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Refining GreenSTEP: Impacts of Vehicle Technologies and ITS/Operational Improvements on Travel Speed and Fuel Consumption Curves

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Refining GreenSTEP: Impacts of Vehicle Technologies and ITS/Operational Improvements on Travel Speed and Fuel Consumption Curves

Report on Task 2: Incorporation of Operations and ITS Improvements

November 2011

Prepared by

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EXECUTIVE SUMMARY

This report describes analysis undertaken to establish a method for incorporating traffic operations and ITS strategies into the GreenSTEP model. We first discuss operations impacts on fuel economy and delay from the literature. Then, an investigation of delay adjustments in GreenSTEP shows that different methods of representing delay changes lead to similar (and small) impacts on fuel economy. From this result we establish average speed adjustment by congestion level as the preferred method for incorporating delay effects from operations improvements.

An investigation of aggregate traffic operations impacts produces estimates of base speeds without operations improvements, maximum speeds with full operational improvements, and existing deployments by city size for each congestion level. These estimates are made for ramp metering, incident management, traffic signal coordination, and access management strategies. Additionally, a comparison of constant-speed and drive schedule-based fuel-speed curves generates estimates of potential fuel benefits from eco-driving and speed-smoothing traffic management strategies. Results show that the cumulative impact of delay-based operations strategies on fuel economy is small, though speed-smoothing effects can be large.

The operations impacts estimates are used to provide guidance for estimates of operations efficacy in delay reductions and speed smoothing for the GreenSTEP model. The proposed implementation strategy includes an efficacy estimates tool for the net effects of operations strategies, and identifies locations in the model where those effects can be included. Traffic operations impacts on travel demand are separately applied as travel demand management inputs to the existing GreenSTEP model.

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1 Task 2 Introduction

A general introduction to this project is contained in the companion document: *Final Report for Refining GreenSTEP, Task 1*, which also describes modeling and analysis results for Task 1. The content of the present report describes Task 2: Incorporation of Operations and ITS Improvements. Execution of this task requires development of a method for incorporating traffic operations and Intelligent Transportation System (ITS) improvements into the GreenSTEP model.

Active Traffic Management (ATM) – including ITS strategies – has been presented as a way to mitigate congestion and alleviate its negative impacts (Federal Highway Administration, 2007). Common ATM and ITS strategies include ramp metering, variable speed limits, advanced/adaptive traffic signal coordination, and High-Occupancy Vehicle (HOV) lanes. Varying congestion levels have an impact on fuel economy and greenhouse gas (GHG) emissions from vehicles (see *Final Report for Refining GreenSTEP, Task 1*). Thus, changes in traffic operations and implementation of ATM are expected to impact fuel economy and vehicle emissions (U.S. Environmental Protection Agency, 1998).

The objective of this Task is to develop a method for incorporation of traffic operations strategies into the GreenSTEP modeling framework. This will allow ATM strategies to be included among the policies included as inputs into GreenSTEP. In order to accomplish this, we must determine both the expected impacts of traffic management strategies on fuel consumption and how those impacts can be represented in GreenSTEP. The remainder of this report is laid out as follows. First we present the background information and literature on traffic management strategies and their effects on fuel consumption and GHG emissions, followed by a description of the modeling and analysis methodology of this investigation. The subsequent sections show results for the fuel impacts of different methods of congestion adjustments in GreenSTEP, and the expected impacts of traffic operations improvements. Finally, a description of the proposed GreenSTEP traffic operations modeling strategy is presented.

2 Literature on Traffic Operations and Fuel Economy

The general impacts of congestion on vehicle fuel economy are discussed in the *Final Report for Refining GreenSTEP, Task 1*. Operations strategies such as ATM can influence fuel economy and emissions in two ways. First, these strategies can reduce the level of congestion and increase the average travel speed, which impacts fuel consumption rates. Second, reductions in speed variability can also result from these operations strategies and again influence fuel economy. The Fuel-Speed Curves (FSC) used to represent fuel economy in varying levels of congestion are representative of average, aggregate conditions. Thus, operations strategies can change not just where traffic is represented on the FSC (by impacting congestion level) but also the shape of the curve itself (by impacting microscopic traffic flow characteristics). We can classify the first effect as "congestion mitigation" and the second as "speed smoothing"; both illustrated in Figure 1.

