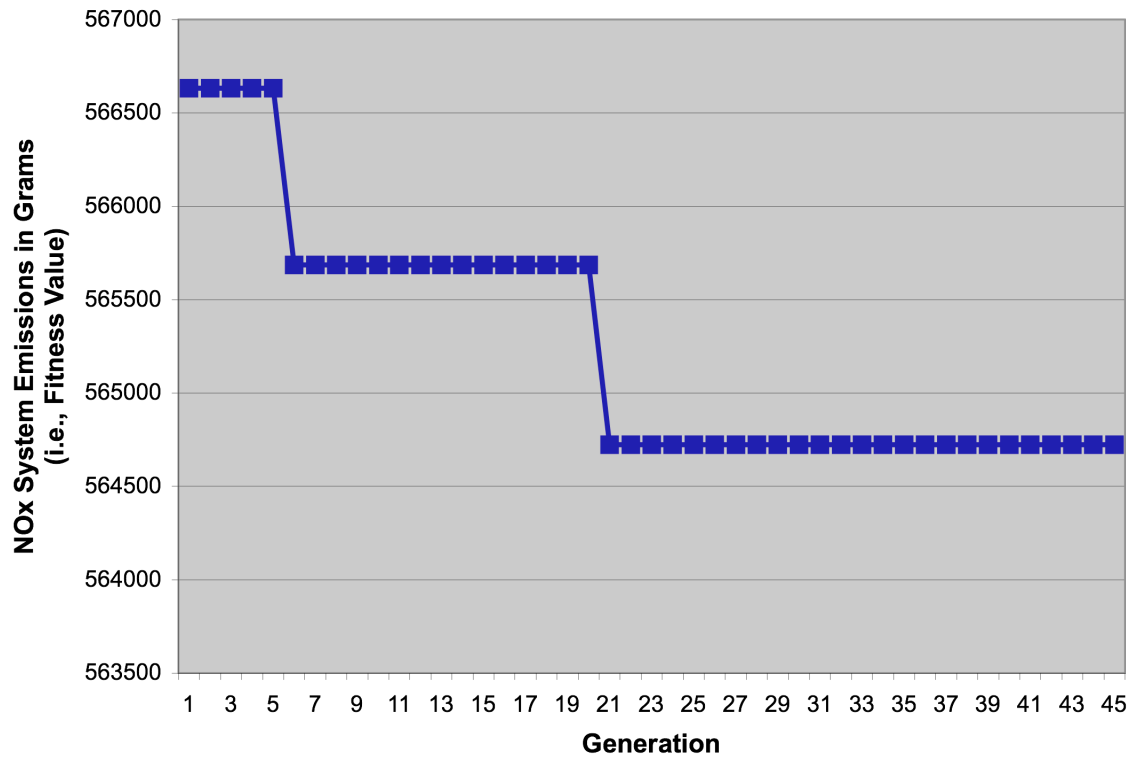


Figure 9. NOx System Emissions Convergence for Anaheim Network with Fixed Demand

Figure 9 demonstrates that NOx system emissions converges at approximately 20 generations for the fixed demand scenario on the Anaheim network. Despite the Anaheim network's larger size, the time to convergence shown above is similar to the time to convergence for NOx system emissions on the Sioux Falls network.

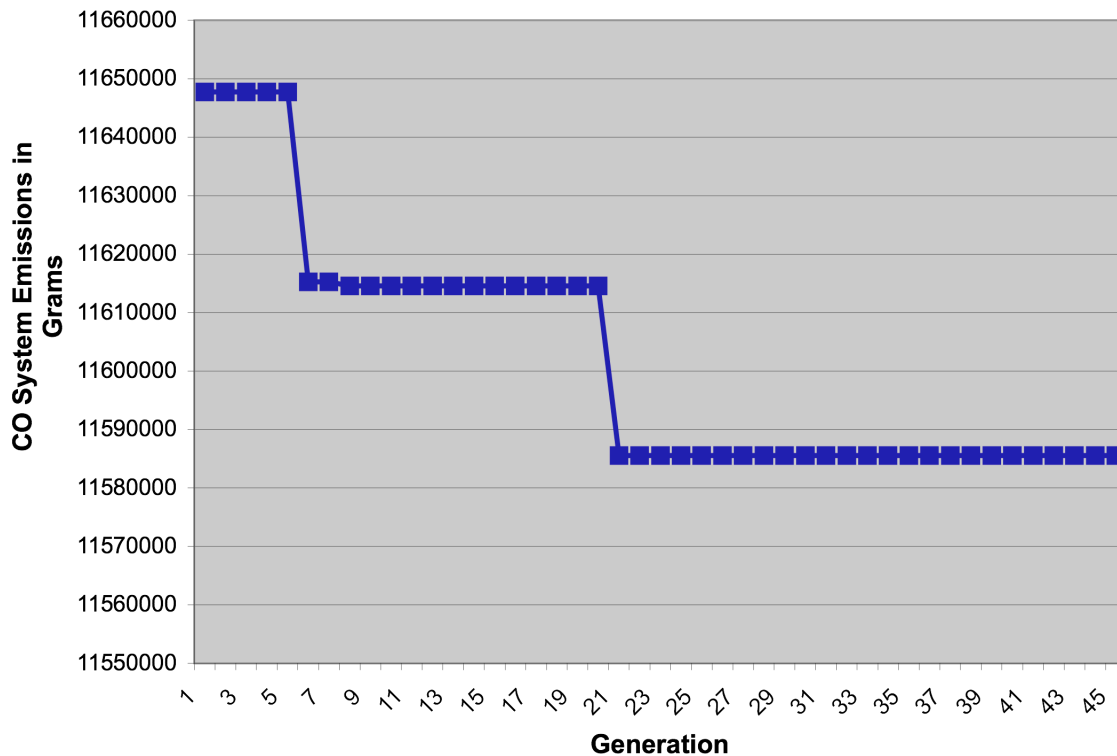


Figure 10. CO System Emissions Convergence for Anaheim Network with Fixed Demand

Figure 10 demonstrates that CO system emissions converges at approximately 21 generations for the fixed demand scenario on the Anaheim network. Despite the Anaheim network’s larger size, the time to convergence shown above is similar to the time to convergence for CO system emissions on the Sioux Falls network.

As illustrated in figures 8 through 10, each objective value changes minimally or not at all after generation 32. This is consistent across each of the Anaheim network with fixed demand analysis scenarios even as base congestion on the network and the available budget increase.

To explore the influence of increasing the number of links eligible for improvement within a network, the number of links eligible on the Anaheim network was

increased from 40 to 100 links (4.36% of network links to 10.92% of network links). In this instance, the number of generations was increased to 60 generations to ensure solution convergence. Figures 11, 12, and 13 illustrate the time to convergence for VOC system emissions, NOx system emissions, and CO system emissions for the Anaheim network with fixed demand, moderately congested conditions, a budget of 72,000 vehicles/hour, and 10.92% of network links eligible for improvement.

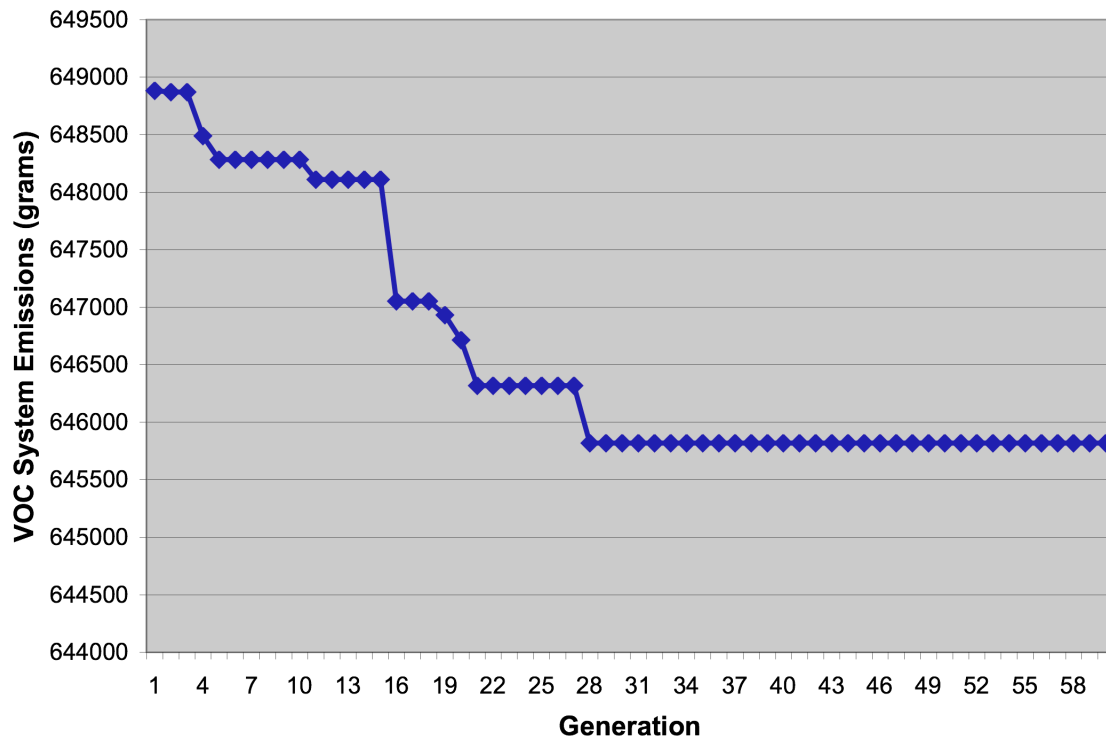


Figure 11. VOC System Emissions Convergence for Anaheim Network with Fixed Demand and 10.92% of Network Links Eligible for Improvement

Figure 11 demonstrates the time to convergence for VOC system emissions appears is approximately 27 generations for the fixed demand scenario with a higher percent of links eligible for improvement. The time to convergence for VOC system emissions under this analysis scenario is similar to the time to convergence on the

Anaheim network with fewer links eligible for improvement (27 generations versus 32 generations). In the case designing for minimal VOC system emissions, increasing the number of eligible links by 6% does not appear to greatly influence the time to convergence.

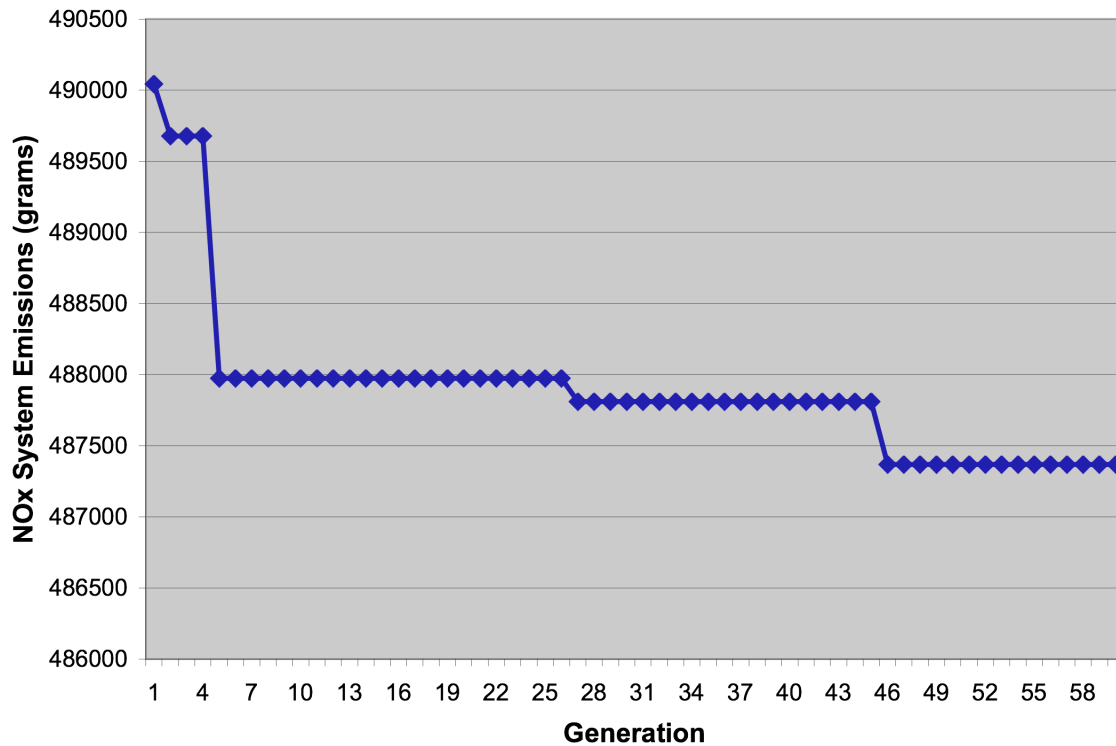


Figure 12. NOx System Emissions Convergence for Anaheim Network with Fixed Demand and 10.92% of Network Links Eligible for Improvement

Figure 12 illustrates that NOx system emissions converge at approximately 45 generations for the fixed demand scenario with a higher percent of links eligible for improvement. The time to convergence for NOx system emissions under this analysis scenario is noticeably larger than its time to convergence on the Anaheim network with fewer links eligible for improvement. The scenario with 100 eligible links took approximately 25 more generations to converge than the scenario with 40 eligible links.

Unlike VOC system emissions, in the case designing for minimal NOx system emissions, increasing the number of eligible links by 6% does appear to influence the number of generations in which the solution converges.

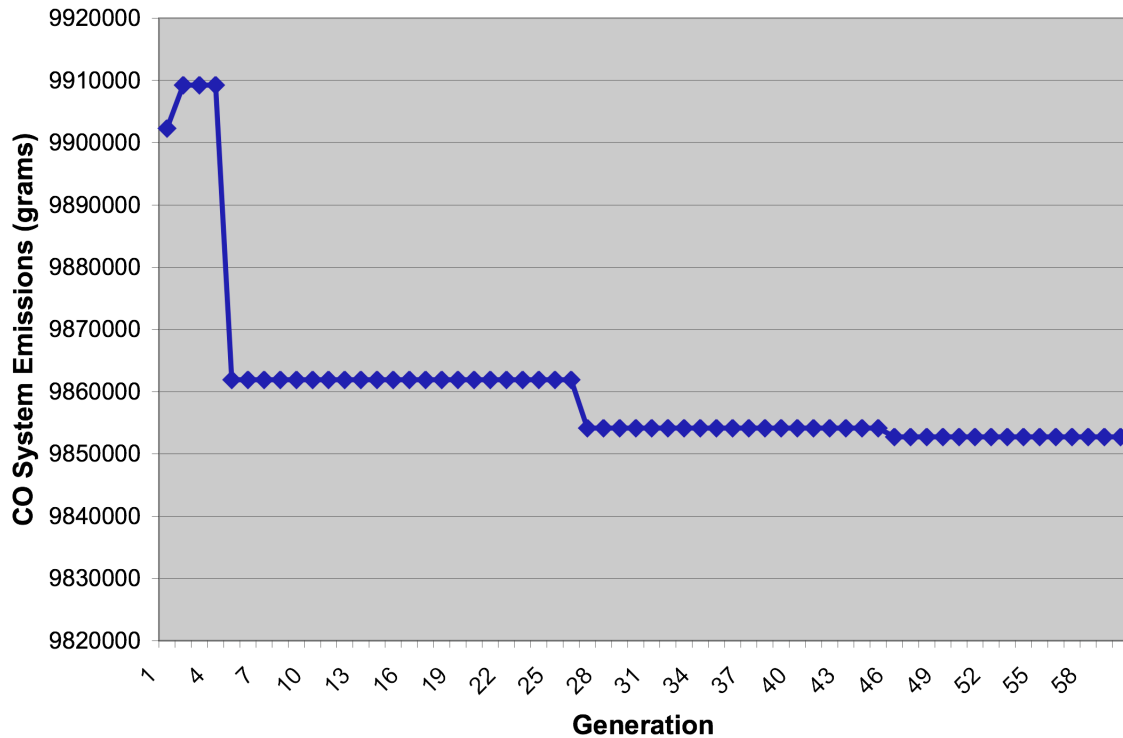


Figure 13. CO System Emissions Convergence for Anaheim Network with Fixed Demand and 10.92% of Network Links Eligible for Improvement

Figure 13 demonstrates time to convergence for CO system emissions converge is approximately 47 generations for the fixed demand scenario with a higher percent of links eligible for improvement. The time to convergence for CO system emissions under this analysis scenario is noticeably larger than its time to converge on the Anaheim network with fewer links eligible for improvement. The scenario with 100 eligible links took approximately 26 more generations than the scenario with 40 eligible links. Similar to NOx system emissions, in the case designing for minimal CO system emissions,

increasing the number of eligible links by 6% does appear to influence the number of generations to reach convergence.

As is evident from figures 11 through 13, each system emissions value changes minimally or not at all after generation 45 for the analysis scenarios with a larger percent of the Anaheim network eligible for improvement.

In the analyses incorporating demand uncertainty, the number of realizations was kept at 50 realizations and the number of generation was kept at 30 generations. Thirty generations was deemed reasonable based on the tendency of fixed demand Sioux Falls network analysis scenarios to converge by or around 30 generations. Figures 14, 15, and 16 illustrate the time to convergence for VOC system emissions, NOx system emissions, and CO system emissions for a moderately congested Sioux Falls network with 35% demand uncertainty, a budget of 18,000 vehicles/hour and 94.7% of network links eligible for improvement.

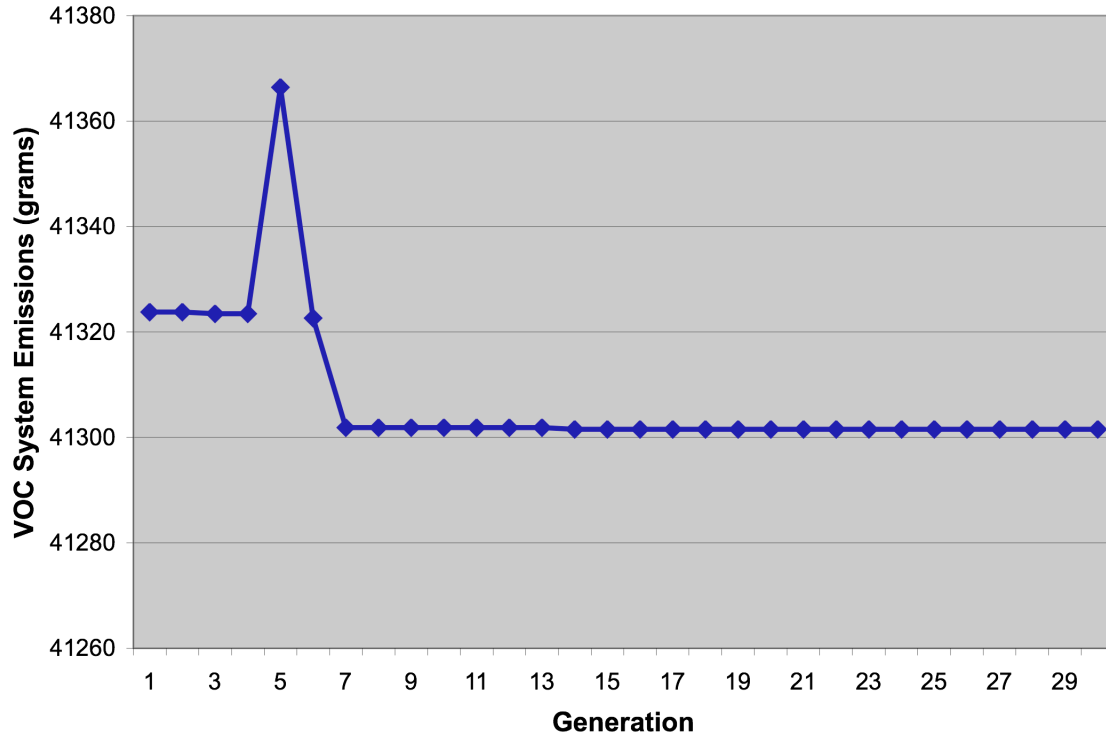


Figure 14. VOC System Emissions Convergence for Sioux Falls Network with Demand Uncertainty

As can be seen in Figure 14, time to convergence for VOC system emissions is approximately 7 generations for demand uncertainty of 35% on the Sioux Falls network. In this analysis scenario, incorporating demand uncertainty does not appear to noticeably increase time to convergence for VOC system emissions; time to convergence with fixed demand was approximately 6 generations.

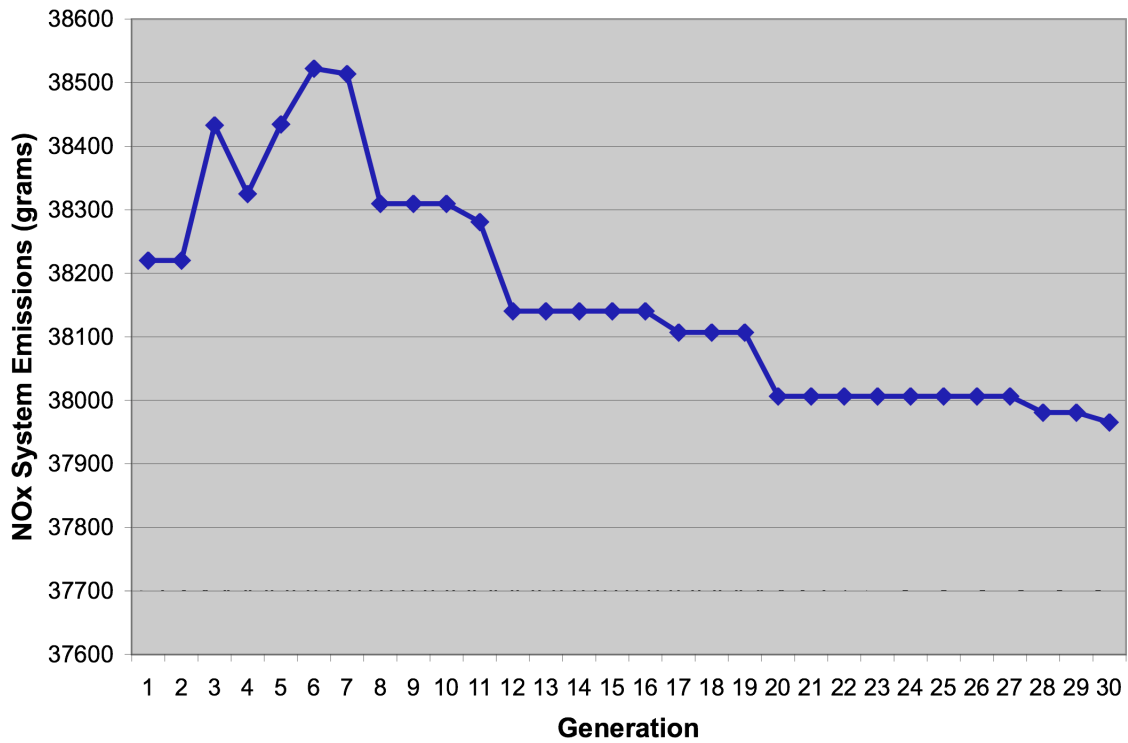


Figure 15. NOx System Emissions Convergence Sioux Falls Network with Demand Uncertainty

As can be seen in Figure 15, time to convergence for NOx system emissions is approximately 20 to 27 generations. There are further changes in the objective value after 20 generations. However, the cumulative magnitude of these changes is 0.11%, which falls below the 0.25% convergence threshold discussed above. The fixed demand scenario converged in approximately 26 generations, so 20 to 27 generations seems to be within a reasonable range for a scenario with 35% demand uncertainty.