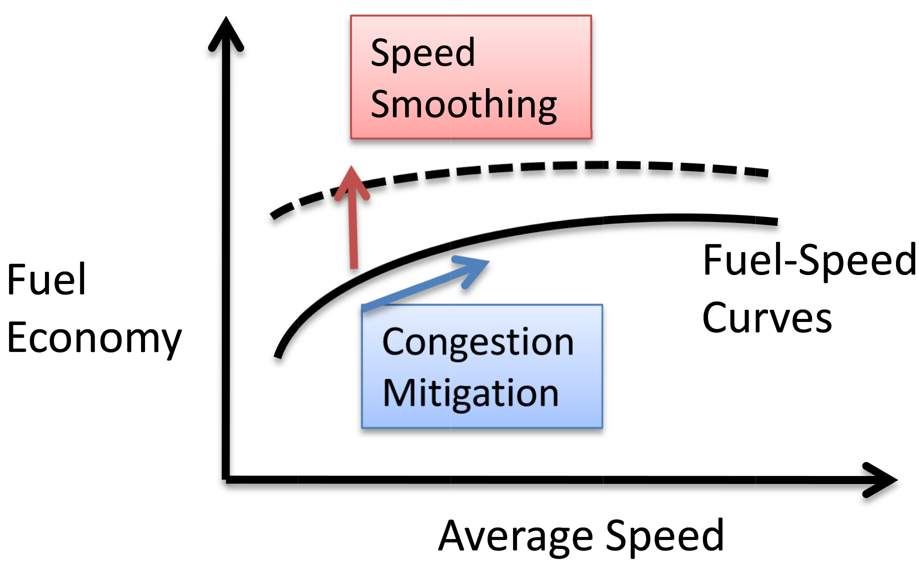

Figure 1. Illustration of Operations Impacts on Fuel-Speed Curves

Traffic operations improvements can impact many facets of traffic flow and vehicle operating loads. The most commonly measured impacts are on vehicle delay, vehicular throughput/roadway capacity, free-flow speed, and extent/intensity of congestion. The macroscopic impacts of operations improvements are addressed in various reports by the Texas Transportation Institute, including the Urban Mobility Report (UMR) (Schrank & Lomax, 2009a) and the Oregon Department of Transportation (ODOT) Operations Performance Measures Final Report (Eisele & Lomax, 2004). These reports focus on quantifying changes in total vehicular delay associated with regional operations strategies. Other widely-used resources for estimating the effects of operations strategies include the Federal Highway Administration's HERS-ST model (Federal Highway Administration, 2002) and Cambridge Systematics's ITS Deployment Analysis System (IDAS - http://idas.camsys.com/) – both of which are utilized by the UMR methodology.

In addition to these broadly-scoped tools, a multitude of published papers address the modeled or measured impacts of individual operations strategies in more limited contexts. The ITS Benefits, Costs, and Lessons Learned database maintained by the U.S. Department of Transportation (http://www.benefitcost.its.dot.gov/) is a resource for case studies on ITS deployments throughout the country. Unfortunately, these studies are rarely consistent in methodology and metrics, so they cannot be directly compared without additional analysis.

What follows in this section of this report is a broad overview of impacts for an array of operations strategies, focused on generalized effects as much as possible. This review will be used to inform the methodology by which operations impacts are incorporated into GreenSTEP. Ten common operations improvements are discussed below and summarized in Table 1. Note that because of insufficient data, not all strategies presented here are explicitly included in the final methodology.