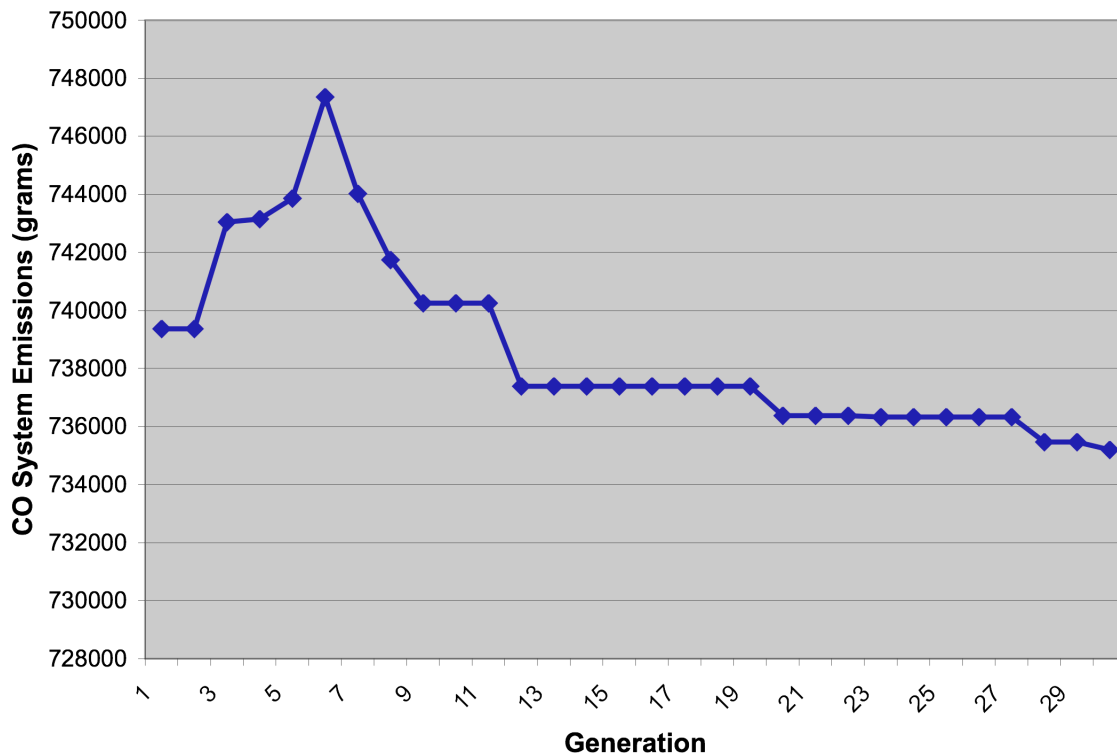


Figure 16. CO System Emissions Convergence Sioux Falls Network with Demand Uncertainty

As illustrated in Figure 16, time to convergence for CO system emissions occurs in 20 to 27 generations, similar to the time to convergence for NO_x system emissions. The CO system emissions value does decrease slightly (another 0.16%) after generation 20; this seems reasonable since its convergence under fixed demand occurred around 30 generations. The 0.16% decrease is well below the convergence threshold (0.25%), therefore, the solution resulting from 30 generations is deemed suitable.

Overall, the GA solution method employed for the emissions network design problem appears to be efficient, as objective values tend to reach convergence in 20 to 45 generations. Relaxing the budget constraint, increasing demand on the network, increasing the percent of eligible links on the network and/or incorporating demand

uncertainty tended to influence time to convergence in some analysis scenarios, but clear or predictable trends were not evident.

RESULTS

From the analysis scenarios conducted, emerging trends were identified and organized into three categories: 1) general findings; 2) the effect designing to minimize each objective has on system performance (i.e., total travel time and system emissions); and 3) the solution characteristics when certain objectives are minimized. The following sub-sections discuss the trends within each of these categories.

General Findings

Two interesting and important general findings emerged from the analysis results. The first finding: the do-nothing scenario did not result in lower vehicle emissions in any of the 36 analysis scenarios examined. Across the analysis scenarios, a system change or set of changes to the road network could always be made to reduce each of the three air pollutants. The second finding: adding smaller increments of capacity to the network had a limited effect on model results. Both of these findings are discussed further below.

System Performance versus Do-Nothing Scenarios

Figures 17 and 18 illustrate the percent improvement of each performance measure (i.e., total travel time, VOC system emissions, NOx system emissions, and CO system emissions) relative to their respective values in the do-nothing scenario. The percent improvement over their respective values in the do-nothing scenario (i.e., percent reduction) for each is based on their respective values when the network is designed to minimize each.

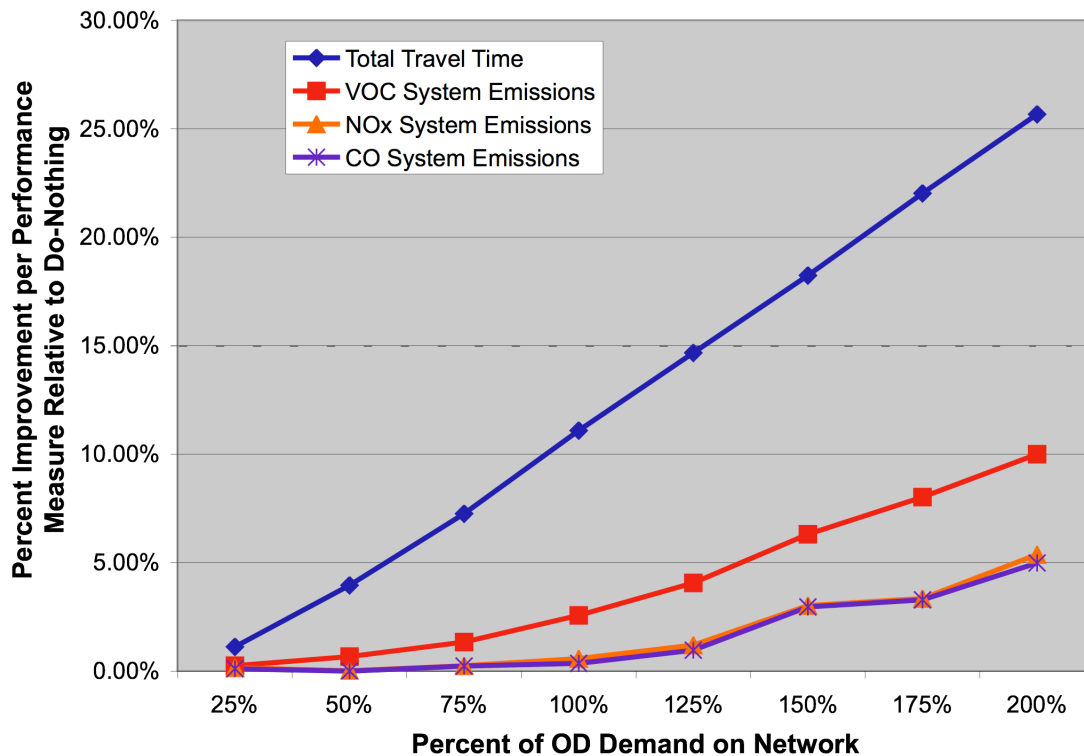


Figure 17. Percent Improvement in Performance Measures Relative to Do-Nothing Scenarios as Demand Increases on Sioux Falls Network

As can be seen in Figure 17, as demand increases or base congestion increases on the network the potential reduction in each performance measure increases. The largest improvements are in total travel time and VOC system emissions (decreases in total travel time and VOC system emissions are as much as 25% and 10%, respectively). However, NOx and CO system emissions also show definitive decreases relative to the do-nothing scenario. This is particularly noticeable at higher levels of congestion with as much as a 5% decrease in both NOx and CO system emissions. Similar findings were found in the analysis conducted on the Anaheim network and shown in Figure 18.

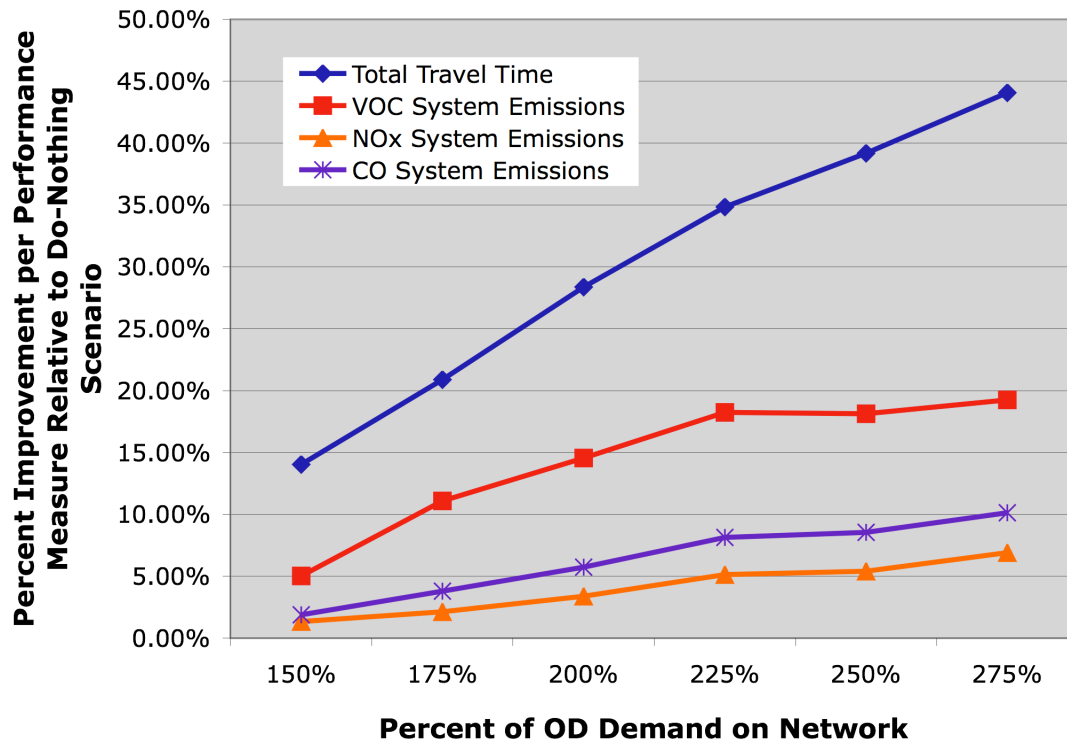


Figure 18. Percent Improvement in Performance Measures Relative to Do-Nothing Scenarios as Demand Increases on Anaheim Network

Similar to results on the Sioux Fall network, the largest improvements (or reductions relative to the do-nothing scenario) are in total travel time and VOC system emissions. Across the demand scenarios, total travel time reductions range from approximately 15% to nearly 45%. VOC system emissions reductions range from 5% to nearly 20%. NOx and CO system emissions are also substantial ranging from 1% to as much as 10% for CO system emissions. These results are especially impressive given only 4.36% of the Anaheim network was eligible for improvement. Even larger reductions are likely under scenarios where more of the network is eligible for improvement, because the model will have more options to further optimize system performance.

The increase in potential improvement for each performance measure as demand increases is consistent for both test networks. Furthermore, it is evident on both test networks the do-nothing scenario does not result in minimal emissions for any of the analysis scenarios. Percent reductions in emissions (VOC, NO_x, or CO) range from approximately 1% in nearly free flow conditions to 10% at higher levels of base congestion. These findings demonstrate: 1) doing nothing to the road network can increase air pollutant emissions; and 2) the more congested a road network is the more important it is to identify and make road network changes that will reduce vehicle emissions.

Smaller Increments of Capacity versus Larger Increments of Capacity

As noted, adding smaller increments of capacity was explored to see if this approach effected the model's ability to design for minimal total travel time, VOC system emissions, NO_x system emissions, and CO system emissions. The analysis results indicate adding smaller increments of capacity does not alter or produce different solution characteristics trends (when compared to adding larger increments of capacity). However, different results were found when comparing system performance measures.

The only apparent difference between adding smaller increments of capacity and larger increments of capacity were marginal changes in the system performance measures. Adding smaller increments of capacity resulted in a marginal additional decrease in NO_x and CO system emissions (when the network was designed to minimize each). Conversely, adding smaller increments of capacity resulted in a marginal increase in total travel time (when the network was designed to minimize total travel time). Adding smaller increments of capacity to the network further decreases NO_x system emissions by 0.25% and CO system emissions by 0.30%. In contrast, total travel time increases by 0.24%.

While the percent differences noted above are relatively small, the trends seem reasonable considering how each performance measure changes with average speed (see Chapter 2 for plots of each performance measure versus average vehicle speed). Travel time decreases monotonically as speed increases, therefore larger increments of capacity added to a link translates to faster speeds and lower travel time. Conversely, NO_x and CO emissions' relationship to average vehicle speed is bowl-shaped; therefore, smaller increments of capacity increase speeds some but not too much translating to lower NO_x and CO emissions.

Summary of General Findings

From the discussion above, it is clear as network congestion increases it is increasingly important to identify and make road network changes to minimize air pollutant emissions. As congestion increases, the potential reduction in air pollutant emissions over doing nothing increases. Furthermore, it appears adding smaller increments of capacity spread across a network is a more effective approach to decreasing NO_x and CO system emissions than adding larger increments of capacity to fewer roadways in the network. In contrast, adding larger increments of capacity to fewer roadways appears more effective at reducing total travel time. These are valuable trends for system managers to know as each can help begin to inform the decisions made and approaches used in planning for and identifying modifications to a road network. Additional useful trends are discussed in the subsequent sections.

Effects on System Performance

In this research, system performance is characterized by four different measures: 1) total travel time; 2) total VOC emissions; 3) total NO_x emissions; and 4) total CO emissions. As each of these measures is minimized within a given scenario the other

three each change accordingly ultimately reflecting the tradeoffs between designing to minimize each. These tradeoffs are discussed below. First, by illustrating the percent differences between each performance measures minimal value compared to its value when another performance measure is minimized. Second, by presenting pareto-optimal curves of total travel time versus each air pollutant. Finally, the influence of demand uncertainty on each performance measure is discussed.

Percent Differences in Each Performance Measure as Other Performance Measures are Minimized

Over the course of the analysis scenarios summarized in Table 2 and Table 3, it became evident that designing for minimal total system travel time does not guarantee each of the air pollutants is minimized. This is consistent with findings from the traffic assignment and network pricing literature incorporating emissions. Research in those fields found routing vehicles or pricing networks to influence route choice such that vehicle emissions are minimal was consistently different than routing vehicles or pricing networks to minimize total travel time (see Rilett and Benedek, 1994; Benedek and Rilett, 1998; Sugawara and Niemeier, 2002; Yin and Lawphongpanich, 2006; Ahn and Rakha, 2008). It was also found routing vehicles for minimal emissions often conflicted with routing vehicles for minimal total travel time such that minimizing one increased the other (see Rilett and Benedek, 1994; Benedek and Rilett, 1998; Sugawara and Niemeier, 2002; Yin and Lawphongpanich, 2006; Ahn and Rakha, 2008).

In the emissions network design model, total system travel time and VOC system emissions behave similarly (i.e., when one is minimized the other also tends to be minimized). Also, NO_x and CO system emissions tend to behave similarly, but usually in contrast to total system travel time and VOC system emissions. Analysis results also indicate the differences between designing for minimal total travel time or VOC system

emissions versus designing for minimal NO_x or CO system emissions tend to increase as the number of links eligible for improvement increase and as the base congestion for a network increases (i.e., demand for travel on the network increases). Interestingly, the differences tend to vary little for a given demand level (i.e., base congestion level) despite increasing the available budget.

The trends noted above are illustrated by the following sets of figures. Figures 19 through 24 demonstrate the increase in each performance measure (over their respective minimal values) when the network is designed for minimal total travel time or minimal CO system emissions. These scenarios were chosen because VOC system emissions behaves similarly to total travel time and NO_x system emissions behaves similarly to CO system emissions. Figures 19 through 24 also demonstrate the differences between performance measures change relatively little for a given demand level even as the available budget increases.

Figures 19 through 21 illustrate the increase in each performance measure (relative to their respective minimal values) when the network is designed for minimal total travel time.

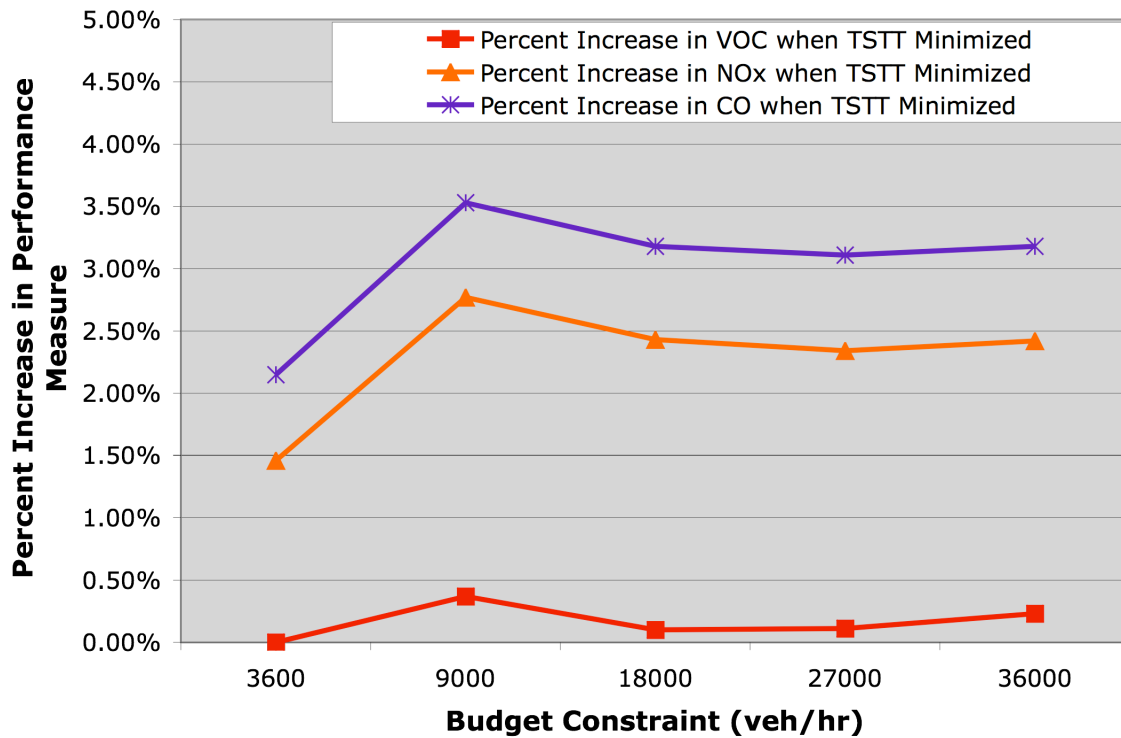


Figure 19. Percent Increase in each Performance Measure when Total Travel Time is Minimized on Sioux Falls Network (Small Increments of Capacity Added)

The lowest horizontal line in Figure 19 corresponds to the percent increase in VOC system emissions (compared to its minimal value) when the network is designed for minimal total travel time. As can be seen, VOC system emissions increase relatively little (less than 0.50%) when the network is designed for minimal total travel time. In contrast, NOx and CO system emissions increase 1.50% to 3.50% with CO system emissions increasing more than NOx system emissions. Similar trends related to when the network is designed for minimal total travel time are illustrated in Figure 20 and Figure 21. These figures show results from analysis on the Sioux Falls network (when larger increments of capacity were added) and on the Anaheim network.

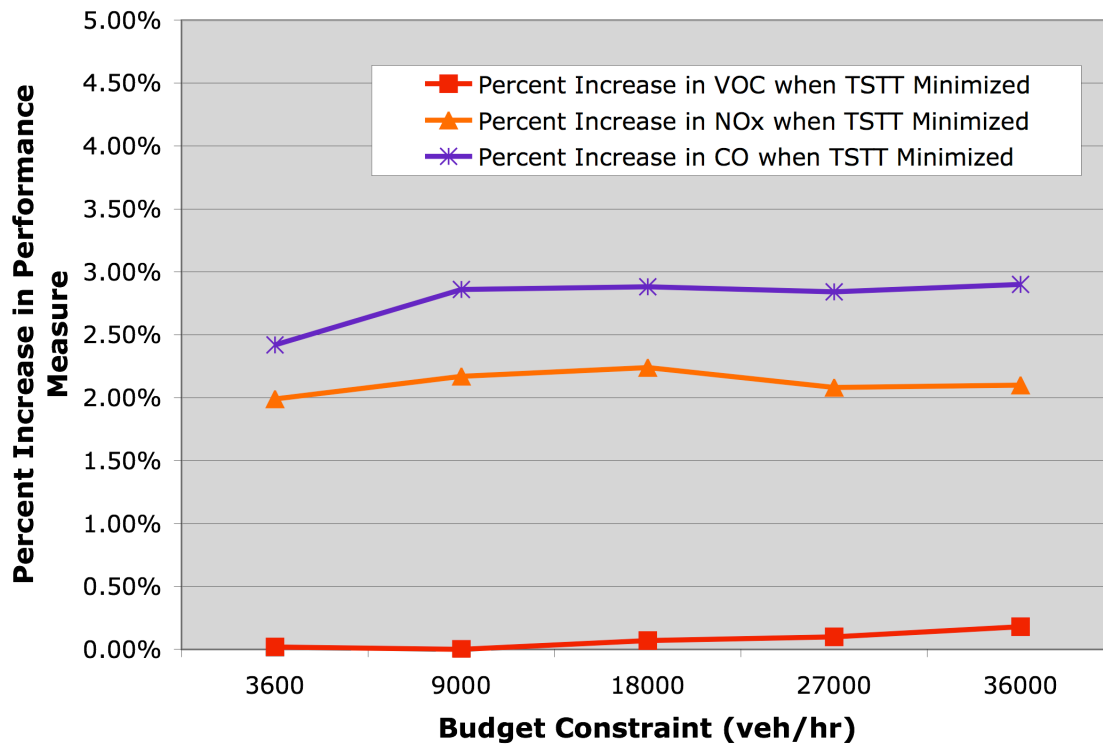


Figure 20. Percent Increase in each Performance Measure when Total Travel Time is Minimized on Sioux Falls Network (Larger Increments of Capacity Added)

Figure 20 illustrates the increase in VOC system emissions, when the network is designed for minimal total travel time, is relatively small (less than 0.25%). However, the increase in NOx and CO system emissions ranges from 2% to 3%. Despite adding larger increments of capacity to the Sioux Falls network, these results are consistent with those shown in Figure 19. Figure 19 and Figure 20 also demonstrate relative differences between each pollutant and total travel time remains approximately the same despite the increase in available budget.

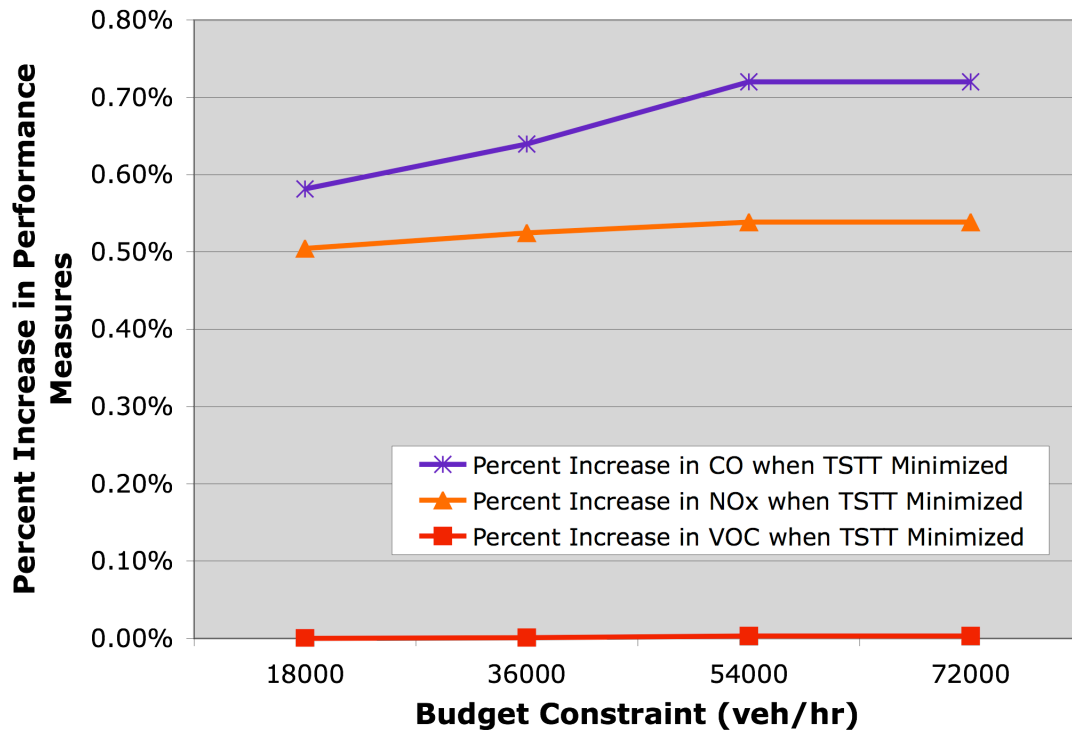


Figure 21. Percent Increase in each Performance Measure when Total Travel Time is Minimized on Anaheim Network

Figure 21 illustrates the same basic trends as was seen from the analysis on the Sioux Fall network. On the Anaheim network, VOC system emissions do not increase at all when the network is designed for minimal total travel time. In contrast, NOx and CO system emissions increase 0.50% to 0.75%. The relative magnitude of the increase is smaller than that seen on the Sioux Falls network. This is likely because only 4.36% of the Anaheim network is eligible for improvement compared to 94.7% of the Sioux Falls network. The relative difference between total travel time and NOx and CO system emissions would increase as higher percentages of the total network became eligible for improvement. As seen in figures 19 and 20, the relative differences between each

pollutant and total travel time remain approximately the same even as the available budget increases.