Table 1. Summary of Operations Improvements and Expected Impacts

Operations Improvement	Facility	Primary Effects which Impact Fuel Consumption
Ramp Metering	Freeway	Reduce recurring congestion/delay
Incident Management	Arterial & Freeway	Reduce incident-related congestion/delay
HOV Lanes	Freeway	Reduce vehicle-trip generation; speed changes for some vehicles, but net speed and capacity effects unclear
Signal Coordination	Arterial	Increase capacity/speed; smooth flow
Access Management	Arterial	Reduce incidents; possible recurring delay increase; capacity effects vary
Eco-Driving	Arterial & Freeway	Smooth speed/flow
Variable Speed Limits	Freeway	Reduce incidents; smooth speed/flow; reduce high speeds
Speed Limit Reduction/Enforcement	Freeway	Reduce high speeds
Truck Lanes	Freeway	Reduce congestion/delay for heavy vehicles; possible capacity change
Transit Priority	Arterial & Freeway	Reduce congestion/delay for transit vehicles; improve transit quality of service; possible capacity change

2.1 Freeway Ramp Metering

Ramp metering is a form of freeway traffic management that regulates the entry of vehicles from on-ramps. Ramp metering can reduce freeway delay by keeping mainline vehicle density below unstable levels. It creates delay for vehicles entering the freeway, but this is typically more than offset by the higher speeds and postponed congestion on the freeway facility. The Urban Mobility Report cites a delay reduction of 0 to 12%, with an average of 3%, for 25 U.S. urban areas with ramp metering (Schrank & Lomax, 2009b). Significant delay reductions were only found for large and very large urban areas. The report provides percent delay reduction estimates from ramp metering based on an analysis of UMR, HERS, and IDAS data, including a detailed case study of ramp metering in Minnesota. This same methodology is presented in the ODOT Operations Performance Measures (OPM) report. While the UMR metric is total delay, ramp metering most directly impacts the extent and severity of freeway congestion by postponing flow breakdown.

2.2 Freeway Incident Management

Incident Response programs are designed to quickly detect and remove incidents which impede traffic flow. The UMR study reports incident-related freeway delay reductions of 0 to 40%, with an average of 8%, for the 79 U.S. urban areas with incident response programs. This reflects the combined effects of both service patrols to address the incidents and surveillance cameras to detect the incidents. Effects were seen in all sizes of urban area, though the impacts were greater in larger cities. The report provides percent of incident delay reduction estimates from service patrols and surveillance cameras based on UMR and HERS data. This approach is different from the one currently employed in GreenSTEP. The UMR approach applies different effectiveness to incident management programs for different congestion levels, while GreenSTEP currently applies a uniform efficacy to all congestion levels. The most direct impact of incident management is a reduction in the extent of incident-related congestion.

2.3 Freeway HOV Lanes

Freeway High-Occupancy Vehicle (HOV) lanes provide higher-speed mobility for vehicles with more passengers when there is congestion, with the intent of reducing person-delay. Prioritizing HOV improves person-throughput (and reduces person-delay) for a fixed vehicle capacity and can potentially reduce travel demand by encouraging ride sharing through travel time benefits. But segregating HOV can also impact traffic flow efficiency in the roadway. The cumulative effects of HOV lanes are still not well established, partly because the major effects (on carpooling behavior and traffic flow) occur on very different time scales.

There was recently debate in California as to whether HOV lanes in the San Francisco area are increasing or reducing congestion (Cassidy, Daganzo, Jang, & Chung, 2006; Chen, Varaiya, & Kwon, 2005). Chen et al. (2005) claim that HOV lanes result in lower overall speeds and vehicular capacity on the freeway. Cassidy et al. (2006) counter that HOV lanes do not increase total delay, and only redistribute delay from high-occupancy to low-occupancy vehicles. Their assertion is supported by Menendez and Daganzo (2007) who determined that HOV lanes do not generally decrease bottleneck throughput – a key metric for network efficiency. Dahlgren (1998) points out that the effects of HOV lanes (both on car sharing and traffic flow) depend on lane utilization, and claims that adding general purpose lanes is often more effective at reducing total delay than adding HOV lanes. Fuel use per vehicle is generally lower in HOV lanes because of higher speeds and greater efficiency there (Boriboonsomsin & Barth, 2007), but the net effect on fuel consumption compared to no lane restrictions has not yet been demonstrated. Furthermore, the fuel effects will depend on lane configuration and are varied (Boriboonsomsin & Barth, 2008).

The UMR study estimates HOV-related delay reductions of about 3% for the 16 U.S. urban areas where data were available. This estimate is made by comparing existing delay to delay if HOV travelers were in the general purpose lanes – a method which appears to include added capacity effects for the HOV lanes. The assumptions about traveler behavior and HOV lane configuration in the methodology are not clear. From a traffic operations perspective, there is not conclusive evidence to predict how HOV lanes impact average fuel consumption per vehicle, when compared with no occupancy restrictions on the same amount of lane-miles. The net delay and fuel effects will depend on the utilization and congestion levels.

2.4 Arterial Signal Coordination

Traffic signal coordination (particularly for adaptive traffic signals) can reduce delay by increasing throughput on arterials in peak flow directions. UMR analysis estimates delay reductions of up to 9% due to signal coordination, with more potential savings from more sophisticated control systems. A study of 90 urban areas suggests an average arterial delay savings of about 1%. The UMR provides percent recurring delay reduction estimates for each of the 5 congestion levels, segmented by control logic (actuated versus progressive/adaptive) and signal density (<3/mi, 3-6/mi, or >6/mi). The expected reductions range from 0 to 6%. This methodology is based on HERS, IDAS, and UMR data, and is equivalent to the suggestions in the ODOT Operations Performance Measures report. Unal et al. (2003) found percentage emissions reductions roughly in line with travel time savings, although there can be separate efficiency savings by smoothing the traffic flow, beyond the travel time effects.

2.5 Arterial Access Management

Access management on arterials can increase speeds by reducing the number of enter/exit points on the arterial and reduce crashes by reducing conflict points. At the same time, improvements such as raised medians can reduce throughput by causing turning queue spillback during heavy congestion. The UMR estimates recurring delay *increases* of up to 15% and incident delay *decreases* of up to 22% from raised median access management. The UMR provides estimates of recurring delay increases and incident delay decreases for access management at different congestion levels. Other types of access management, such as reduced business ingress/egress points, are unlikely to present spillback problems which reduce throughput and increase recurring delay. Few other comprehensive data sets are available, though, to predict regional effects of arterial access management.

2.6 Eco-Driving

Eco-driving is driving behavior which minimizes fuel use over a given distance. This generally includes a more even driving pattern with fewer and gentler accelerations, and lower maximum speeds. A recent study by Barth and Boriboonsomsin (2009) reported eco-driving fuel savings of 2 to 20%, depending on the level of congestion, without an appreciable change in travel time in most conditions. They provide values for average fuel savings based on freeway Level of Service (LOS). Eco-driving can be implemented simply by public awareness campaigns (active eco-driving), or can include advanced vehicle technologies and vehicle-to-infrastructure interactions such as Intelligent Speed Adaptation (ISA), as demonstrated by Servin, Boriboonsomsin, and Barth (2006) (passive eco-driving).

2.7 Variable Speed Limits

The potential fuel-related benefits of freeway Variable Speed Limits (VSL) stem from reduced crashes (and the associated congestion) at the backs of freeway queues, steadier vehicle speeds during peak periods, and lower maximum speeds during VSL activation times. Zegeye et al. (2010) show potential benefits for roadside air quality using VSL to reduce emissions, though neither fuel nor CO_2 are modeled. Some researchers have modeled VSL and shown reduced incident delay but increased recurring delay (Allaby, Hellinga, & Bullock, 2006; Lee, Hellinga, & Saccomanno, 2004). The recurring delay, however, could also be reduced if the VSL system were effective in reducing mainline traffic flow instability and postponing flow breakdown much as a ramp metering system would. A recent detailed modeling and empirical analysis was inconclusive as to the net effects of VSL on recurring delay and congestion (Papageorgiou, Kosmatopoulos, & Papamichail, 2008). The primary expected fuel-related impacts, then, are reduced incident delay, steadier traffic flow, and lower free-flow speeds.