Figures 22 through 24 demonstrate the increase in each performance measure (relative to their respective minimal values) when the network is designed for minimal CO system emissions.

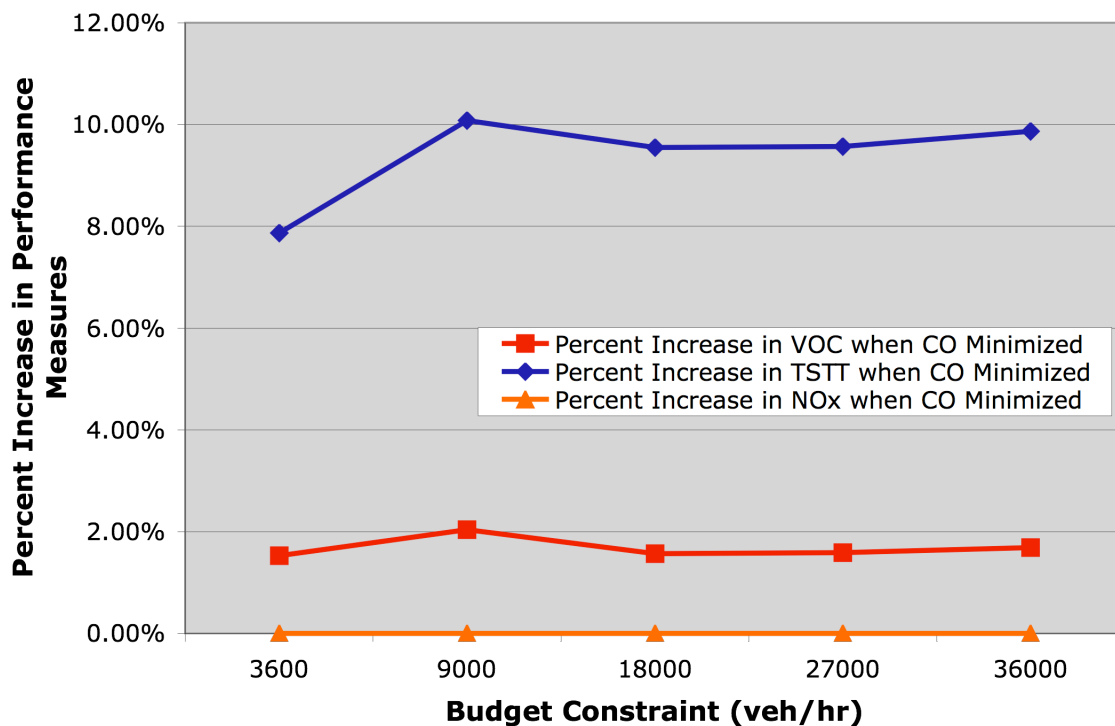


Figure 22. Percent Increase in each Performance Measure when CO System Emissions are Minimized on Sioux Falls Network (Small Increments of Capacity Added)

The lowest horizontal line in Figure 22 (essentially overlaying the horizontal axis) corresponds to the percent increase in NOx system emissions (compared to its minimal value) when the network is designed for minimal CO system emissions. As can be seen, NOx system emissions increase relatively little or not all when the network is designed for minimal CO system emissions. In contrast, VOC system emissions and total travel

time increase approximately 1.50% to 10.00% with total travel time increasing more than VOC system emissions. Similar trends, related to when the network is designed for minimal CO system emissions, were found in additional analysis on the Sioux Falls and Anaheim networks. These results are illustrated in Figure 23 and Figure 24.

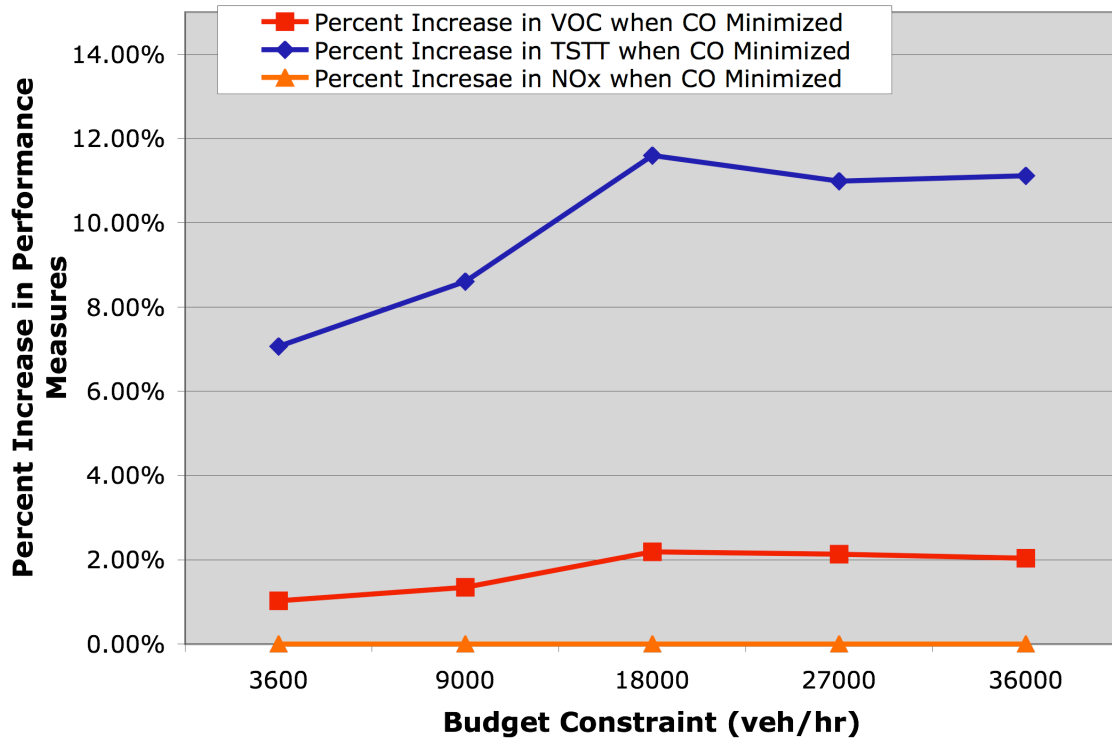


Figure 23. Percent Increase in each Performance Measure when CO System Emissions are Minimized on Sioux Falls Network (Larger Increments of Capacity Added)

Figure 23 demonstrates NOx system emissions, again, tends to be minimal when the network is designed for minimal CO system emissions. Similar to previous findings, VOC system emissions and total travel time tend to increase by 1% to nearly 12% when the network is designed for minimal CO system emissions. Total travel time increases the most (relative to its minimal value). These findings are consistent with the Sioux

Falls network analysis in which smaller increments of capacity were added to the network (see Figure 22).

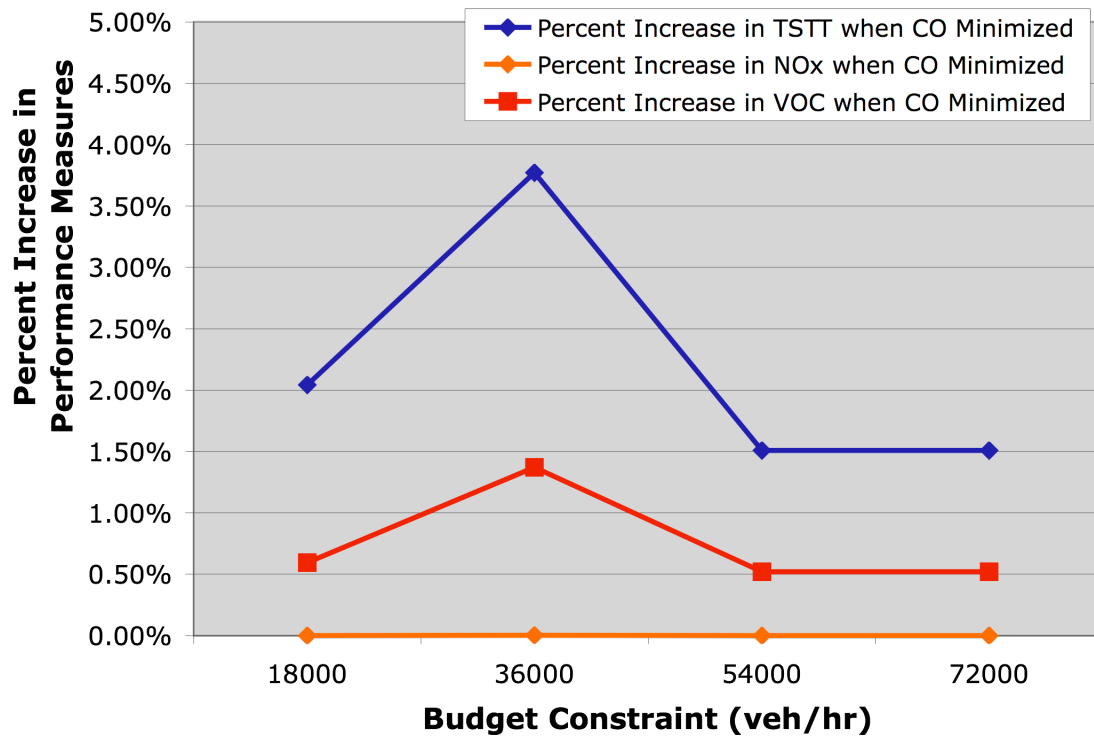


Figure 24. Percent Increase in each Performance Measure when CO System Emissions are Minimized on Anaheim Network

Figure 24 illustrates the basic trends noted from Figure 22 and Figure 23 remain valid. NOx system emissions tend to be minimal when the network is designed for minimal CO system emissions. In contrast, VOC system emissions and total travel time increase by 0.5% to nearly 4%. The relative differences are smaller than the relative differences seen on the Sioux Falls network; this is likely due to the smaller percent of eligible links on the Anaheim network (4.36%) compared to the Sioux Falls network (94.7%). The uncharacteristic spike in the relative differences shown in Figure 24 is likely because the emissions network design problem is highly non-linear, which means

while trends can be extracted from the results there will occasionally be unexpected variations.

Figures 25 and 26 illustrate: the difference between each performance measure increases as demand or base congestion on the network increases. In these figures, the difference between total travel time and total CO system emissions are plotted because VOC and NOx system emissions are so closely related to total travel time and CO system emissions, respectively.

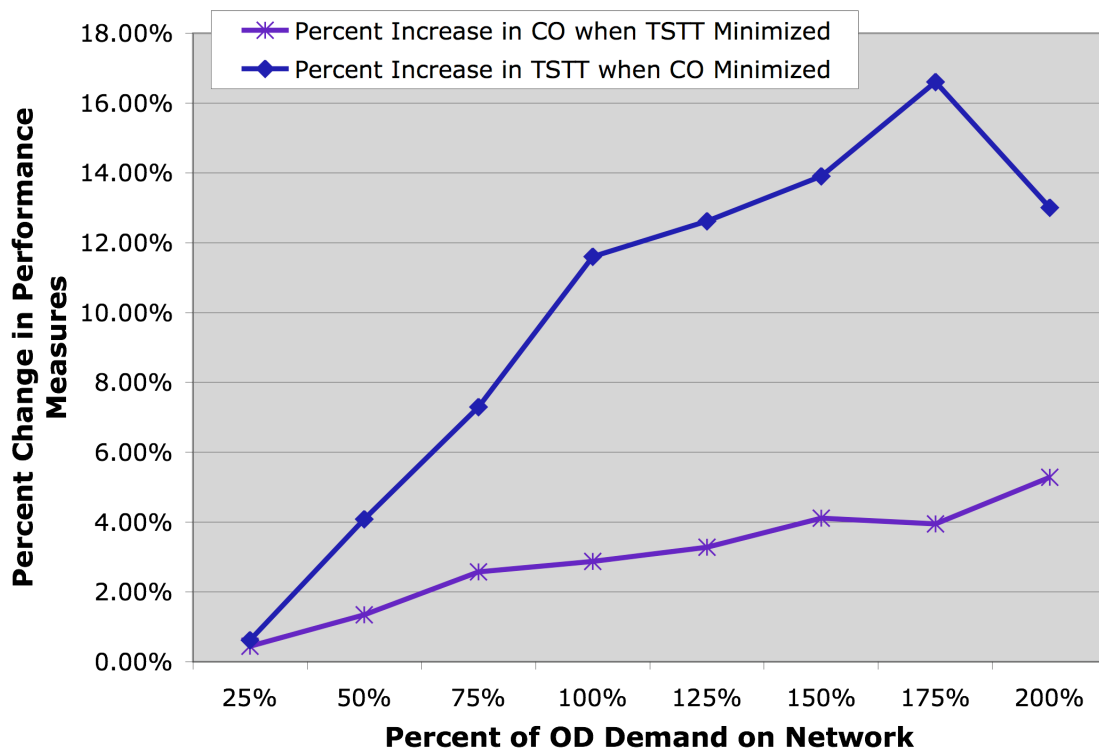


Figure 25. Percent Increase in CO System Emissions and Total Travel Time as Demand Increases on the Sioux Falls Network

As can be seen Figure 25, the difference between minimal CO system emissions and CO system emissions when the network is designed for minimal total travel time increases substantially as demand increases. In the case of the Sioux Falls network, the

difference in CO system emissions went from approximately 1.00% increase over minimal CO system emissions to nearly a 6% increase over minimal CO system emissions when the network is designed for minimal total travel time. Similar to the relationship shown with CO system emissions, the difference between minimal total travel time and total travel time when the network is designed for minimal CO system emissions increases considerably as demand on the network increases. On the Sioux Falls network, the percent increase in total travel time ranged from approximately 1.00% increase at uncongested conditions to nearly a 17% increase under congested conditions. This trend illustrates the importance of considering emissions (rather than only total travel time) in network design particularly at higher levels of congestion.

The trend above is not readily apparent by looking at the corresponding analysis results from the Anaheim network; these results are shown in Figure 26. Instead, the results from the Anaheim network appear to be more heavily influenced by the number of links eligible for improvement.

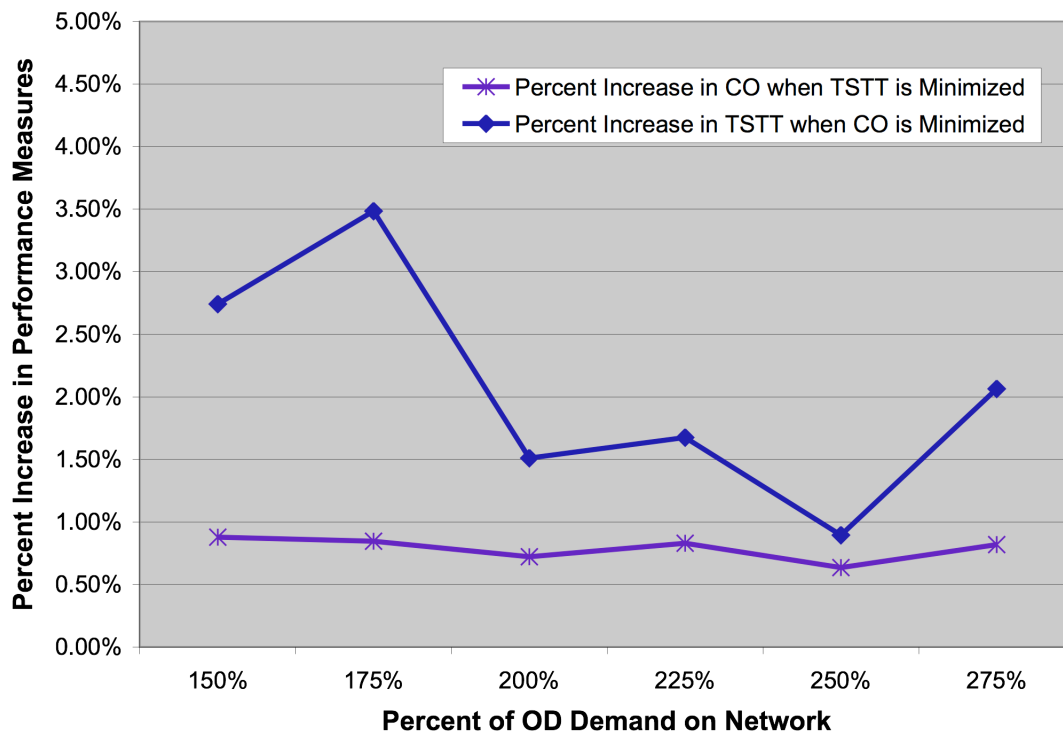


Figure 26. Percent Increase in CO System Emissions and Total Travel Time as Demand Increases on the Anaheim Network

As evident from Figure 26, the trend of increasing disparity between each performance measure as demand increases (shown in Figure 25) does not appear in the results summarized in Figure 26. This may be because the analysis scenarios run with Anaheim network have a relatively small number of links eligible for improvement (i.e., 4.36% of network links are eligible for improvement) compared to the Sioux Falls network, in which 94.7% of the network links are eligible for improvement. The changes for each performance measure may also be connected to the percent of links eligible for improvement in a network.

In the instance of the Anaheim network, the percent difference between each performance measure increases as the percent of links eligible for improvement on the network increases. For example, when 40 of the 916 links are eligible for improvement

and the network is designed for minimal CO system emissions, total travel time increases by about 1.50% (over its minimal value for a given budget). Simply increasing the number of links eligible for improvement from 40 to 100 links results in a 5.11% increase in total travel time (over its minimal value). Similar increases are also seen when CO and NO_x system emissions are compared to their respective values when the network is designed for minimal total travel time. For example, when 40 of the 916 links are eligible for improvement and the network is designed for minimal total travel time, CO system emissions increase by about 0.72% (over its minimal value for a given budget). Under the same scenario with 100 eligible links, CO system emissions increase by about 1.11% (over its minimal value).

Collectively, the different relationships between travel time and each pollutant illustrate, in scenarios with fixed demand, designing for minimal travel time nearly always guarantees minimal VOC system emissions; however, there is a distinct trade-off because NO_x and CO system emissions tend to be 0.75% to 6.00% higher than their respective minimal values. The magnitude of the increase in NO_x and CO system emissions depends on the network and specific scenario attributes. Similarly, designing for minimal NO_x or CO system emissions nearly always guarantees minimizing the other, but total travel time increases by 1.00% to 17.00% relative to its minimal value. Again, the magnitude of the increase in total travel time depends on the network and specific scenario attributes. The higher differences noted above tend to occur when base congestion (i.e., demand on the network) increases or when the percent of links eligible for improvement on the network increases.

Pareto-Optimal Curves

Based on the results shown above in Figures 19 through 26, it is evident there are tradeoffs between designing a network for minimal total travel time and designing it to

minimize a specific pollutant, especially minimal NO_x or CO system emissions. This relationship can be modeled by plotting pareto-optimal curves (for each analysis scenario). Pareto-optimal curves were developed by plotting the feasible and best solutions (i.e., non-dominated solutions) for designing for minimal travel time versus the feasible and best solutions for designing to minimize each pollutant. In doing so, the relationship between the total travel time objective and each pollutant becomes evident. From the analysis scenarios, it is apparent the relationship between total travel time and each pollutant is relatively consistent across the analysis scenarios (for Sioux Falls and Anaheim networks) with fixed demand. These relationships are presented and discussed below.

Total travel time and VOC system emissions objectives behave similarly. When travel time increases or decreases, VOC system emissions increases or decreases, respectively. Furthermore, the relationship appears to be linear on a consistent basis. Figures 27 through 29 illustrate this relationship for a number of different fixed demand analysis scenarios.

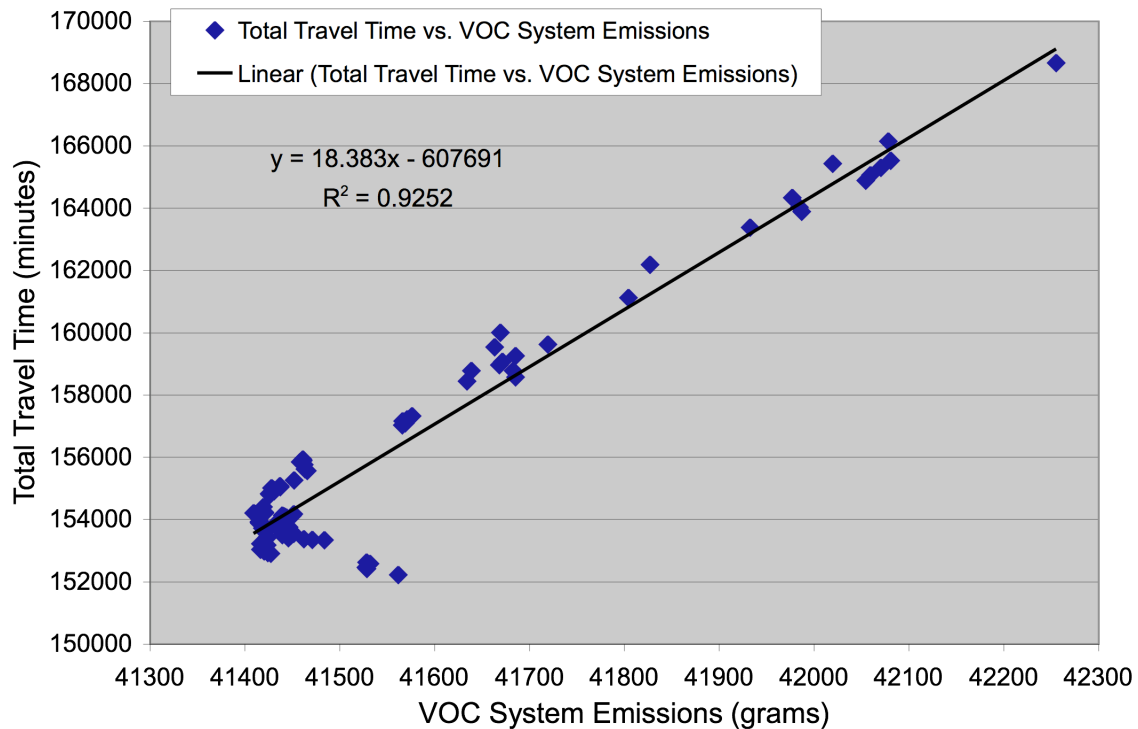


Figure 27. Total Travel Time vs. VOC System Emissions, Non-Dominated Solutions for Sioux Falls Network, 18,000 vehicles/hour Budget, 100% OD Demand, Small Increments of Capacity Added

Figure 27 is from analysis on the Sioux Falls network with 100% of the OD demand table loaded on the network and a capacity budget of 18,000 vehicles/hour and smaller increments of capacity were added to the network. The resulting linear relationship between the best (i.e., minimal) total travel time solutions and the best VOC system emissions solutions is clear from Figure 27. It is also evident the relationship is relatively strong with an R-square value of 0.9252.

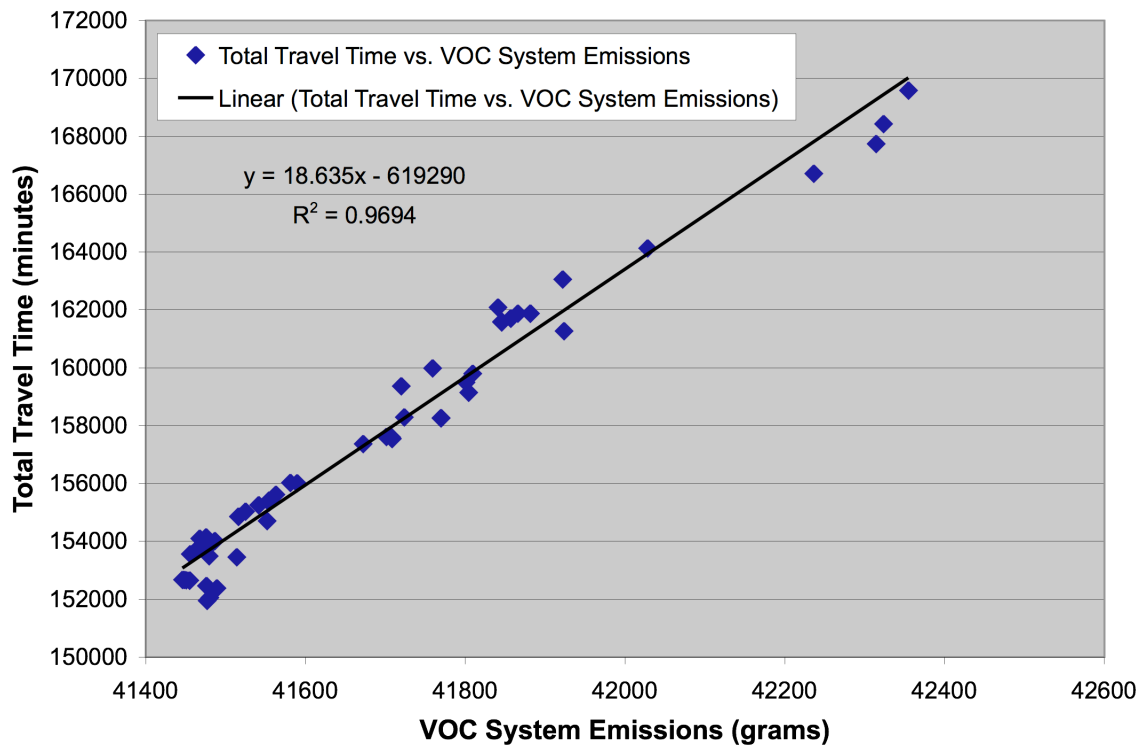


Figure 28. Total Travel Time vs. VOC System Emissions, Non-Dominated Solutions for Sioux Falls Network, 18,000 vehicles/hour Budget, 100% OD Demand, Larger Increments of Capacity Added

The plot above is from analysis on the Sioux Falls network with 100% of the OD demand table loaded on the network and a capacity budget of 18,000 vehicles/hour. The above plot is from a scenario in which larger increments of capacity were added to the network. The resulting linear relationship between the best (i.e., minimal) total travel time solutions and the best VOC system emissions solutions is evident in Figure 28. It is also evident the relationship is relatively strong with an R-square value of 0.9694. The equation defining the relationship between total travel time and VOC system emissions is also relatively consistent for a given network.

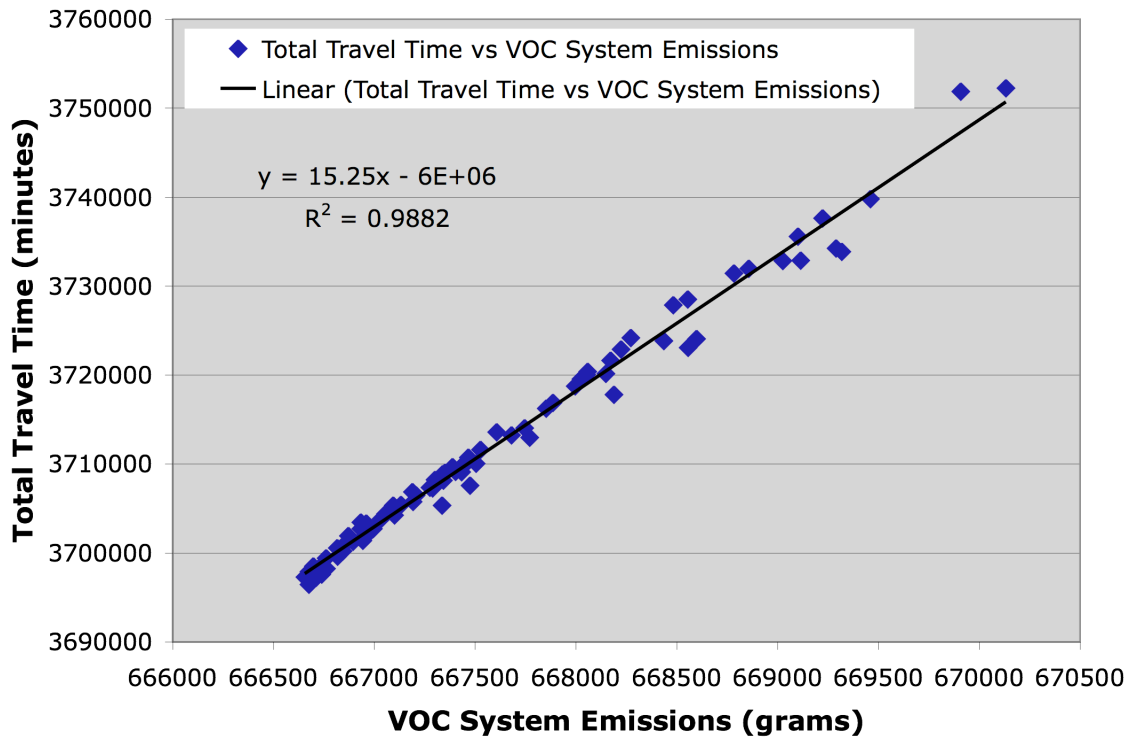


Figure 29. Total Travel Time vs. VOC System Emissions, Non-Dominated Solutions for Anaheim Network, 72,000 vehicles/hour Budget, 200% OD Demand

Figure 29 is from analysis on the Anaheim network with 200% of the OD demand table loaded on the network and a capacity budget of 72,000 vehicles/hour. The resulting linear relationship between the best (i.e., minimal) total travel time solutions and the best VOC system emissions solutions is clear in Figure 29. It is also evident the relationship is relatively strong with an R-square value of 0.9882.

Given that travel time and VOC emissions have similar shaped curves when plotted against average vehicle speed (see plots in Chapter 2), the positive, linear relationship between total travel time and VOC system emissions is reasonable. Each total system value increases or decreases monotonically with the other, which is

consistent with the shape of their respective disaggregated values plotted as average vehicle speed increases.

Total travel time and NOx system emissions objectives behave in contrast to each other. When travel time increases or decreases, NOx system emissions tend to do the opposite. Unlike the relationship between VOC system emissions and total travel time, the relationship between total travel time and NOx system emissions appears to be a second degree polynomial in which NOx system emissions increase as total travel time decreases and vice versa. Figures 30 through 32 illustrate this relationship for a number of different fixed demand analysis scenarios.

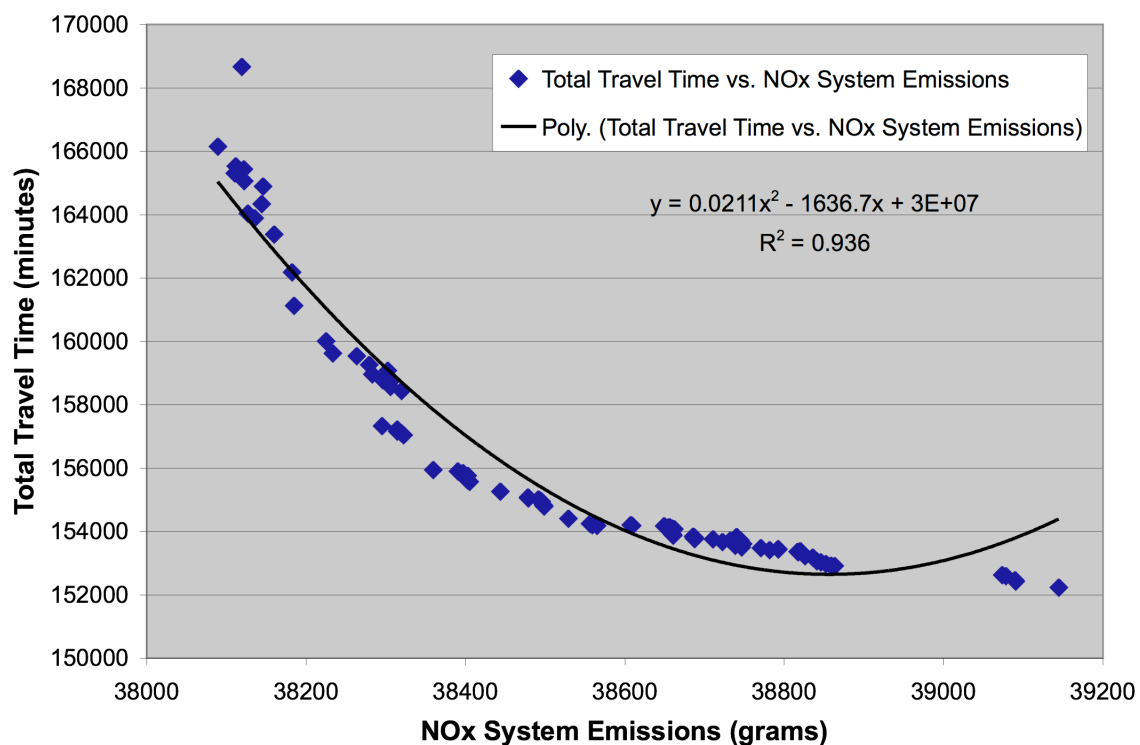


Figure 30. Total Travel Time vs. NOx System Emissions, Non-Dominated Solutions for Sioux Falls Network, 18,000 vehicles/hour Budget, 100% OD Demand, Small Increments of Capacity Added

The plot above is from analysis on the Sioux Falls network with 100% of the OD demand table loaded on the network and a capacity budget of 18,000 vehicles/hour with smaller increments of capacity added to the network. The resulting second-degree polynomial relationship between the best (i.e., minimal) total travel time solutions and the best NOx system emissions solutions is evident from Figure 30. It is also clear the relationship is relatively strong with an R-square value of 0.936.

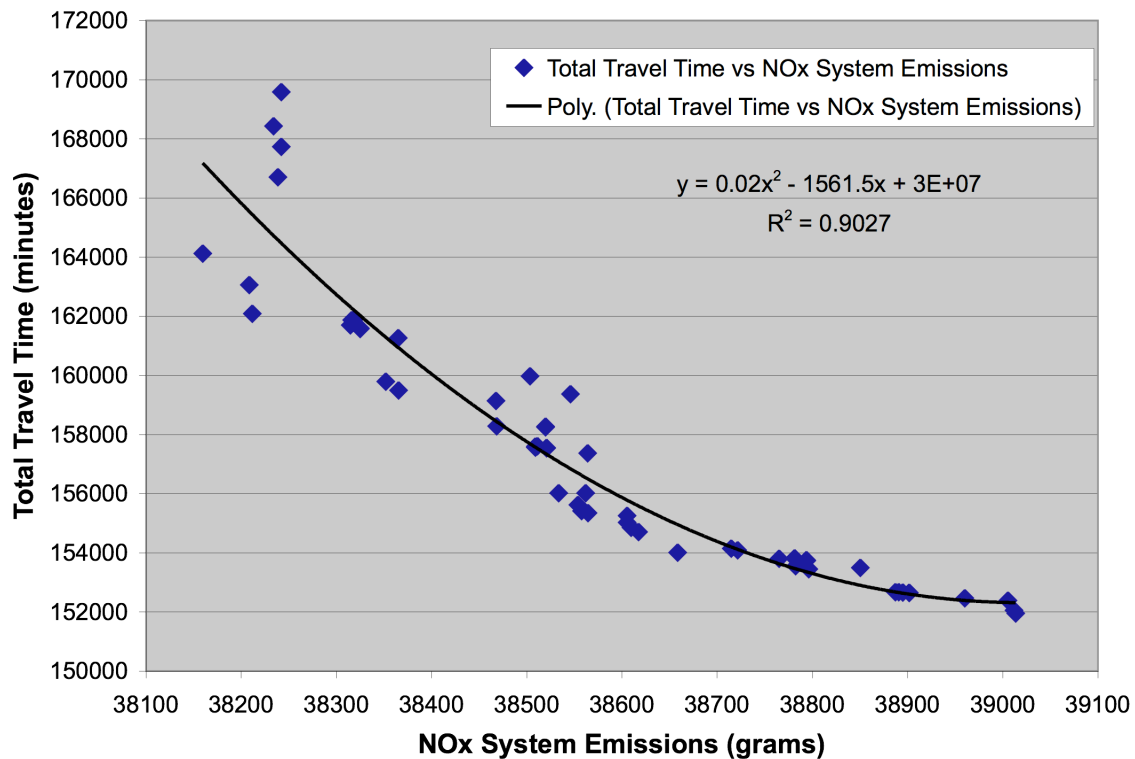


Figure 31. Total Travel Time vs. NOx System Emissions, Non-Dominated Solutions for Sioux Falls Network, 18,000 vehicles/hour Budget, 100% OD Demand, Larger Increments of Capacity Added

The plot above is from analysis on the Sioux Falls network with 100% of the OD demand table loaded on the network and a capacity budget of 18,000 vehicles/hour. The above plot is from a scenario in which larger increments of capacity were added to the network. The resulting second-degree polynomial relationship between the best (i.e.,

minimal) total travel time solutions and the best NOx system emissions solutions is clear in Figure 31. It is also evident the relationship is relatively strong with an R-square value of 0.9027. The second-degree polynomial equation defining the total travel time and NOx system emissions relationship is also relatively consistent for a given network.

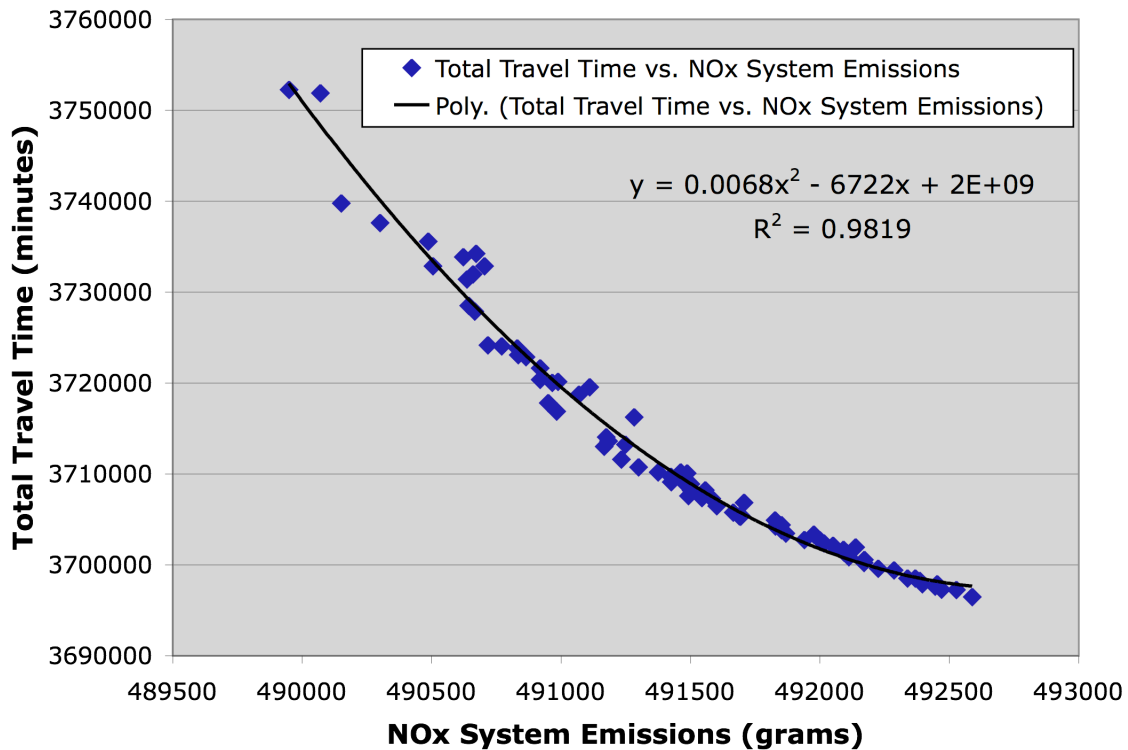


Figure 32. Total Travel Time vs. NOx System Emissions, Non-Dominated Solutions for Anaheim Network, 72,000 vehicles/hour Budget, 200% OD Demand

The plot above is from analysis on the Anaheim network with 200% of the OD demand table loaded on the network and a capacity budget of 72,000 vehicles/hour. The resulting second-degree polynomial relationship between the best (i.e., minimal) total travel time solutions and the best NOx system emissions solutions is clear in Figure 32. It is also evident the relationship is relatively strong with an R-square value of 0.9819.

Given that travel time and NOx emissions have dissimilar shaped curves when plotted against average vehicle speed (see plots in Chapter 2) and NOx emissions rate plotted against average speed is bowl-shaped, the second-degree polynomial relationship between their system values seems reasonable. The contrasting relationship in their total system values (e.g., when one increases the other decreases and vice versa) indicates the nature of the solutions selected to minimize each (i.e., system improvements selected) are fundamentally different. As a result, the solutions create notable differences in overall network performance. The difference in their solution characteristics is explored further in the sub-section titled Solution Characteristics.

Total travel time and CO system emissions objectives behave in contrast to each other, which is similar to the relationship between total travel time and NOx system emissions. When travel time increases or decreases, CO system emissions tends to do the opposite. The relationship between total travel time and CO system emissions appears to be a second-degree polynomial in which CO system emissions increase as total travel time decreases and vice versa. Figures 33 through 35 illustrate this relationship for a number of different fixed demand analysis scenarios.

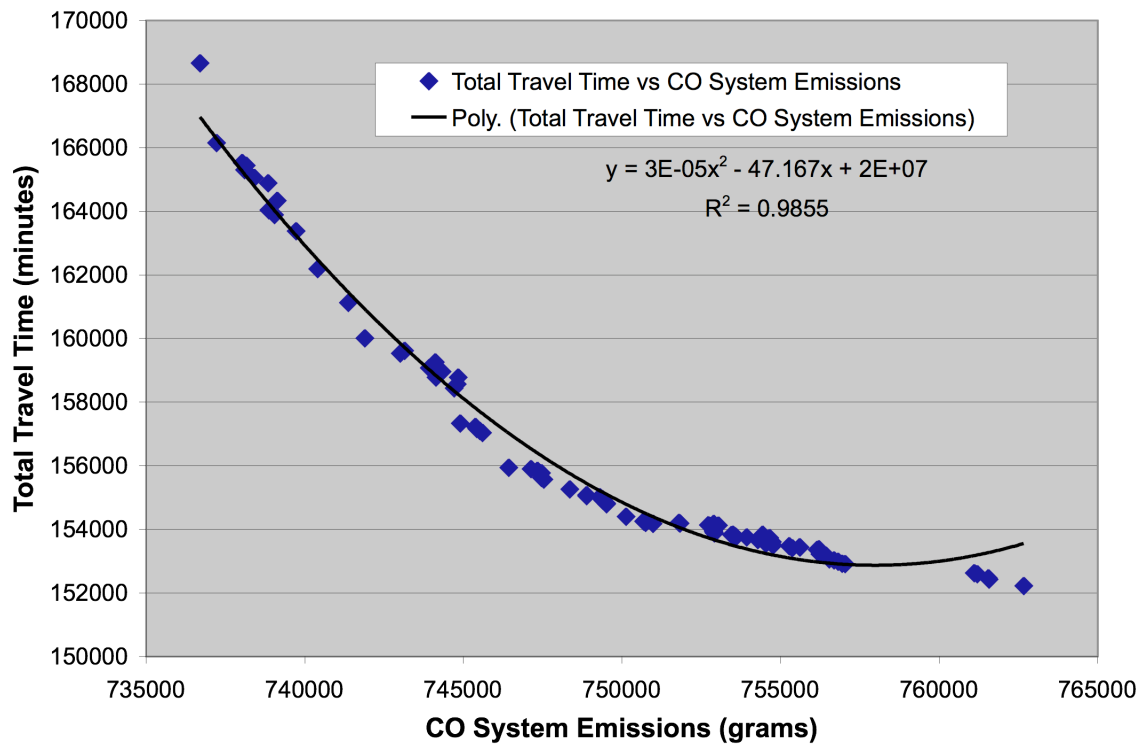


Figure 33. Total Travel Time vs. CO System Emissions, Non-Dominated Solutions for Sioux Falls Network, 18,000 vehicles/hour Budget, 100% OD Demand, Small Increments of Capacity Added

Figure 33 is from analysis on the Sioux Falls network with 100% of the OD demand table loaded on the network and a capacity budget of 18,000 vehicles/hour and a scenario in which smaller increments of capacity were added to the network. The resulting second-degree polynomial relationship between the best (i.e., minimal) total travel time solutions and the best CO system emissions solutions is clear in Figure 33. It is also evident the relationship is relatively strong with an R-square value of 0.9855.

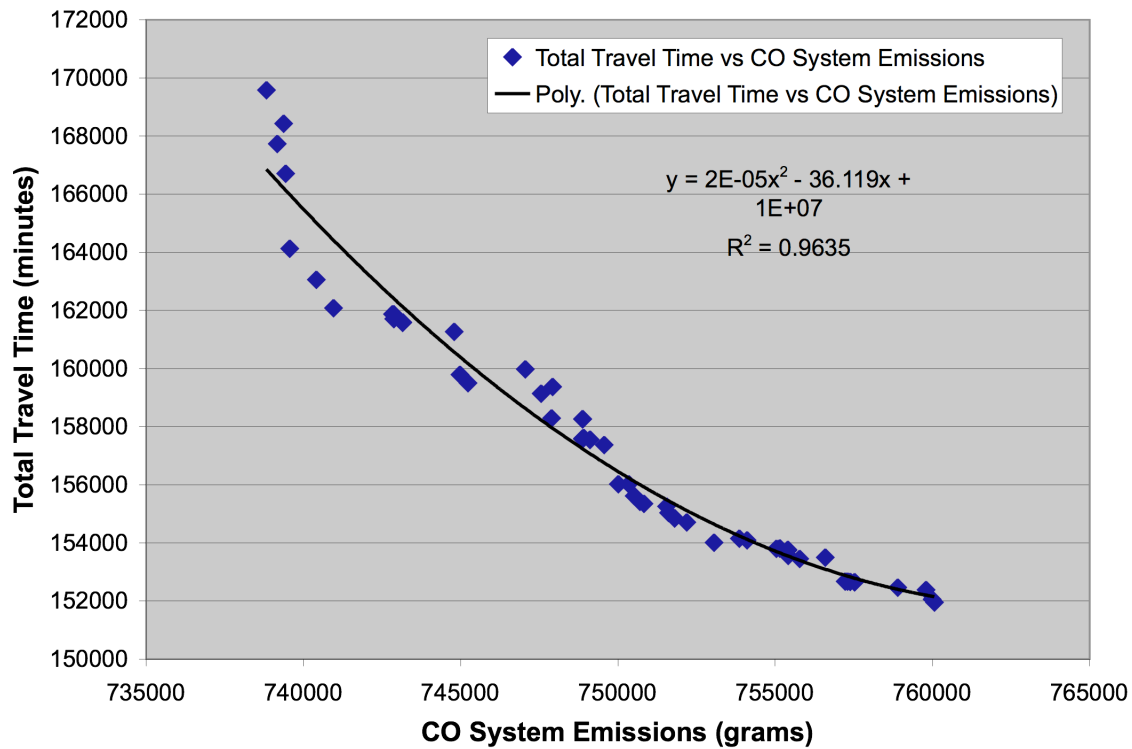


Figure 34. Total Travel Time vs. CO System Emissions, Non-Dominated Solutions for Sioux Falls Network, 18,000 vehicles/hour Budget, 100% OD Demand, Larger Increments of Capacity Added

The plot above is from analysis on the Sioux Falls network with 100% of the OD demand table loaded on the network and a capacity budget of 18,000 vehicles/hour and a scenario in which larger increments of capacity were added to the network. The resulting second-degree polynomial relationship between the best (i.e., minimal) total travel time solutions and the best CO system emissions solutions is clear in Figure 34. It is also evident the relationship is relatively strong with an R-square value of 0.9635. The second-degree polynomial equation defining the total travel time and NOx system emissions relationship remains relatively consistent for a given network.