2.8 Speed Enforcement and Speed Limit Reductions

Lower speed limits (and enforced speed limits) reduce the fuel impacts of inefficient high-speed driving. Cascetta, Punzo, and Sorvillo (2010) studied the impact of a new 50mph speed limit in Naples (with automated enforcement) and found average fuel savings of about 5% from a reduction in speeds. Keller et al. (2008) found a 4% reduction in NO_x emissions by reducing the speed limit to 50mph, though fuel and CO_2 were not modeled. There are also potential safety benefits which could result in reduced incident delay, though they are not well quantified.

2.9 Truck Lanes

Commercial Vehicle Prioritization can move high-emitting vehicles through congested areas at improved efficiency (and often also accommodate transit buses). Chu and Meyer (2009) estimated the emissions benefits of adding truck-only toll (TOT) lanes in Atlanta (on highly congested corridors) as around 60% reduction in fuel use. This was primarily due to small speed increases in the general purpose lanes and large speed increases for medium and heavy duty vehicles. An important consideration, though, is whether the truck-only lane is appropriated from general purpose lane stock or added as new capacity, as both the travel time and induced demand effects can be quite different (Roorda et al., 2010). As with HOV lanes, the net fuel effects of vehicle class segregation when compared with no restrictions on the same supply of lane-miles are not clear. Due to the different performance characteristics of heavy-duty vehicles, it is possible that efficiency improvements for a small number of high-emitting vehicles could outweigh some increased congestion in the general purpose lanes. The fuel-related impacts of truck lanes are decreased delay for trucks and potential capacity changes for other vehicle classes (increases or decreases, depending on the configuration).

2.10 Transit Priority

Transit priority serves the double purpose of improving transit vehicle efficiency and increasing the quality of the transit service. Transit priority can happen on arterials through transit signal priority (TSP – early or extended green phases) or on freeways through shared truck/transit lanes. Dion, Rakha, and Zhang (2004) found fuel savings of around 1% for arterial TSP, with bus travel time savings of up to 3.5%. Transit buses using dedicated right-of-way (e.g. truck-only lanes) would have more substantial travel time savings in heavily congested areas. As with the truck lanes, the net effect for all vehicles of these prioritization strategies is not well quantified. The effects of signal priority and priority lanes can be approximated as parallel to the effects of arterial signal coordination and truck-only lanes, but only applied to transit buses. The primary fuel-related impacts are decreased delay for transit vehicles, improved transit service quality, and potential capacity changes for other vehicle classes (increases or decreases).

In summary, traffic operations improvements can impact the severity or extent of congestion, and fuel economy at a given level of congestion. For most traffic operations strategies the effect on fuel economy is not quantified in the literature, though some delay and speed impacts have been estimated on a broad scale. The effects of ATM are context-dependent and the results from individual deployments vary. In order to include varying traffic operations impacts in GreenSTEP, we must estimate both the expected effects of improvements and the baseline deployments for the observed congestion levels. We must also determine how indirect influences on fuel economy (such as delay reductions) can be reflected in GreenSTEP. The next section describes the methodology of this study, aiming to accomplish these tasks.

3 Methodology

In this section we first describe the current method of modeling congestion in GreenSTEP. We then present the general proposed approach to incorporating operations strategies into GreenSTEP. As stated above, incorporating operations strategies in GreenSTEP requires determination of: 1) how operations impacts can be represented in GreenSTEP, 2) the expected impacts of varying levels of operations strategy deployments, and 3) the baseline operations deployments represented in the current model. The methods for executing these three steps are described at the end of this section.

3.1 GreenSTEP and Congestion

The current method of modeling congestion in GreenSTEP is discussed in the *Final Report for Refining GreenSTEP, Task 1*. Besides impacts of overall congestion level and speed on fuel economy (through the FSC), GreenSTEP accounts for three other fuel economy adjustments: incident management, eco-driving, and low rolling-resistance tires. Incident management is included as an interpolation between average recurring and non-recurring congested speeds at each congestion level from the UMR analysis. Eco-driving and low rolling-resistance tires are included as a simple scaling of the average fuel economy (after adjusting for congestion). As a convenience for the reader, Table 2 presents the recurring (without incidents) and non-recurring (with incidents) average speeds at each congestion level used in the GreenSTEP model.