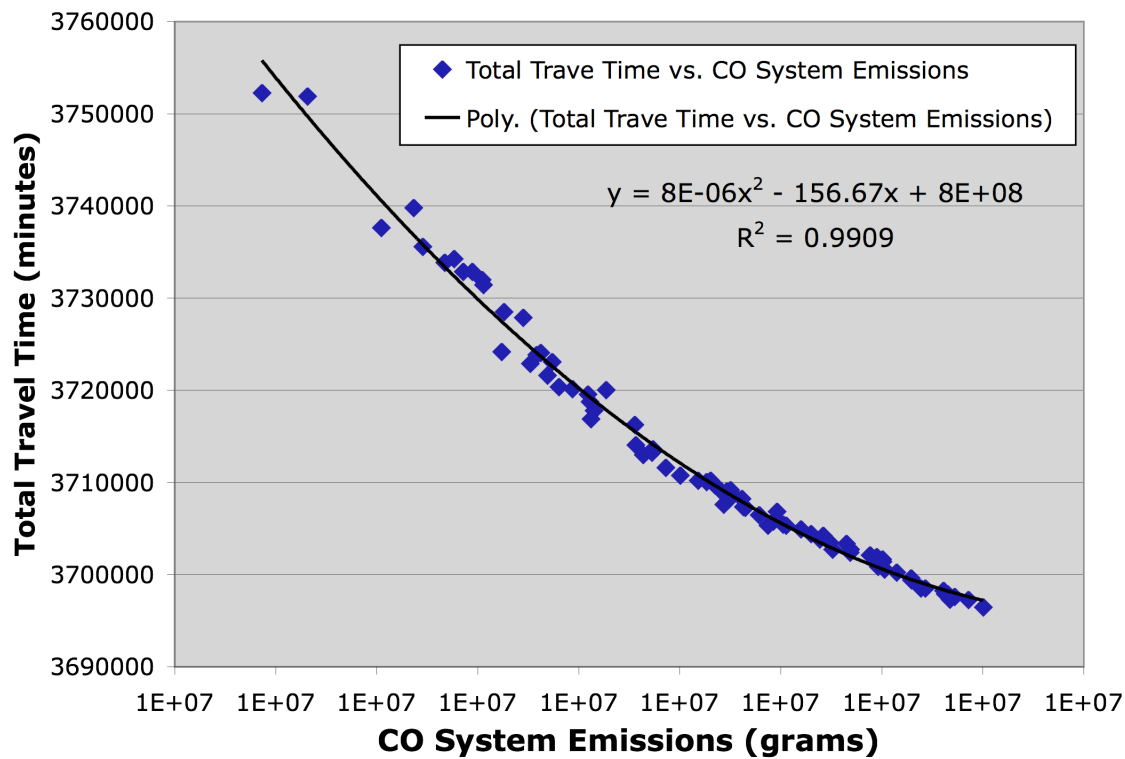


Figure 35. Total Travel Time vs. CO System Emissions, Non-Dominated Solutions for Anaheim Network, 72,000 vehicles/hour Budget, 200% OD Demand

The plot above is from analysis on the Anaheim network with 200% of the OD demand table loaded on the network and a capacity budget of 72,000 vehicles/hour. The resulting second-degree polynomial relationship between the best (i.e., minimal) total travel time solutions and the best CO system emissions solutions is clear in Figure 35. It is also evident the relationship is relatively strong with an R-square value of 0.9909.

Given that travel time and CO emissions have dissimilar shaped curves when plotted against average vehicle speed (see plots in Chapter 2) and the CO emissions rate plotted against average speed is bowl-shaped, the second-degree polynomial relationship between them seems reasonable. The second-degree polynomial is not as pronounced as the second-degree polynomial describing the relationship between total travel time and

NOx system emissions. This is likely related to the fact that the CO emissions rate versus average speed curve does not have as distinct of a bowl-shape as the NOx emissions rate versus average speed curve. Similar to NOx system emissions, the contrasting relationship in travel time and CO emissions total system values (e.g., when one increases the other decreases and vice versa) indicates the nature of the solutions selected to minimize each (i.e., system improvements selected) are fundamentally different. As a result, the solutions create notable differences in overall network performance. The difference in their solution characteristics is explored further in the sub-section titled Solution Characteristics.

As discussed and illustrated above, the relationship between total travel time and total VOC emissions tends to be linear, the relationship between total travel time and total NOx emissions tends to be a second-degree polynomial, and the relationship between travel time and total CO emissions also tends to be a second-degree polynomial. The consistency of these relationships is illustrated in Figure 36 through Figure 40. These figures show the R-square values for each of the relationships (i.e., total travel time vs. VOC system emissions, total travel time vs. NOx system emissions, and total travel time vs. CO system emissions) across the analysis scenarios for both test networks.

Figures 36 through 38 demonstrate how each of the above relationships change as the available budget increases.

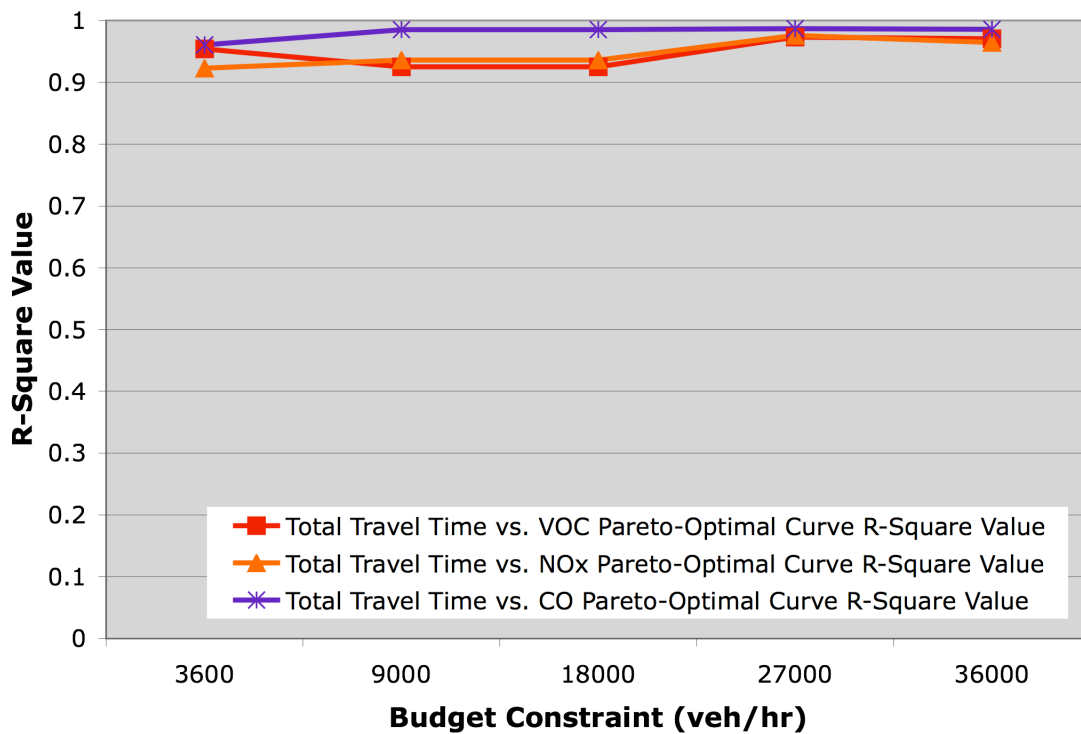


Figure 36. Pareto-Optimal R-Square Values as Budget Varies – Sioux Falls Network with Smaller Capacity Increments Added

Figure 36 illustrates the R-square values corresponding to the pareto-optimal curves of total travel time and each air pollutant. The plot in Figure 36 demonstrates each relationship (e.g., total travel time versus NOx system emissions) fits their respective curve or function type relatively well with R-square values greater than 0.90 as the available budget varies. The fit of each relationship tends to become stronger as the available budget increases. This is likely due to the fact that the solution method is able to find more feasible, good solutions as the budget constraint is relaxed, which in turn helps better define the relationships between total travel time and each pollutant.

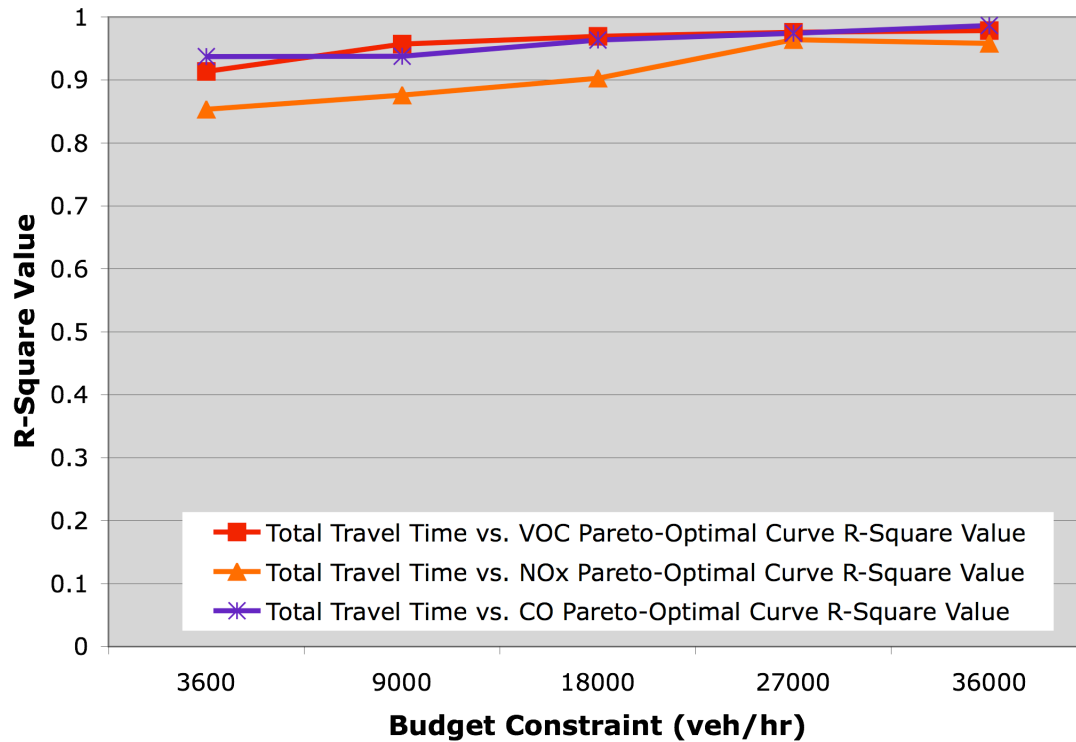


Figure 37. Pareto-Optimal R-Square Values as Budget Varies – Sioux Falls Network with Larger Capacity Increments Added

Figure 37 illustrates the R-square values corresponding to the pareto-optimal curves of total travel time and each air pollutant. The plot in Figure 37 demonstrates a trend consistent with that shown in Figure 36. Each relationship (e.g., total travel time versus CO system emissions) has a relatively strong fit to their respective defining function (e.g., linear) with R-square values of 0.85 or higher. The R-square value for each relationship tends to increase as the available budget increases. As noted previously, the stronger fit is attributed to more feasible, good solutions found as the budget constraint relaxes.

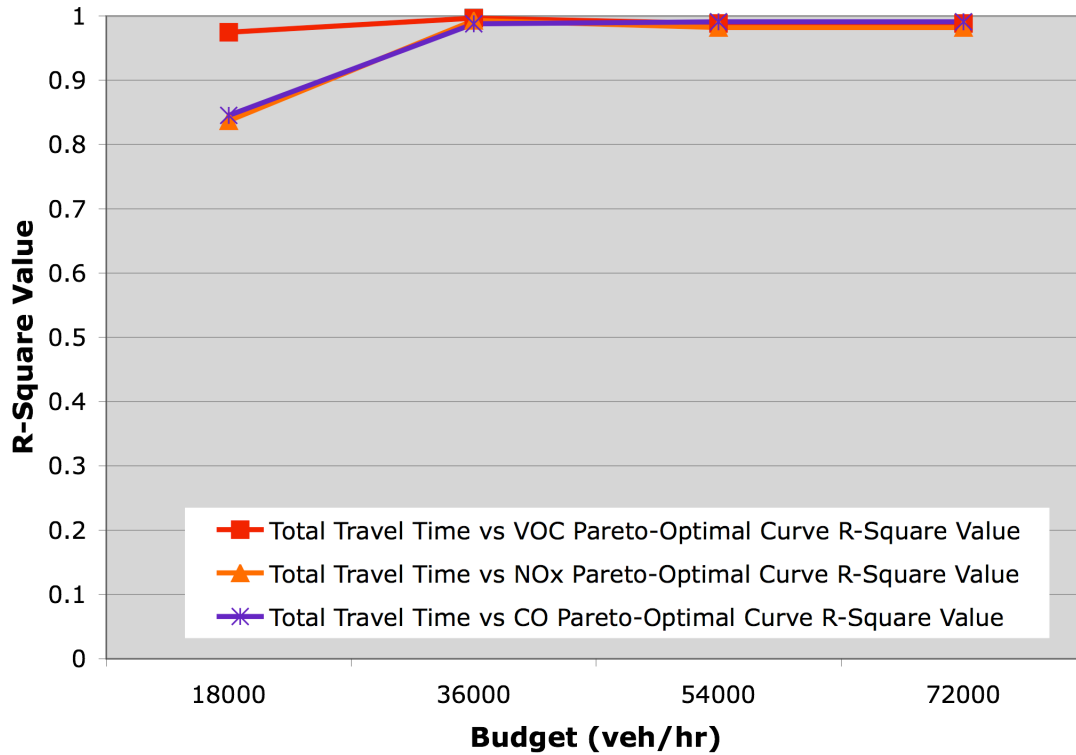


Figure 38. Pareto-Optimal R-Square Values as Budget Varies – Anaheim Network

Results from analysis on the Anaheim network, shown in Figure 38, are consistent with those from the Sioux Falls network. The relationships between total travel time and each pollutant (e.g., total travel time versus CO system emissions) have a relatively strong fit to their respective defining function (e.g., linear) with R-square values of 0.80 or higher. The R-square value for each relationship tends to increase as the available budget increases. As noted previously, the stronger fit is attributed to more feasible, good solutions found as the budget constraint relaxes.

Figures 39 and 40 illustrate how the R-square values change as demand (i.e., base congestion) on the network increases; results are shown from the Sioux Falls and Anaheim network analysis scenarios.

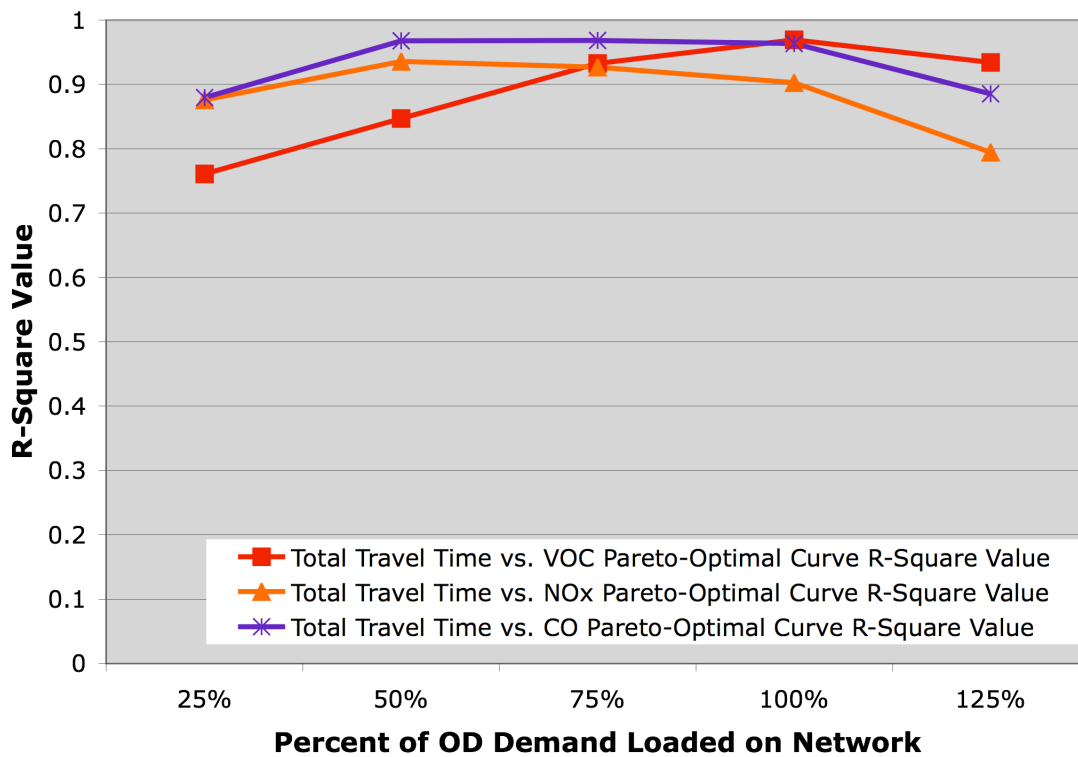


Figure 39. Pareto-Optimal R-Square Values as Demand (i.e., Congestion) Varies – Sioux Falls Network

As illustrated in Figure 39, the relationships between total travel time and each pollutant remain relatively strong as base congestion on the network increases with each R-square value near or greater than 0.75. However, it is clear the best fits tend to be under moderately congested to congested conditions (75% to 100% of OD demand on the Sioux Falls network). The relationships between total travel time and each pollutant are less strong under uncongested conditions or severely congested conditions. Similar to the influence of the available budget, it seems likely the lower R-square values are due to the reduced number of feasible, good solutions found. Under uncongested or severely congested conditions the number of feasible, good solutions are likely lower compared to moderately congested and congested conditions. In uncongested conditions, the system

is operating so well few improvements exist that can improve system performance. In severely congested conditions, the system is operating so poorly there is a smaller set of valuable, good improvements. In both instances (uncongested and severely congested conditions), this results in fewer solution points with which to define the relationships between total travel time and each pollutant.

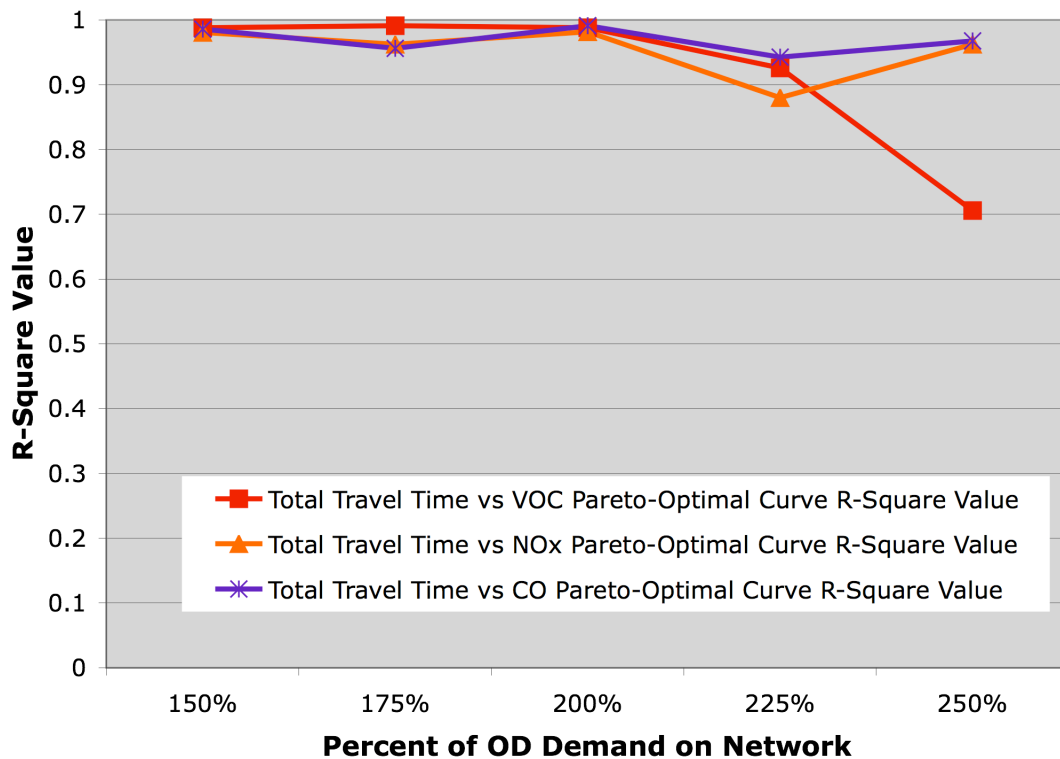


Figure 40. Pareto-Optimal R-Square Values as Demand (i.e., Congestion) Varies – Anaheim Network

As can be seen in Figure 40, the R-square values from analysis on the Anaheim network are relatively consistent with results from the Sioux Falls analysis scenarios. The relationships between total travel time and each pollutant remain relatively strong as base congestion on the network increases with each R-square value near or greater than 0.70. However, it is clear the best fits tend to be under moderately congested to

congested conditions (150% to 200% of OD demand on the network). The relationships between total travel time and each pollutant are less strong under severely congested conditions. Unlike the results on the Sioux Falls network, the R-square values are relatively high even at the lower levels of demand on the Anaheim network. This is likely because uncongested conditions on the Anaheim network are not as uncongested as the uncongested conditions on the Sioux Falls network.

Pareto-optimal curves and R-square values displayed above demonstrate the relatively consistent relationships between total travel time and system emissions of each pollutant. Such curves and relationships can be useful in the context of transportation planning enabling system managers to select system changes that fall somewhere in the middle of the total travel time versus NO_x (or CO) system emissions curves thereby striking a balance between the conflicting performance measures. Or, system managers can select changes that fall at either end of the curve, but can do so understanding the tradeoffs with regards to total travel time or system emissions.

Influence of Demand Uncertainty on System Performance

Results from incorporating demand uncertainty into the Sioux Falls network indicate: 1) accounting for demand uncertainty results in better system performance for each objective (i.e., designs achieve lower total travel time and lower emissions); and 2) the pareto-optimal curves between expected total travel time and each pollutant have similar shapes to those under fixed demand. Each of these results is discussed in more detail below. Collectively, the results demonstrate the value of incorporating demand uncertainty considerations into the emissions network design problem.

Figure 41 through Figure 44 illustrate the expected value of each performance measure (e.g., VOC system emissions) when the problem was solved to minimize each measure considering demand uncertainty. These expected values are compared to the

expected values calculated with the solutions found under the fixed demand analysis scenarios. The overall trend across the four figures is: accounting for demand uncertainty in network design improves expected system performance particularly as demand uncertainty increases. This is true when designing for minimal expected total travel time or any of the three pollutants.

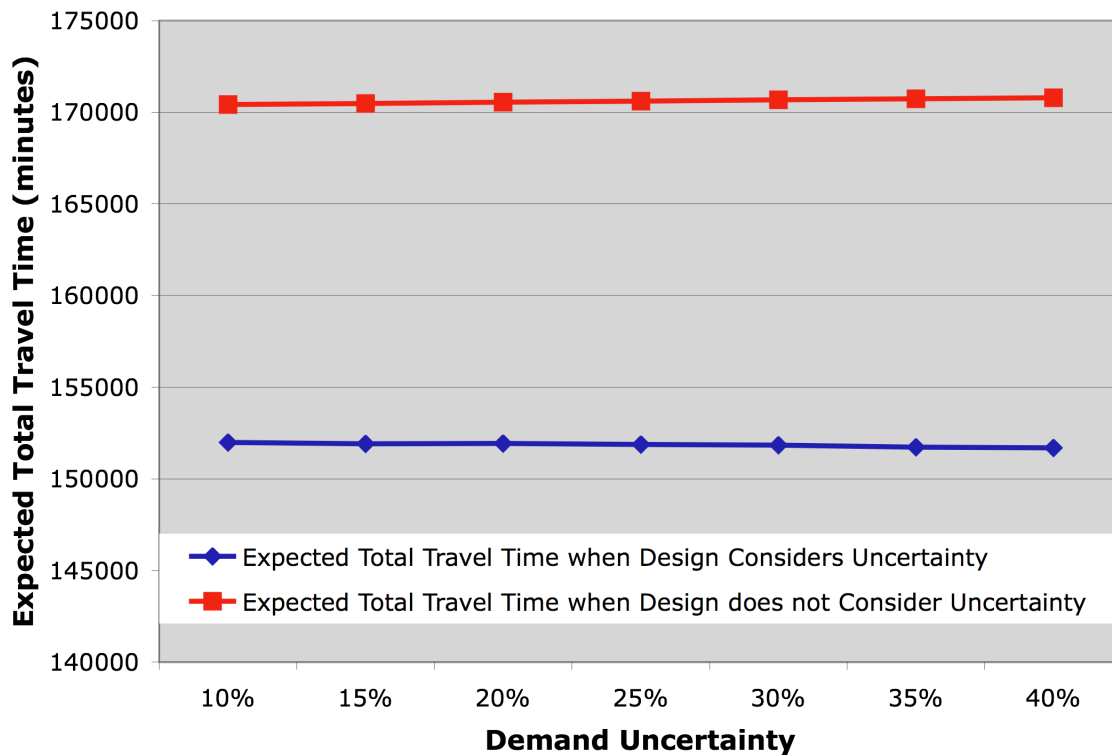


Figure 41. Total Travel Time with Fixed Demand Compared to Expected Total Travel Time with Uncertain Demand – Sioux Falls Network

Figure 41 illustrates expected total travel time on the system is approximately 18,500 to 19,100 minutes lower when the network design problem and solution method consider demand uncertainty in searching for system improvements to minimize expected total travel time. The optimal solution found to minimize total travel time under the fixed demand scenario results in 18,500 to 19,100 minutes additional travel time on the

network when demand uncertainty increases. Therefore, the fixed demand solution is expected to perform significantly worse on an actual network than a solution based upon designing for demand uncertainty. These findings underscore the importance of considering demand uncertainty when designing a network for minimal total travel time and are consistent with findings from Waller et al. (2001).

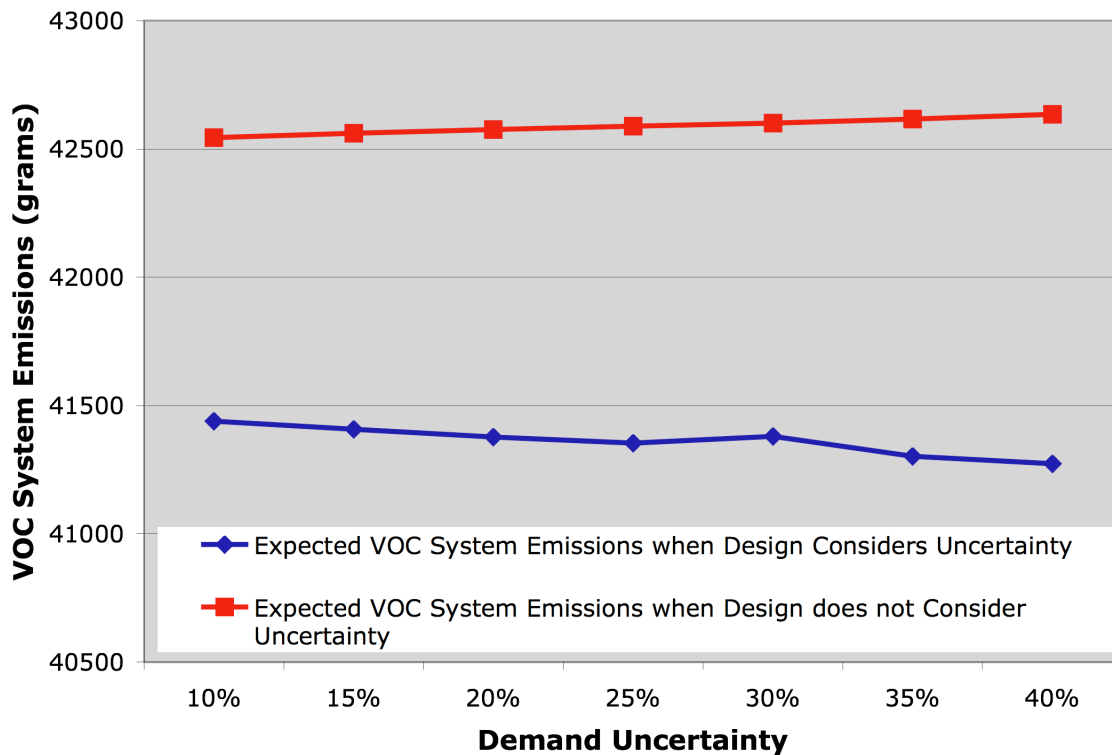


Figure 42. VOC System Emissions with Fixed Demand Compared to Expected VOC System Emissions with Uncertain Demand – Sioux Falls Network

Similar to total travel time, Figure 42 demonstrates the fixed demand solution to minimize VOC system emissions results in 11,000 to 13,050 additional grams of VOC emissions compared to the solution arrived at when demand uncertainty is incorporated into the problem. Therefore, the fixed demand solution would result in substantially more VOC system emissions under actual network conditions than the solution arrived at

when demand uncertainty is incorporated into the problem. It is also clear from Figure 42 that the difference in performance between the fixed demand solution and the uncertain demand solution increases as demand uncertainty increases. Therefore, as demand uncertainty increases the need to consider demand uncertainty when identifying changes to the network also increases in importance.

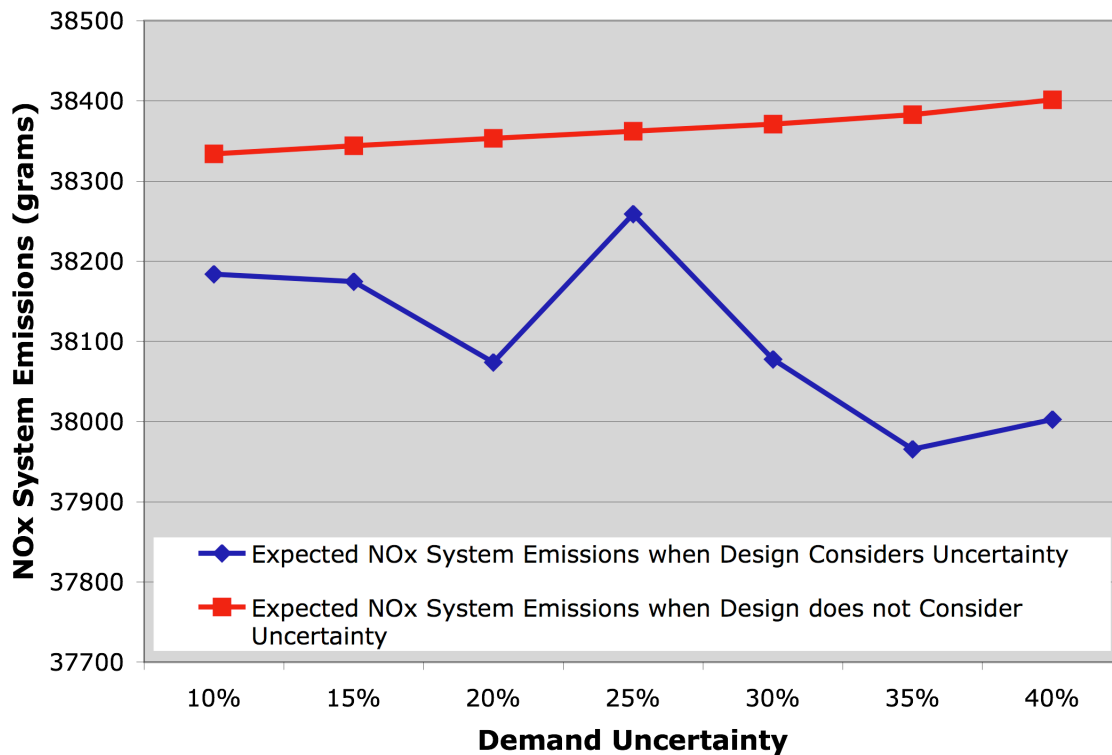


Figure 43. NOx System Emissions with Fixed Demand Compared to Expected NOx System Emissions with Uncertain Demand – Sioux Falls Network

Figure 43 indicates the optimal solution found to minimize NOx system emissions under the fixed demand scenario results in 150 to 420 additional grams of NOx emissions on the network when demand varies. The differences in the amount of NOx emissions are significant considering: 1) the allowable annual average NOx emissions level for a metropolitan region is 0.0001 grams/m³ (EPA, 2009d); and 2) the analysis results above

consider a moderately congested base demand associated with only the peak evening period of a single day. Therefore, the fixed demand solution to minimize NOx system emissions would perform significantly worse on an actual network than a solution arrived at by designing for demand uncertainty. Similar to the findings for VOC system emissions, it is also clear the difference between NOx system emissions under the fixed demand and uncertain demand solutions increase with increasing demand uncertainty. Both of these findings further reinforce the value of incorporating demand uncertainty into network design.

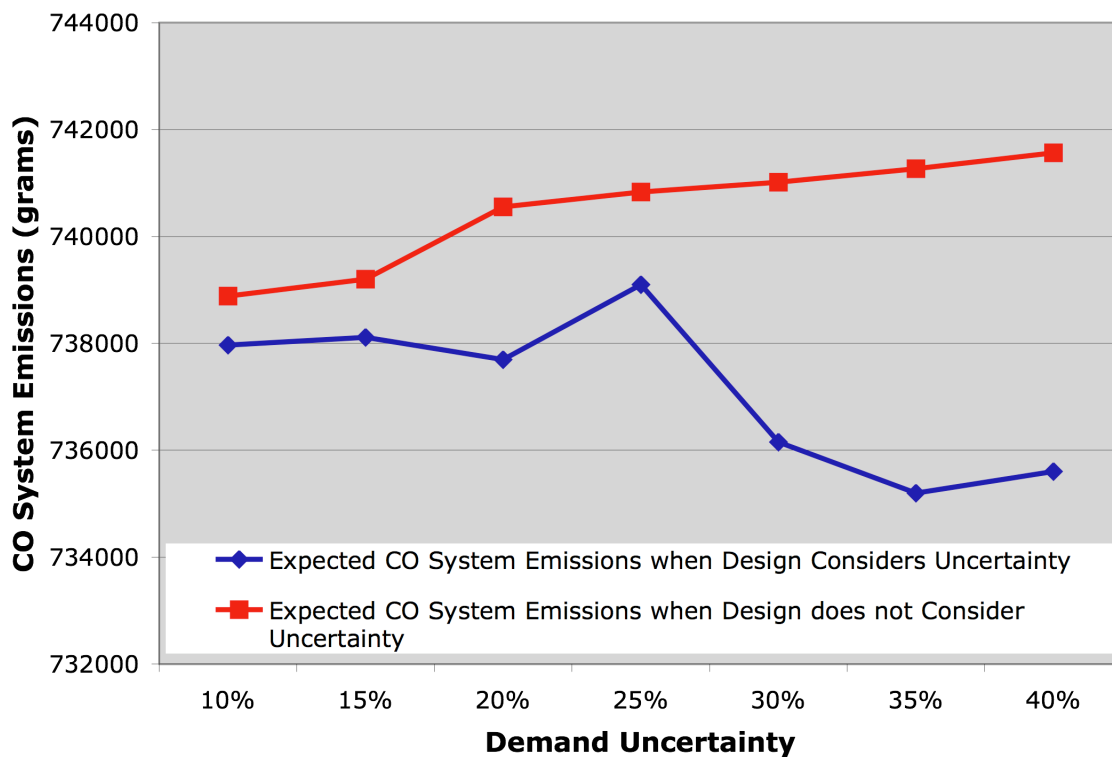


Figure 44. CO System Emissions with Fixed Demand Compared to Expected CO System Emissions with Uncertain Demand – Sioux Falls Network

Figure 44 illustrates the fixed demand solution to minimize CO system emissions consistently performs worse than the solution found incorporating demand uncertainty.

The fixed demand solution would result in 900 to 6,000 additional grams of CO emissions. It is also evident from Figure 44 that the difference in performance increases as demand uncertainty increases. The differences in the amount of CO emissions are significant considering: 1) the allowable CO emissions level for a metropolitan region is 0.04 grams/m³ for a 1-hour average and the 8-hour average measurement limit is 0.01 grams/m³ (EPA, 2009d); and 2) the analysis results above consider a moderately congested base demand associated with only the peak evening period of a single day. These findings further reinforce the value of and need to incorporate demand uncertainty into network design.

As noted, accounting for demand uncertainty in network design improves expected system performance particularly as demand uncertainty increases. This is consistently true for each of the system performance measures considered as shown in Figures 41 through 44. Due to the relationship between NO_x emissions and average vehicle speed as well as CO emissions and average vehicle speed, accounting for demand uncertainty is particularly critical for these performance measures. Designs that create too high or too low of average vehicle speeds can be detrimental to minimizing NO_x and CO system emissions; therefore, finding the right balance, the most robust solutions for long term variations in demand (i.e., demand uncertainty) is paramount.

The second significant finding from incorporating demand uncertainty is: the pareto-optimal curves defining the relationship between total travel time and each pollutant remained similar. When demand uncertainty is incorporated into the network design problem, the linear relationship between expected total travel time and expected VOC system emissions remains valid. Similarly, a second-degree polynomial still defines the relationship between expected total travel time and expected NO_x system emissions. Also, a second-degree polynomial still defines the relationship between

expected total travel time and expected CO system emissions. However, the precise equations defining each relationship under demand uncertainty are different than those under fixed demand. Overall, these findings are significant because it means system managers can expect the same basic relationships between total travel time and each air pollutant to remain valid even as demand uncertainty increases.

Figure 45 illustrates the R-square values for the relationships between expected total travel time and the expected system emissions for each pollutant.

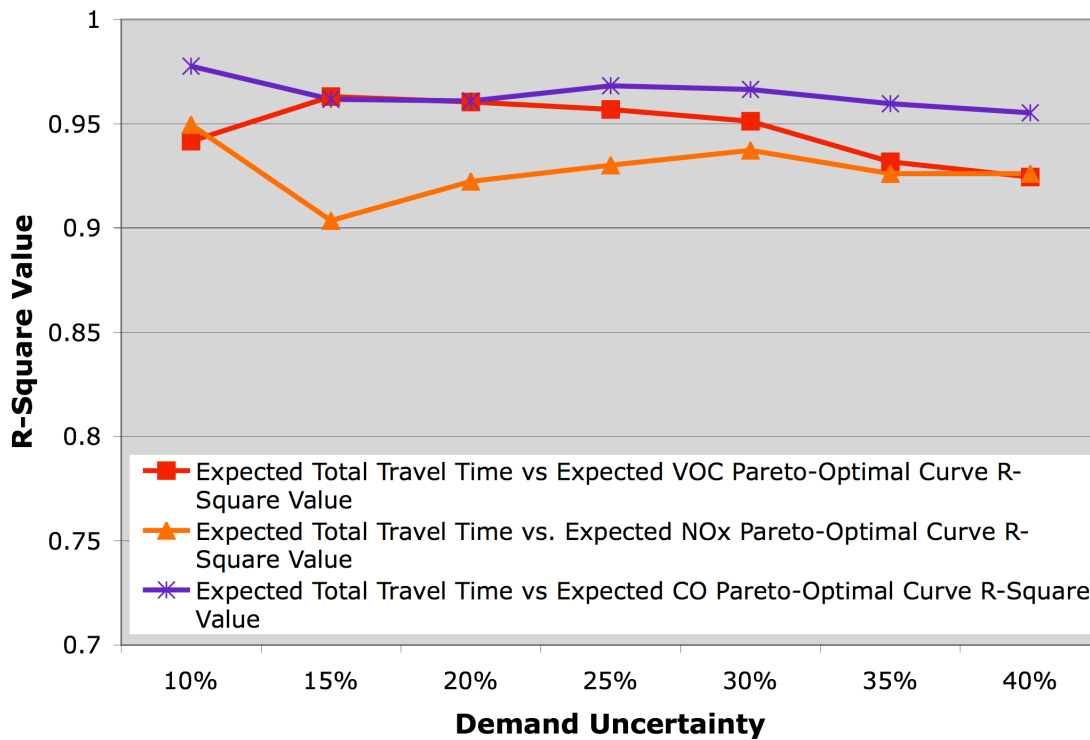


Figure 45. R-Square Values for Pareto-Optimal Curves as Demand Uncertainty Increases

As can be seen in Figure 45, the R-square value for each type of relationship remains relatively strong (greater than 0.9) as demand uncertainty increases. However, the fluctuations in the values do not have an apparent consistent trend as demand uncertainty increases. Furthermore, the precise equations defining each relationship vary

more across each scenario compared to the relatively consistent equations under the fixed demand analysis scenarios.

Incorporating demand uncertainty illustrates: 1) accounting for demand uncertainty is critical for consistently improving system performance on a network subject to variations in demand; and 2) the nature of the relationships between total travel time and each pollutant remained the same under demand uncertainty. Modeling the emissions network design problem with demand uncertainty provides more robust and realistic solutions for designing a network for minimal expected total travel time and/or designing a network for minimal expected emissions.

Summary of Effects on System Performance

Analysis on the Sioux Falls and Anaheim networks illustrate the following notable findings with regards to system performance.

1) Designing for minimal total travel time and minimal VOC system emissions is similar. When total travel time is minimal, VOC system emissions also tends to be minimal and vice versa.

2) Designing for minimal NO_x system emissions and minimal CO system emissions is similar; when one is minimized, the other also tends to be minimized.

3) When a network is designed for minimal total travel time or minimal VOC system emissions, NO_x and CO system emissions tend to increase relative to their respective minimal values. The magnitude of the increase depends on the level of base congestion on the network and the percent of the network eligible for improvement. In the analysis for this research, the increase in NO_x and CO system emissions ranged from 0.75% to 6%.

4) When a network is designed for minimal NO_x system emissions or minimal CO system emissions, total travel time and VOC system emissions tend to increase

relative to their respective minimal values. Again, the magnitude of the increase depends on the level of base congestion on the network and the percent of the network eligible for improvement. In the analysis for this research, the increase in total travel time and VOC system emissions ranged from 1% to 17%.

5) The relationship between total travel time and each pollutant can be defined relatively consistently by either a linear function or a second-degree polynomial function. These relationships are consistent across networks as well as under fixed or uncertain demand.

6) Accounting for demand uncertainty produces more robust, reliable, and effective solutions to improve system performance. The fixed demand solutions perform significantly worse (in terms of total travel time and emissions of each pollutant) in situations where demand varies. Accounting for demand uncertainty is critical for finding solutions effective at improving system performance on networks subject to variations in demand.

These findings and corresponding trends noted above are potentially useful for system managers faced with the task of identifying changes to regional road networks to improve system performance under an emissions constrained environment. Each of the findings above provides insight into the tradeoffs in system performance between designing a network for minimal total travel time versus a specific pollutant. These insights can be valuable in informing planning policies and the general approach taken to planning road network modifications. It is clear from the findings above, minimizing network congestion does not produce minimal emissions of critical criteria pollutants such as NO_x or CO. The following sub-section discusses the solution characteristics when the network is designed for minimal total travel time versus the solution characteristics when the network is designed to minimize emissions.

Solution Characteristics

The solution characteristics for the various analysis scenarios were explored to better understand some of the fundamental differences between designing a network for minimal total travel time versus designing a network for minimal system emissions. Based on the literature review related to traffic assignment and network pricing research incorporating emissions, we expected designs minimizing total travel time and VOC system emissions to favor capacity additions to freeways over arterials. This was expected based on similar findings in the traffic assignment and network pricing research incorporating emissions and seemed reasonable as free flow travel time on freeways is higher than free flow travel time on arterial roadways (see Rilett and Benedek, 1994; Benedek and Rilett, 1998; Sugawara and Niemeier, 2002; Yin and Lawphongpanich, 2006; Ahn and Rakha, 2008). However, no such trend existed within the emission network design model results. Instead, we saw trends related to the amount of the available budget used to minimize each performance measure and the types of system improvements made when each performance measure was minimized. The following two sub-sections discuss these trends.

Influence of Available Budget

The results from analysis scenarios with the base congestion fixed and the amount of available budget variable revealed differences in how much of the available budget is used to minimize each of the performance measures. From analysis scenarios on the Sioux Falls network, a general trend emerged in which minimizing total travel time and VOC system emissions appear to consistently use more of the available budget than minimizing NOx and CO system emissions. Figures 47 through 50 illustrate this trend.

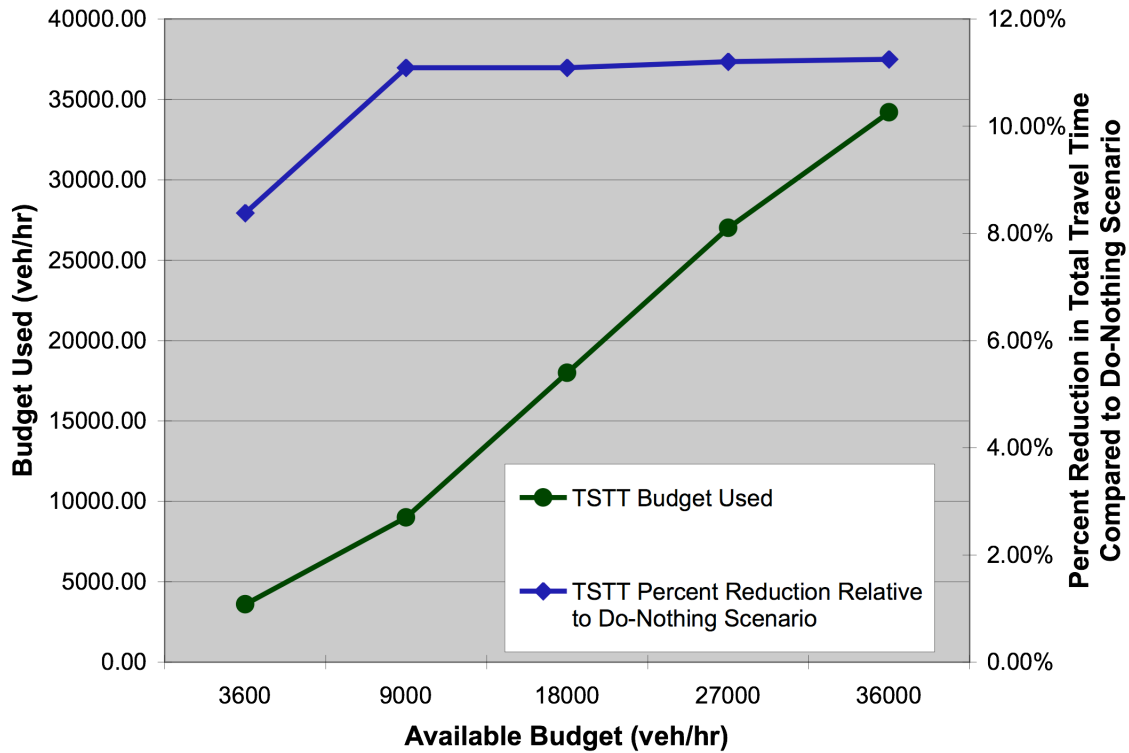


Figure 47. Budget Used in Minimizing Total Travel Time and Percent Reduction in Total Travel Time Relative to Do-Nothing Scenario on Sioux Falls Network

Figure 47 illustrates that the majority of the percent reduction in total travel time relative to total travel time in the do-nothing scenario can be achieved by adding 9,000 vehicles/hour of capacity to the network. Spending additional resources to add more capacity only increases the percent reduction in total travel time marginally. Figure 47 also illustrates that for each analysis scenario, most, if not all, of the available capacity budget is used when designing the network for minimal total travel time.