Table 2. Average Speeds (in mph) Associated with Congestion Levels in GreenSTEP

Congestion Level	Freeways – with incidents	Freeways – without incidents	Arterials –with incidents	Arterials – without incidents
None	60.0	60.0	30.0	30.0
Moderate	50.8	56.2	25.0	29.4
Heavy	44.8	53.2	23.7	28.5
Severe	35.5	47.5	22.5	27.7
Extreme	24.8	40.0	20.8	26.4

In the current version of GreenSTEP, congestion only impacts fuel economy and fuel costs: the delay costs of congestion do not feedback to inform the vehicle travel demand estimation in GreenSTEP. Per capita freeway lane-miles supply is a factor for estimating household Daily Vehicle Miles Traveled (DVMT), but congestion levels and arterial lane-miles supply are not. During GreenSTEP model development, household DVMT was not found to be significantly sensitive to arterial lane-mile supply. Freeway lane-mile supply has a relatively small independent effect on DVMT (i.e. not considering the effects of freeways on land use patterns). The updated version of GreenSTEP includes an iterative function to split DVMT between freeway and arterial facilities, based on their respective adjusted speeds (i.e. including the effects congestion) (Gregor, 2011).

In its current version, GreenSTEP implicitly includes typical operations improvements by basing congestion level distribution of DVMT on observed speed and congestion data from U.S. urban areas. The observed congestion levels in these cities include the effects of existing traffic operations improvements. This means that the baseline for congestion and operations adjustments is not a roadway network void of traffic operational improvements, but a network with a set of "typical" improvements for a given congestion level based on existing state-of-practice in the U.S. Assumedly, there is a relationship between the extent of traffic operations improvements and the level of congestion in urban areas, since cities will respond to worsening congestion with operational countermeasures.

3.2 Outline of Proposed Approach

The impacts of operational improvements can be accounted for in GreenSTEP in multiple ways. For example, a strategy such as ramp metering which reduces the amount of recurring congestion can be included by changing the distribution of DMVT by congestion level, changing the average speeds at each congestion level, or even changing the effective supply of roadway lane-miles. Given this flexibility, some key considerations for integrating these (and other) operations improvements into GreenSTEP are to:

1. Avoid double-counting strategies with multiple effects,
2. Accurately reflect cumulative effects of multiple strategies (are they additive or mutually exclusive?),
3. Align with the modeling design and scope of GreenSTEP (which has no roadway network), and
4. Compare operations strategies with the baseline deployments.

Since GreenSTEP is a high-level strategic planning model with no defined roadway network, a generalized approach to incorporating traffic operations effects is most appropriate. We group operations effects into five categories: 1) recurring congestion, 2) non-recurring congestion, 3) free-speed reduction, 4) speed-smoothing, and 5) trip generation/mode choice. Then, operations can be accounted for in GreenSTEP based on which operations effects are expected and to what extent – with the assumption that a local implementation strategy can be developed to reach those operations results. This approach has the advantages of allowing novel but unspecified operations strategies to be considered (model flexibility), and avoiding specificity in projecting operations strategy deployments – helpful because effects can be highly context sensitive.

The recommended two-step approach for incorporating operations improvements into GreenSTEP is to provide efficacy estimates for a set of operations effects categories, which are then mapped to adjustments within GreenSTEP. This approach is illustrated in Figure 2. The efficacy estimates are based on level of deployment in each metropolitan area (relative to baseline deployments) and bounded by the findings in the literature for impacts of each strategy type. Realistic bounds are set on the potential efficacy, which are scaled to level of deployment. Since the baseline speed and congestion level distribution in GreenSTEP includes existing operations improvements, the efficacy estimates include both positive and negative adjustments, for over/under investment in operational improvements (as compared to similarly sized areas in the current state-of-practice).