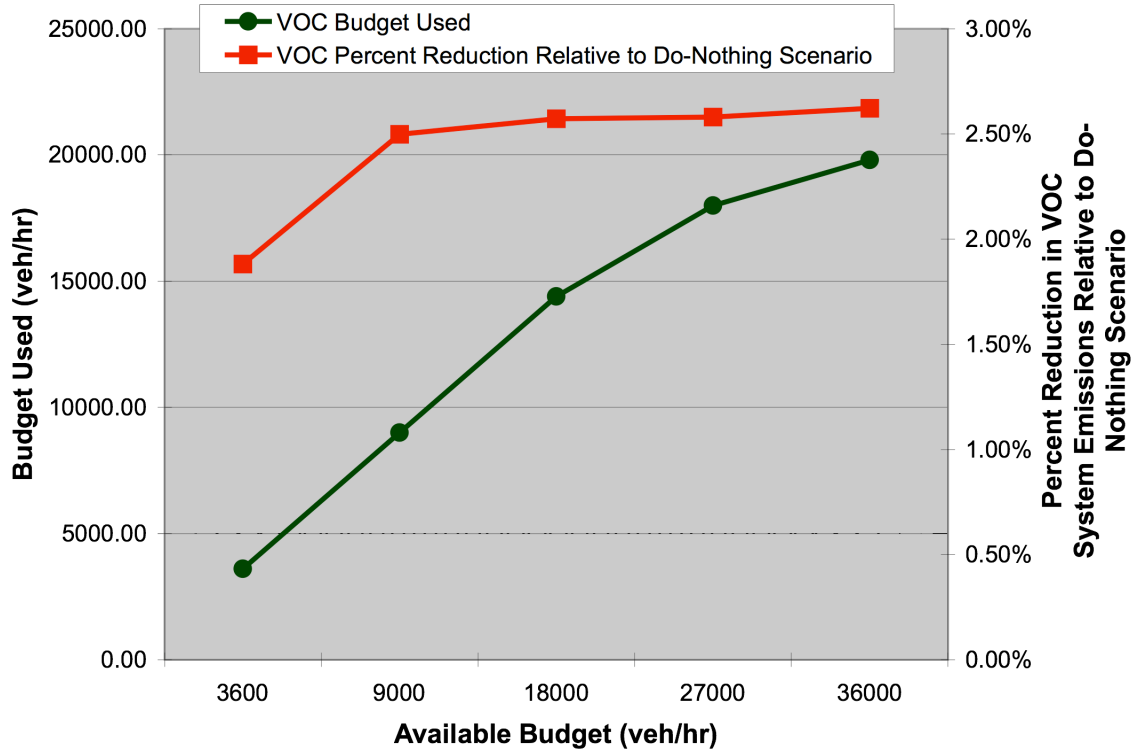


Figure 48. Budget Used in Minimizing VOC System Emissions and Percent Reduction in VOC System Emissions Relative to Do-Nothing Scenario on Sioux Falls Network

Similar to when the network is designed for minimal total travel time, Figure 48 illustrates the majority of the percent reduction in VOC system emissions relative to VOC system emissions in the do-nothing scenario can be achieved by adding 9,000 vehicles/hour of capacity to the network. Spending additional resources to add more capacity only increases the percent reduction in VOC system emissions marginally. Figure 48 also demonstrates that for each analysis scenario, most, if not all, of the available capacity budget is used when designing the network for minimal VOC system emissions.

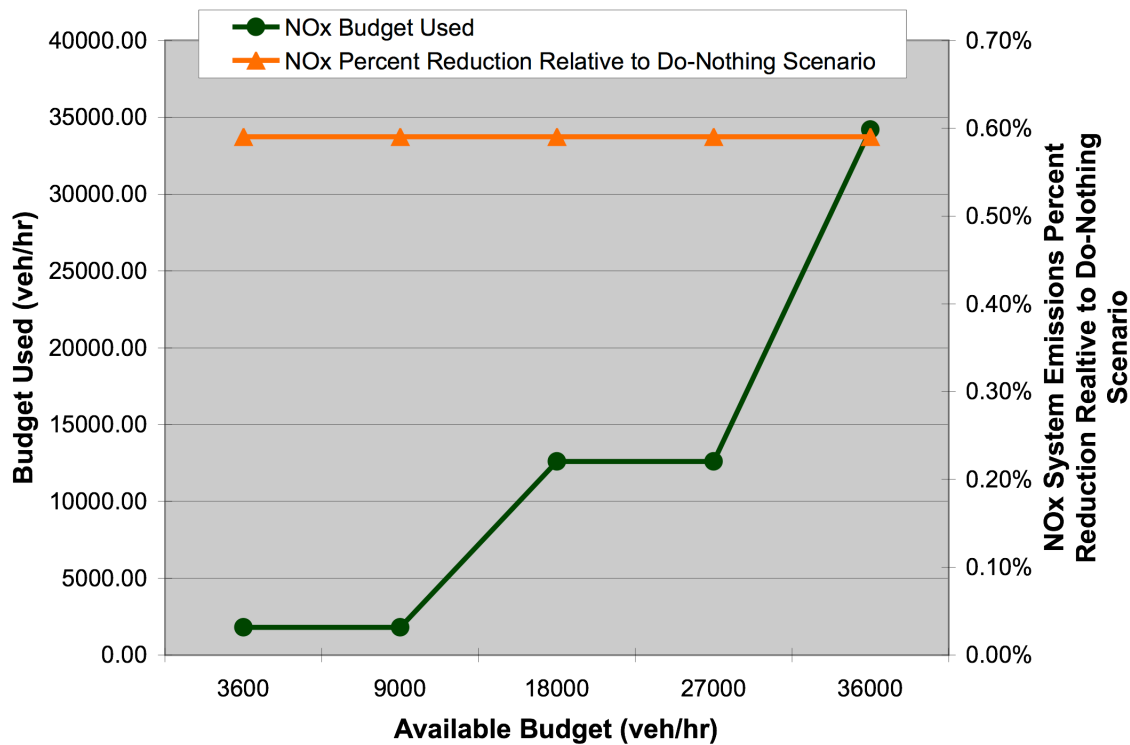


Figure 49. Budget Used in Minimizing NOx System Emissions and Percent Reduction in NOx System Emissions Relative to Do-Nothing Scenario on Sioux Falls Network

Similar to when the network is designed for minimal total travel time and VOC system emissions, Figure 49 illustrates the majority of the percent reduction in NOx system emissions relative to NOx system emissions in the do-nothing scenario can be achieved without spending large amounts of the available budget. However, dissimilar to total travel time and VOC system emissions, Figure 49 demonstrates that for most analysis scenarios, relatively smaller amounts of the available budget are spent when designing the network for minimal NOx system emissions. The exception to this trend is the scenario with the budget limit of 36,000 vehicles/hour.

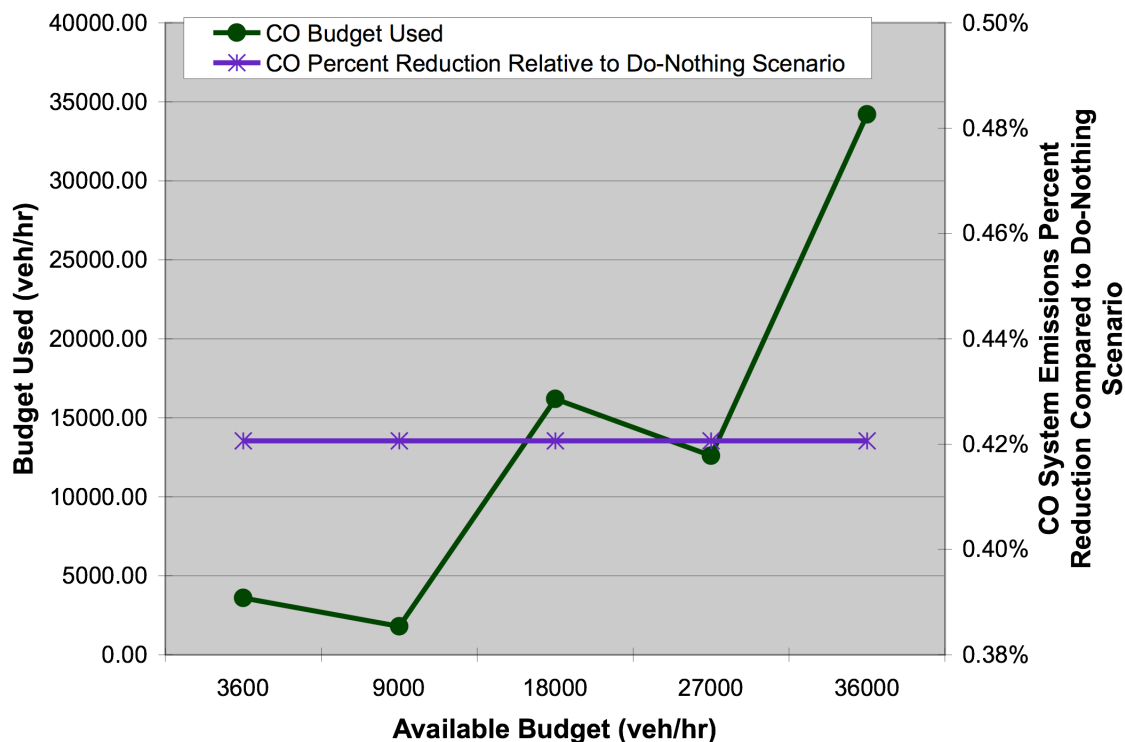


Figure 50. Budget Used in Minimizing CO System Emissions and Percent Reduction in CO System Emissions Relative to Do-Nothing Scenario on Sioux Falls Network

Similar to when the network is designed for each of the previous objectives discussed, Figure 50 illustrates the majority of the percent reduction in CO system emissions relative to CO system emissions in the do-nothing scenario can be achieved without spending large amounts of the available budget. Also, similar to NOx system emissions, Figure 50 demonstrates that for most analysis scenarios, relatively smaller amounts of the available budget are spent when designing the network for minimal CO system emissions. The exception to this is the scenario with 36,000 vehicles/hour budget limit.

Collectively, figures 47 through 50 illustrate to minimize NOx and CO system emissions doing less is often better than doing too much in terms of capacity additions to

the system. However, as noted above, in each analysis scenario the do-nothing scenario did not result in minimal NOx or CO system emissions – some improvements could always be made to further reduce NOx or CO system emissions over the corresponding do-nothing scenario. Nevertheless, the trend in the amount of budget used versus the improvement in the system demonstrates even with a relatively small budget, gains in reducing total travel time, VOC, NOx and CO emissions can be made. These gains are also likely to increase as base congestion or demand on the network increases as demonstrated previously in Figure 17 and Figure 18. Furthermore, in most instances a threshold is reached at which point spending more to reduce total travel time, VOC system emissions, NOx system emissions, or CO system emissions does not result in proportional reductions in total travel time, VOC system emissions, NOx system emissions, or CO system emissions. Therefore, in some instances it may not be worth the additional investment to get such a marginal return.

The following Figures 51 through 54 illustrate the relative difference in each performance measure as the available budget increases for a given demand and set of eligible links on the Anaheim network. In the case of the Anaheim network with 40 eligible links, each of the performance measures tends to improve approximately the same amount over the do-nothing scenario despite increasing the budget available.

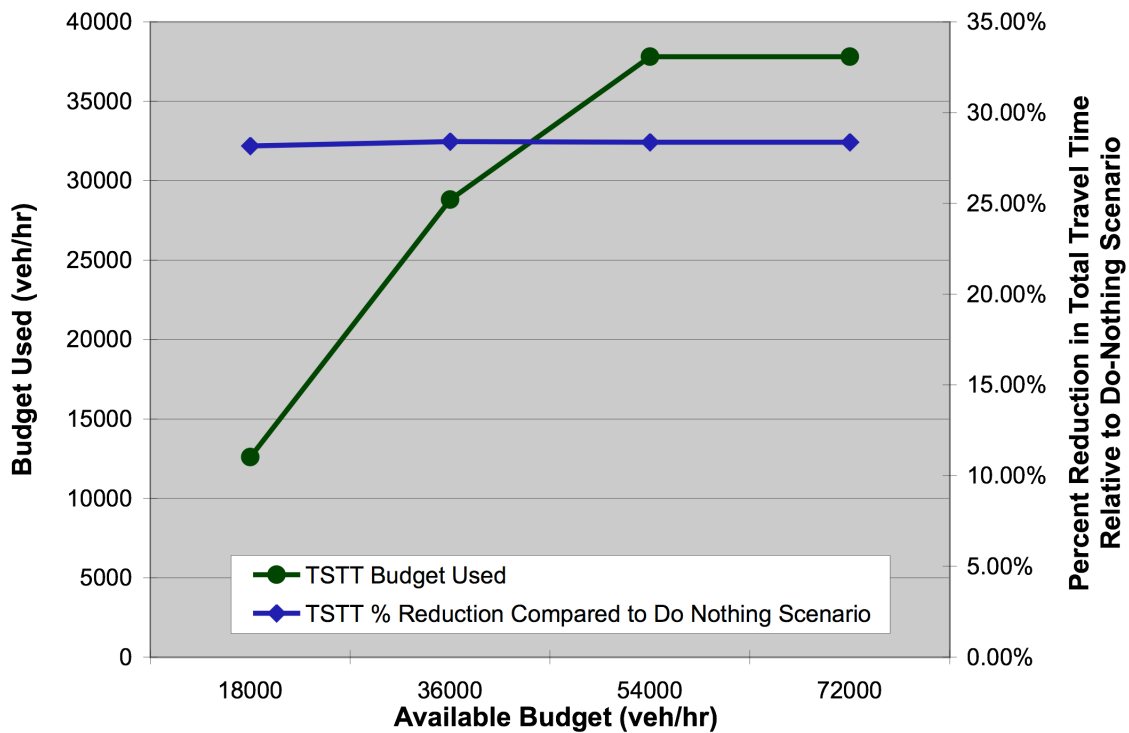


Figure 51. Budget Used in Minimizing Total Travel Time and Percent Reduction in Total Travel Time Relative to Do-Nothing Scenario on Anaheim Network

Figure 51 is consistent with the trend seen in Figure 47 from the analysis on the Sioux Falls network. The majority of the percent reduction in total travel time relative to total travel time in the do-nothing scenario can be achieved with the 18,000 vehicles/hour capacity budget. Spending additional resources to add more capacity increases the percent reduction in total travel time marginally.

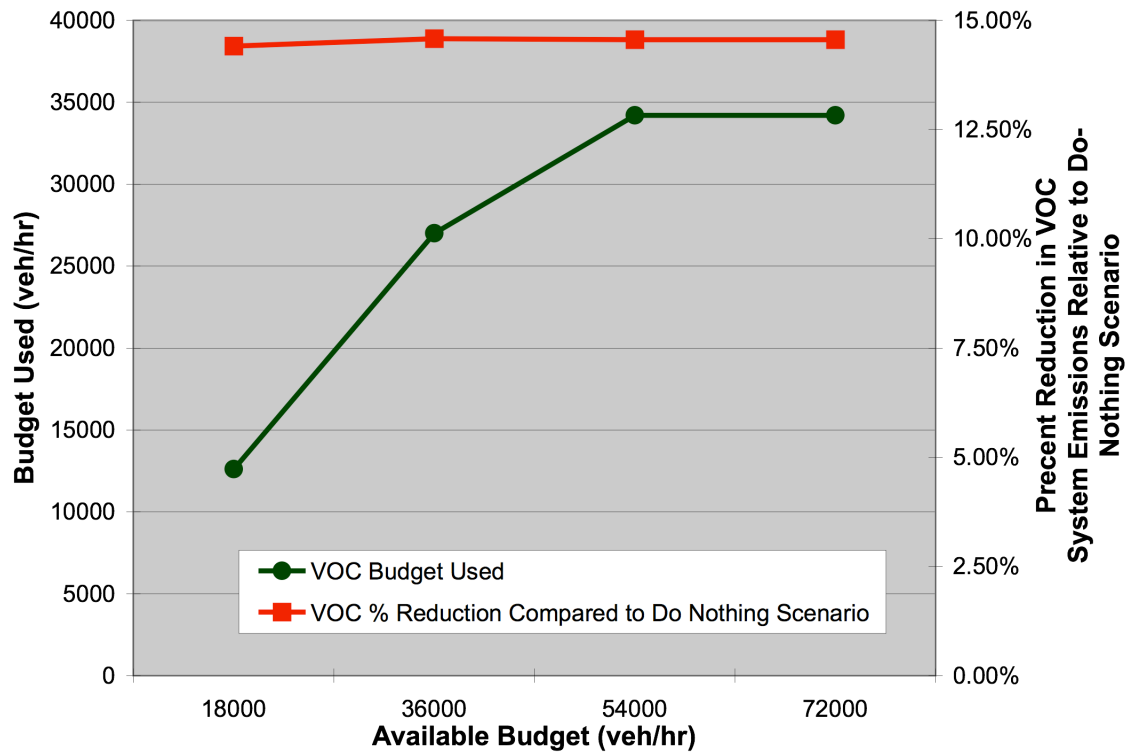


Figure 52. Budget Used in Minimizing VOC System Emissions and Percent Reduction in VOC System Emissions to Do-Nothing Scenario on Anaheim Network

Figure 52 is consistent with the trend seen in Figure 48 from the analysis on the Sioux Falls network. The majority of the percent reduction in VOC system emissions relative to VOC system emissions in the do-nothing scenario can be achieved with the 18,000 vehicles/hour capacity budget. Spending additional resources to add more capacity increases the percent reduction in VOC system emissions marginally.

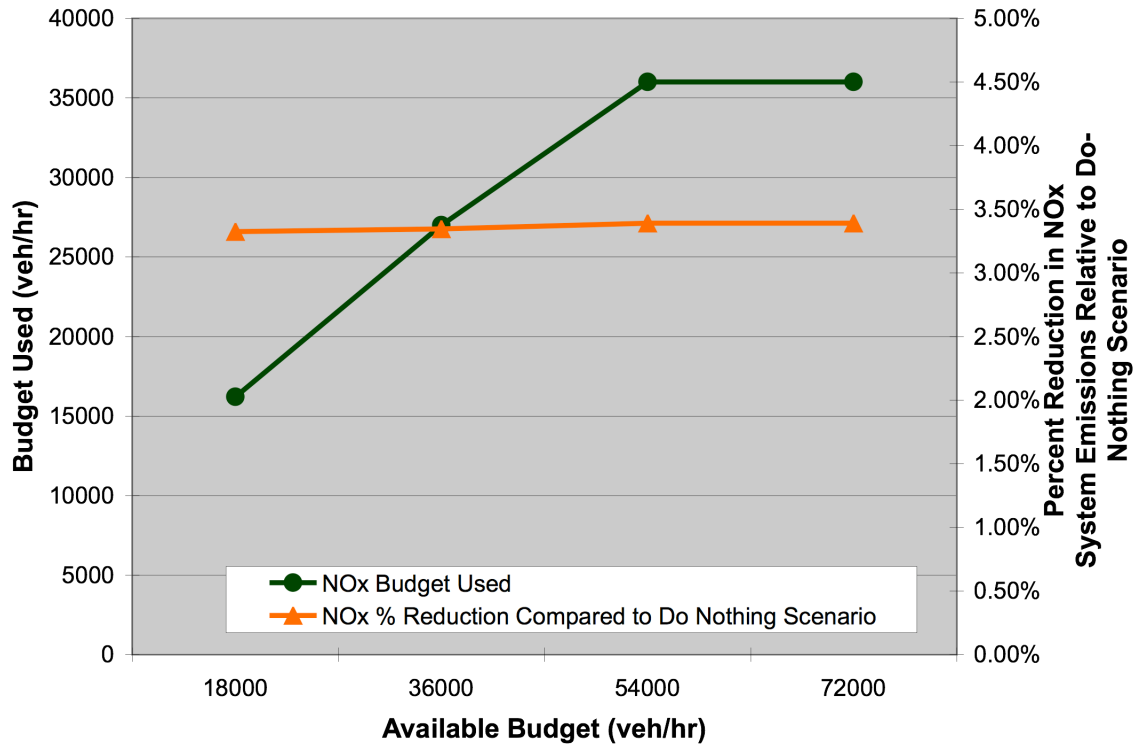


Figure 53. Budget Used in Minimizing NOx System Emissions and Percent Reduction in NOx System Emissions to Do-Nothing Scenario on Anaheim Network

Figure 53 is consistent with the trend seen in Figure 49 from the analysis on the Sioux Falls network. The majority of the percent reduction in NOx system emissions relative to NOx system emissions in the do-nothing scenario can be achieved with the 18,000 vehicles/hour capacity budget. Spending additional resources to add more capacity increases the percent reduction in NOx system emissions marginally.

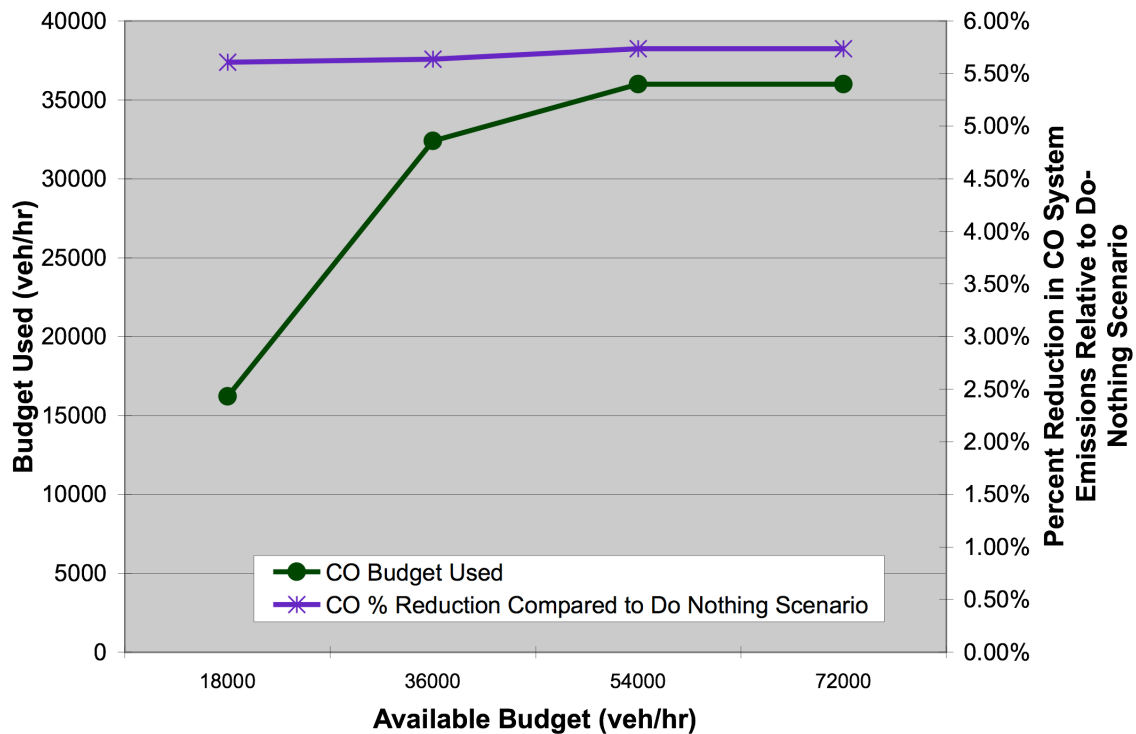


Figure 54. Budget Used in Minimizing CO System Emissions and Percent Reduction in CO System Emissions to Do-Nothing Scenario on Anaheim Network

Figure 54 is consistent with the trend seen in Figure 50 from the analysis on the Sioux Falls network. The majority of the percent reduction in CO system emissions relative to CO system emissions in the do-nothing scenario can be achieved with the 18,000 vehicles/hour capacity budget. Spending additional resources to add more capacity increases the percent reduction in CO system emissions marginally.