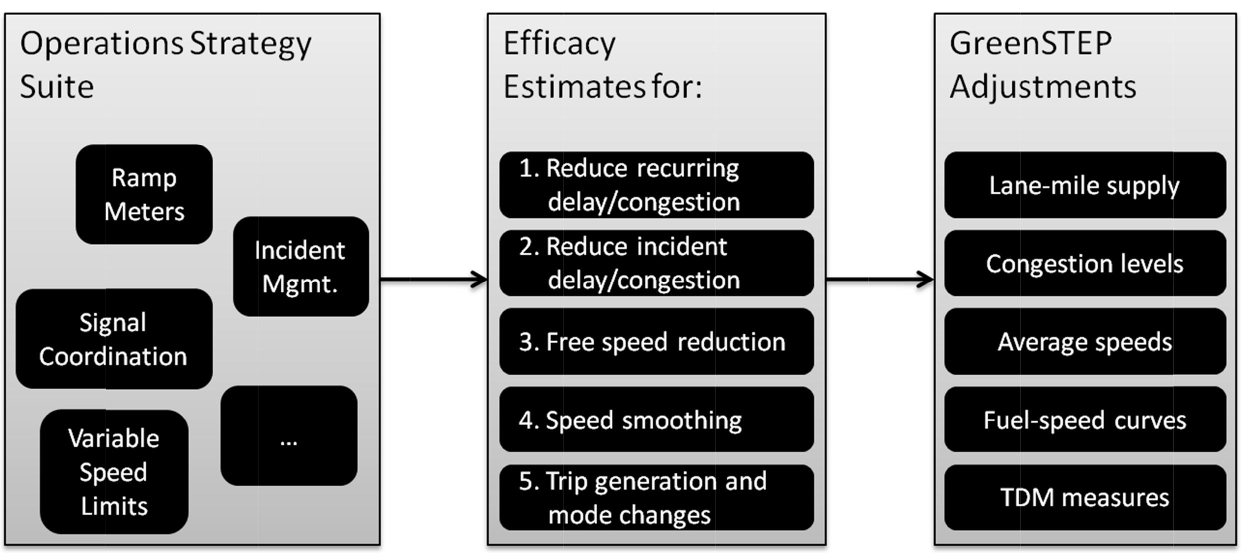

Figure 2. Incorporating Operation Strategies in GreenSTEP

3.3 Adjustments in Green STEP

One key challenge in this task is identifying the appropriate method for making operations adjustments in GreenSTEP for each operations effect type. The adjustments must be both realistic to the strategy's effects and feasible within the structure of GreenSTEP. As illustrated in Figure 2, the potential methods considered here are:

1. Adjust lane-mile supply for a metropolitan area (this can be done early in the model or during the congestion module)
2. Adjust DVMT distribution by congestion level
3. Adjust average speeds for facility-type/congestion-level/vehicle-type combinations
4. Adjust the driving schedules used for fuel-speed curve development, or adjust fuel-speed curves directly
5. Adjustments during the household DVMT-generating processes, based on Travel Demand Management (TDM) measures

These approaches can have overlapping impacts in GreenSTEP. For example, adjustments 1 through 3 all change, ultimately, the distribution of DVMT by speed.

There are other potential methods as well, such as adjustments in earlier model stages (during household decision making). But at the household decision level metropolitan congestion is not yet known, so it is unlikely that traffic-based adjustments will be feasible. For this reason, the GreenSTEP adjustments listed above focus on components of the congestion model. The exception is adjustment 5 (TDM measures), which allows impacts through existing model components.

Macroscopic operations or ITS effects are commonly assessed as changes in total or average delay (see Section 2). The problem with this metric for fuel consumption is that not all delay has the same fuel effects. A one-minute travel time savings for 100 vehicles does not have the same total fuel impact as a 20-minute savings for 5 vehicles. Similarly, a one-minute savings for a vehicle near free-flow speeds has a different fuel impact than a one-minute savings for a vehicle in heavy congestion. For these reasons, we will investigate how different adjustments for delay impact fuel economy estimates in GreenSTEP.