Figures 51 through 54 illustrate the same general threshold trend as discussed with the Sioux Falls network results: spending more does not guarantee proportional improvements for each performance measure.

The key finding from the results, shown in figures 47 through 54, for system managers is: given a relatively small percent of links eligible for improvement on a

network and/or a relatively limited budget, it is not necessary to improve all of those eligible links to obtain meaningful improvements in performance measures. For example, results from the Anaheim network demonstrate with only 4.36% of links eligible for improvement and 18,000 vehicles/hour budget available, total system travel time can be reduced by nearly 30%, VOC system emissions can be reduced by nearly 15%, NOx system emissions can be reduced by approximately 3.5% and CO can be reduced by approximately 6%. Of course, each percent reduction requires a different set of system changes (with similarities existing between travel time and VOC and similarities existing between NOx and CO), so the system manager will need to decide which performance measure(s) is most critical. However, knowing that such substantial gains can be achieved by spending reasonable amounts of resources intelligently and strategically is powerful when planning in a fiscally constrained environment. Finally, as noted above in General Findings, as congestion on the network increases, the potential for improving system performance measures relative to each other and the do-nothing scenario increases. Which, in-turn makes system design incorporating emissions more critical so resources can be used efficiently to obtain the biggest return on investments particularly when road networks are congested and demand uncertain.

Key Difference between System Changes per Performance Measure

As discussed in the sub-section Pareto-Optimal Curves, the contrasting relationship between the total system values of NOx (or CO) and travel time (e.g., when one increases the other decreases and vice versa) indicates the nature of the solutions selected to minimize each (i.e., system improvements selected) are fundamentally different. The fundamental difference found between the solutions to minimize each performance measure is related to link speeds after system changes are made; this is discussed further below.

In instances where total travel time or total VOC emissions are minimized the improvements selected focus on improving as many links as possible such that they operate at or near their free flow speed. It does not appear to matter whether the links are arterials or freeways. The consistent trend is: improvements selected to minimize total travel time and total VOC system emissions are those that improve as many links (of any type) to as close to their free flow speed as possible. In contrast, improvements minimizing NOx and CO system emissions consistently favor sets of improvements that improve some but not all links to near or close to their free flow speed. This trend and relationship is most readily seen by looking at the percent of links at or within 5% of their respective free flow speeds after each performance measure is minimized. Figures 55 and 56 illustrate this trend (as base congestion on the network increases) for the Sioux Falls and Anaheim networks, respectively.

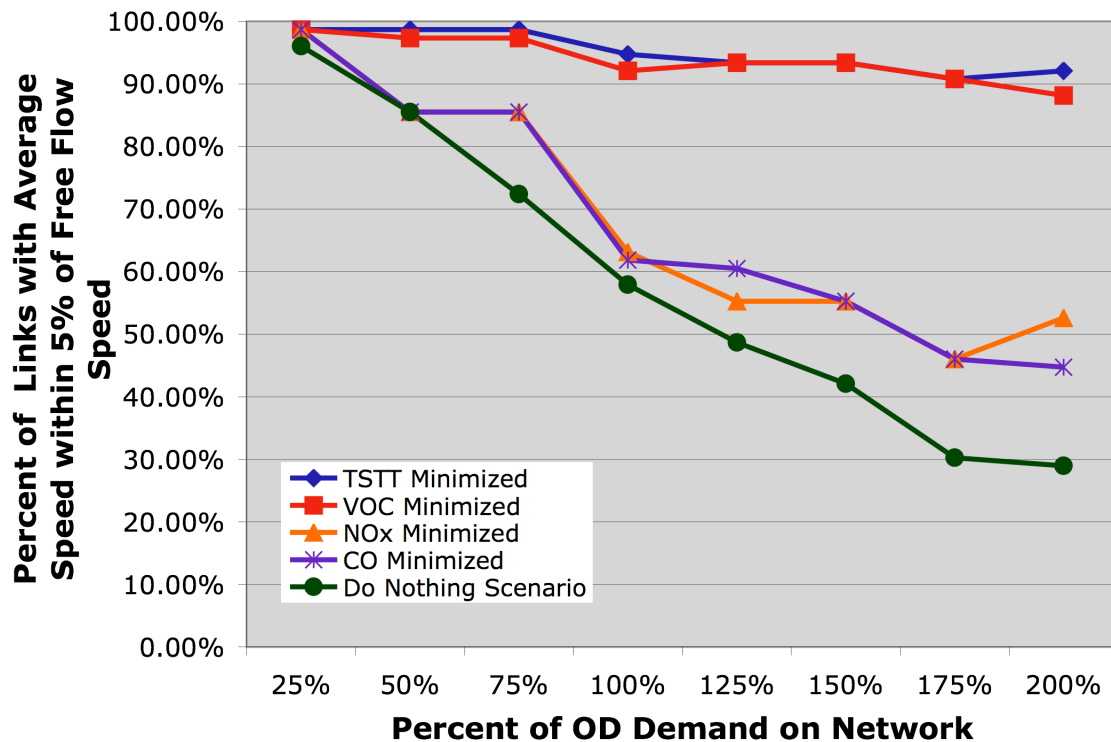


Figure 55. Percent of Eligible Links with Average Speeds within 5% of Free Flow Speed after Improvements to Sioux Falls Network

Figure 55 illustrates when the network is designed for minimal total travel time or minimal VOC system emissions, the additional capacity added to the network creates a relatively high percent of links operating at or within 5% of their respective free flow speeds even as base congestion increases. This is consistent with each of their relationships to average vehicle speed (see plots in Chapter 2). Higher average vehicle speeds result in lower travel time and lower VOC system emissions. However, when the network is designed for minimal NOx or CO system emissions, the additional capacity added (or not added) creates a lower percent of links operating at or near their respective free flow speeds (compared to changes to reduce total travel time or VOC system emissions). However, the improvements to minimize NOx and CO system emissions do

result in a higher percent of links operating at or near free flow speed than the do-nothing scenario. The trends related to minimizing NOx and CO system emissions are consistent with their respective relationships to average vehicle speed. Both have bowl-shape relationships with average vehicle speed (see Chapter 2 for plots), which means higher rates of emissions occur when average vehicle speed is too fast or too slow. Therefore, the improvements to minimize NOx or CO system emissions favor system changes such that average vehicle speeds are just right – not too many links operating too fast or too slow.

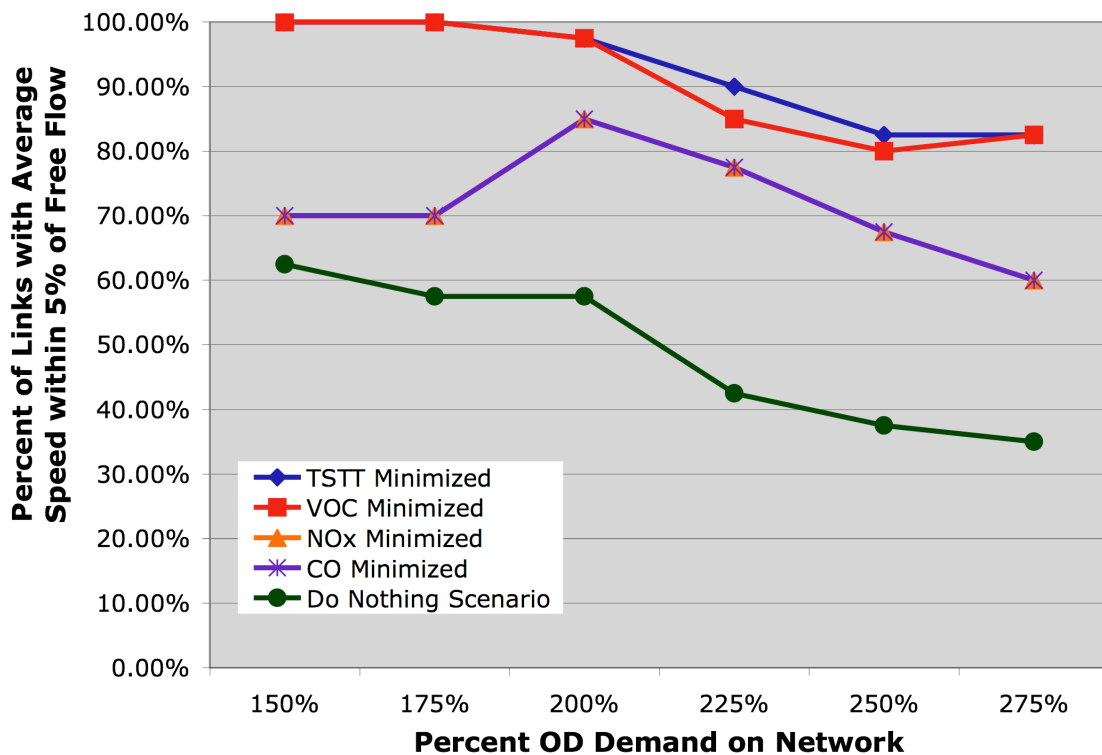


Figure 56. Percent of Eligible Links with Average Speeds within 5% of Free Flow Speed after Improvements to Anaheim Network

Results from analysis on the Anaheim network, shown in Figure 56, are consistent with those from the analysis on Sioux Falls network. When the network is designed for

minimal total travel time or minimal VOC system emissions, the additional capacity added to the network creates a relatively high percent of links operating at or within 5% of their respective free flow speeds even as base congestion increases. As noted above, this is consistent with each of their relationships to average vehicle speed (see plots in Chapter 2). However, when the network is designed for minimal NOx or CO system emissions, the additional capacity added (or not added) creates a lower percent of links operating at or near their respective free flow speeds (compared to changes to reduce total travel time or VOC system emissions). As discussed above, the trends related to minimizing NOx and CO system emissions are consistent with their respective relationships to average vehicle speed (see plots in Chapter 2). The improvements to minimize NOx or CO system emissions favor system changes such that average vehicle speeds are just right – not too many links are operating too fast or too slow.

From the figures above, it is evident that improvements to minimize NOx and CO system emissions result in slightly higher levels of congestion than the improvements that minimize total travel time or VOC system emissions. This is seen from the lower percent of links operating at or near their free flow speed after improvements to minimize NOx and CO system emissions compared to the percentages when the network is designed for minimal total travel time or VOC system emissions. However, congestion resulting from designing for minimal NOx or CO system emissions tend to be less than the levels of congestion experienced under the do-nothing scenario. As noted above, throughout all of the analysis scenarios, the do-nothing scenario did not result in minimal NOx or CO system emissions – some set of improvements (sometimes only a few improvements) could be made to further reduce NOx and CO system emissions.

Summary of Solution Characteristics

Analysis on the Sioux Falls network indicates more budget resources are used when the network is designed for minimal total travel time and VOC system emissions; designing for minimal NO_x and CO system emissions tends to require less of the budget. Analysis on the Sioux Falls and Anaheim network illustrate there is a threshold at which further investment to reduce each performance measure does not reap proportional system improvements. Exploring the types of improvements made when the network is designed to minimize each objective (e.g., total travel time, CO system emissions) reveals there is a relative “sweet spot” at which further network changes improve system performance measures marginally or not all. Improvements to minimize total travel time and VOC system emissions favor changes that result in as many links as possible operating at or near their free flow speed. Improvements to minimize NO_x and CO system emissions favor changes that result in only some links, not too many nor too few, operating at or near their free flow speed. Identifying and understanding the differences in solution characteristics and their connection to using budget resources may help system managers screen initial projects or sets of network projects and in some instances may be useful for targeting certain types of system changes.

SUMMARY

The proposed emissions network design problem was applied to two test networks: 1) Sioux Falls, ND and 2) Anaheim, CA. A total of 36 analysis scenarios were conducted. In these scenarios the influence of the following parameters were explored: 1) available budget; 2) base level of congestion on the network; 3) the percent of the network eligible for improvement; 4) the magnitude of the increments of capacity added to the network; and 5) demand uncertainty. The results from these analysis scenarios were dissected to find trends in system performance and solution characteristics when the

network was designed to minimize each of the four performance measures (i.e., total travel time, VOC system emissions, NOx system emissions, and CO system emissions). The results were also thoroughly analyzed to identify relationships and trade offs between designing to improve performance measure versus another. With regards to the solution method, the genetic algorithm was an effective means to solve the emissions network design problem. Solutions tended to converge in 45 generations or less depending on the size of the network and the base network congestion. As presented above, findings from the analysis results are organized into the following categories: 1) general findings; 2) system performance; and 3) solution characteristics. The critical findings within each category are below.

The notable general findings and findings related to system performance are summarized below. Many of these findings are related to the relationships and tradeoffs between designing to improve (i.e., minimize) one performance measure versus another. These findings also touch on system performance as congestion increases, the effect of adding smaller increments of capacity to the network, and the influence of demand uncertainty.

1) Designing for minimal total travel time (i.e., minimal congestion) does not guarantee minimal system emissions for each pollutant.

2) Designing for minimal total travel time does tend to correspond to minimal VOC system emissions; however, it tends to increase NOx and CO system emissions.

3) Designing for minimal NOx system emissions tends to correspond to minimal CO system emissions and vice versa; however, total travel time tends to increase.

4) The difference between each performance measure's minimal value and value when another measure is minimized (i.e. minimal CO system emissions versus CO

system emissions when total travel time is minimal) increases with congestion (i.e., demand) and number of links eligible for improvement.

5) The difference between each performance measure's value in the do-nothing scenario and its respective minimal value also increases as congestion increases.

6) In each analysis scenario, there was always a system change or set of changes that reduced emissions relative to their respective values in the do-nothing scenario.

7) Adding small increments of capacity to the network (e.g., signal timing coordination rather than adding a lane) was more effective at reducing NO_x and CO system emissions than adding larger increments of capacity to the network.

8) There exist consistent and definable relationships (e.g., linear, second-degree polynomial) between total travel time and each pollutant.

9) Accounting for demand uncertainty when solving the emissions network design problem is critical for consistently improving system performance on networks subject to variations in demand.

These findings are significant because they demonstrate the need to incorporate emissions into network design particularly as congestion or demand uncertainty on a network increases. They also illustrate useful relationships between designing for one performance measure versus another. Finally, the findings demonstrate the importance of accounting for demand uncertainty when designing to improve (i.e., minimize) any of the four performance measures.

The notable findings related to solution characteristics are summarized below. These findings are primarily related to the amount of resources (i.e., available budget) used to improve (i.e., minimize) each performance measure and the corresponding level of improvement in system performance. Also, touched on below is the fundamental

difference in the nature of the capacity additions made to reduce total travel time or VOC system emissions compared to those made to reduce NO_x or CO system emissions.

1) More of the available budget tends to be used when the network is designed for minimal total travel time or VOC system emissions.

2) When designing for minimal NO_x or CO system emissions, the biggest gains can be made with relatively few but strategic capacity additions to the network.

3) When designing to improve (i.e., minimize) any of the four performance measures, there is a threshold at which spending additional resources to add capacity to the network does not result in proportional improvements in system performance.

4) Changes made to the road network to minimize total travel time and VOC system emissions favored capacity additions that improved as many road links as possible to free flow conditions.

5) Changes made to the road network to minimize NO_x and CO system emissions favored capacity additions that improved some, not all, road links to free flow conditions.

The findings related to solution characteristics are significant because they reinforce that designing a road network to operate at or near free flow conditions is detrimental to reducing emissions of critical criteria pollutants NO_x and CO. Furthermore, the findings illustrate significant reductions in NO_x and CO system emissions can be made without spending larger amounts of resources. Notable reductions can be achieved with limited resources.

The following chapter presents a summary of the research conducted here, conclusions from this research, and highlights potential future research related to this work.

Chapter 5: Research Summary, Conclusions and Future Work

RESEARCH SUMMARY

The proposed emissions network design problem was formulated and applied to two test networks. The motivation for formulating the emissions network design problem, applying the emissions network design problem to test networks, and exploring the influence of demand uncertainty can be summarized by four reasons. First, understanding how road network capacity additions influence system emissions is critical to helping regions plan for transportation system improvements particularly regions in or near non-attainment. To effectively improve air quality and sustain that improvement, regions need to take a multifaceted approach to improving their transportation systems and land use patterns – managing and planning modifications for their road network is a critical piece of such a multifaceted approach. Second, the influence of designing a network for minimal emissions has not been (based on the literature review conducted for this research) thoroughly explored. Formulating an emissions network design problem and exploring the implications of applying it to different networks under different contexts fills a gap in the current network design research field. Third, results and findings from related research fields such as traffic assignment, network pricing, and alternatives analysis indicate a likely difference between designing for minimal total travel time versus minimal system emissions. Finally, the influence of demand uncertainty was explored because previous research findings illustrate its significant effect on network design problem solutions where total travel time was minimized.

The emissions network design problem presented here is formulated as a bi-level optimization problem. The upper-level objective function minimizes system emissions of a specific pollutant and the lower-level enforces user-equilibrium route assignment. The

bi-level formulation captures the leader-follower behavior present between system managers and motorists. System managers make decisions as to how to modify the road network (leader) and motorists decide which routes to take (follower). Both sets of decisions influence overall system performance. A genetic algorithm was selected to solve the emissions network design problem. The genetic algorithm was the preferred solution method due to the problem's complexity and size, as well as the genetic algorithm's ability to outperform other meta-heuristics.

A total of 36 analysis scenarios across two test networks were conducted to ultimately provide answers to the questions posed in Chapter 1 and Chapter 2; these questions served as the original motivation for formulating and exploring the emissions network design problem. To answer these questions 36 analysis scenarios were run examining the influence of various parameters on the solutions found and on the relationships between designing for minimal total travel time versus minimizing each pollutant. Based on the results presented in Chapter 4, it is now possible to answer those original questions. The questions posed and their corresponding answers are discussed in the Conclusions section below.

CONCLUSIONS

The six questions below were originally posed in Chapter 1 and Chapter 2. These six questions helped motivate the research conducted and helped frame the research plan (previously presented in Chapter 2).

Question 1: Should regions ignore the growing demand for automobile travel and let congestion worsen?

Answer: Allowing automobile congestion to worsen does not appear to be a sound strategy for reducing emissions. Doing nothing, making no capacity additions to a road network did not produce minimal emissions in any of the analysis scenarios. Regions

still working on developing robust transit systems and/or altering land use patterns to more dense, mixed uses (to make non-auto travel more feasible) would likely benefit, in terms of reduced emissions, from identifying critical capacity additions to their road network to help further reduce emissions in the interim. Similarly, regions with robust transit systems and land use patterns that facilitate non-auto travel, but are still experiencing growing demand for auto-travel may also benefit, in terms of reduced emissions, from strategic capacity additions to their road network.

Question 2: What capacity additions, if any, to road networks are pertinent, reasonable, sound improvements that will help serve demand, but not exacerbate emissions?

Answer: NO_x and CO pollutants are two critical criteria pollutants that also contribute to the formation of other criteria pollutants such as ground-level ozone and fine particulate matter. To minimize system emissions of NO_x and CO, capacity additions to the road network tend to favor those that create average speeds in the range of 30 to 40 mph. Improvements that add smaller amounts of capacity spread across the network also tend to more effectively minimize NO_x and CO system emissions compared to larger capacity additions (e.g., improving signal timing coordination versus adding travel lanes). In designing for minimal NO_x or CO system emissions, some moderate congestion or slower speeds on the network are desirable. However, congested or stop and go conditions (i.e., doing nothing) are not desirable.

Question 3: Are the improvements in Question #2 the same as those that minimize total travel time on the network?

Answer: No. Improvements to minimize total travel time favor capacity additions to the road network such that as many road segments as possible are operating as close to

free flow conditions as possible. Such improvements increase NO_x and CO system emissions.

Question 4: Do network design improvements vary depending on the pollutant being considered?

Answer: Yes. The rate of VOC emissions as average vehicle speed changes tends to behave similarly to travel time. Therefore, when the network is designed for minimal total travel time, VOC system emissions also tends to be minimal. However, NO_x and CO system emissions are not minimal when the network is designed for minimal total travel time. In and of itself, VOC is not a criteria pollutant. It contributes to the formation of other criteria pollutants such as ground-level ozone. To form other criteria pollutants, VOC needs to react with NO_x and CO; therefore, minimizing NO_x and CO emissions appears to be a more effective approach for improving air quality (in terms of criteria pollutants) than designing for minimal VOC system emissions.

Question 5: Are trends in designing to minimize emissions consistent across different regions in the U.S.?

Answer: More analysis with different road networks across the U.S. is needed to thoroughly answer this question. Preliminary analysis with the Sioux Falls and Anaheim road networks indicate the trends in designing to minimize emissions are consistent across different regions.

Question 6: To what degree does demand uncertainty effect designing for minimal emissions?

Answer: Ignoring demand uncertainty significantly increases total travel time and emissions of each pollutant. To reliably minimize total travel time or any of three pollutants, it is necessary to incorporate demand uncertainty into the network design problem and solution method. Solutions found with analysis accounting for demand

uncertainty performed significantly better than the solutions found with fixed demand particularly as demand uncertainty increased.

The answers to the six questions above indicate metropolitan regions could benefit from applying the proposed emissions network design problem within their transportation planning process. Regardless of the existing level of transit and/or non-auto travel, there are likely pertinent, reasonable modifications to their road network that could help further reduce vehicle emissions of criteria pollutants. Furthermore, it is clear designing a road network for minimal congestion is detrimental to reducing vehicle emissions and not making any changes to a road network can also be counterproductive to reducing vehicle emissions. Therefore, an optimization problem such as the emissions network design problem presented here is useful to identify the critical and valuable changes that effectively reduce emissions. It is also clear accounting for demand uncertainty is paramount in developing a set of robust and effective modifications that consistently reduce emissions of criteria pollutants. Finally, even in the absence of being able to apply the emissions network design problem presented here, regions can benefit from knowing the types network changes that tend to produce lower emissions of NO_x and CO, which are noted in the answer to Question #2 above.

FUTURE WORK

Near term possible extensions of this work include applying the emissions network design problem to more road networks spread across the U.S.. This would strengthen the trends identified in this research and/or expose new useful relationships or trends. Similarly, applying the emissions network design problem to larger regional road networks such as Chicago, IL would also be useful to examine the relationships found here on a larger scale. Furthermore, exploring the influence of demand uncertainty on moderate size networks (e.g., Anaheim, CA) as well as large networks (e.g., Chicago, IL)

would help better define the nature of differences between fixed demand solutions and solutions found under demand uncertainty.

A longer term, but paramount extension of this work is to apply the emissions network design problem in a dynamic modeling context using dynamic traffic assignment (DTA) to model motorist behavior and MOVES2010 to model emissions. The dynamic context would be able to account for the influence of vehicle acceleration and deceleration on emissions. Additionally, DTA would be able to model the change in motorists' departure time as well as their different route choices based on expected motorist travel time (or travel cost). Expanding this research to a dynamic context by employing DTA and MOVES2010 has the potential to provide more refined results and guidance with regards to designing a road network for minimal emissions.

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