We now return to the five operations effects categories, with a brief discussion of the relevant potential adjustments in GreenSTEP:

1. **Reduced recurring congestion (indicated by recurring delay)**
   This broad category includes ramp metering, signal coordination, truck lanes, and transit priority effects that reduce delay (if only for certain vehicle classes). It can be accounted for in GreenSTEP by adjusting the effective lane-mile supply, the distribution of DMVT by congestion levels, or the average speeds at congestion levels. Adjusting the average speed for each congestion level is the most straight-forward approach because it can be easily calculated from percent delay reductions at various congestion levels. As stated above, not all delay has the same fuel impacts, so adjusting the amount of vehicles in congestion can have a different effect than adjusting the average speeds for all vehicles in congestion.

   Only adjustments to lane-mile supply early in the model can influence the total amount of DVMT production and so replicate the induced demand that results from congestion mitigation which provides travel time savings. The distribution of DVMT between freeway and arterial facilities, however, is influenced by the congested speeds on each. So adjustments to congestion levels and speeds can influence the distribution of DVMT, if not the total amount. The most appropriate GreenSTEP adjustment for this effect category will be based on the investigation described below in Section 4.1.
2. **Reduced non-recurring congestion (indicated by non-recurring delay)**
   This category includes incident management, access management, and variable speed limits – strategies that reduce either the frequency or duration of incident-related congestion. It can be accounted for using the existing GreenSTEP approach of reducing the amount of incident-related delay in each congestion level (by adjusting the average speed between the recurring and nonrecurring congested speeds). The amount of speed adjustment can also be congestion-level specific, since some operations strategies are more or less effective in heavier congestion. Alternatively, the non-recurring delay adjustment can be made by any of the approaches described above for recurring congestion. Again, the most appropriate GreenSTEP adjustment for this effect category will be based on the investigation described below in Section 4.1.
3. **Reduced freeway free-flow speeds**
   This category includes speed limit reductions, speed enforcement, and variable speed limits that reduce the amount of high-speed freeway travel. It can be accounted for in

GreenSTEP by adjusting the average speed for "uncongested" DVMT. The current freeway free-flow speed in GreenSTEP is 60 mph, so this operations strategy will have little effect with respect to existing conditions. But raising the default or unmitigated free-flow speed would provide more room for free-speed reduction impacts.

4. **Smoothed traffic flow/speeds**

   This category includes eco-driving, variable speed limits, and signal coordination effects that reduce fuel consumption at a given travel speed. It can be accounted for in GreenSTEP by adjusting the fuel-speed curves.

5. **Impacts to trip generation and mode choice**

   This category includes those strategies with the potential to influence travel demand and mode choice such as HOV lanes and transit priority. Adjustments here will be strategy-specific, and can occur through the existing TDM modules in GreenSTEP. For example, HOV lanes which provide travel time benefits for ridesharing can be represented by increased effectiveness of a carpooling (or employer commute options, ECO) program. The improved transit service quality from transit priority can be captured by increasing effective revenue-miles or increasing the effectiveness of transit-related TDM (currently "Transit Fare Reduction").

In summary, the primary adjustments to be investigated are recurring and non-recurring delay impacts from congestion mitigating operations improvements. This investigation is presented in Section 4. We next describe the adopted approach to estimating the impacts of varying operations deployments.

3.4 Estimating Traffic Operations Impacts

3.4.1 Estimation of Delay Impacts

The UMR study on operations effects combines several large data sets to estimate broadly aggregated delay impacts from operations improvements (Schrank & Lomax, 2009b). These results are based on the same data used to estimate the current GreenSTEP congestion model, so they can also be used to estimate the baseline operations deployments. The UMR operations study provides estimates of percent recurring and non-recurring delay reductions for covered delay in each of five congestion levels (the same five congestion levels used in the UMR and in GreenSTEP: None, Moderate, Heavy, Severe, and Extreme). These estimates are provided for freeway ramp metering, freeway incident management, arterial traffic signal coordination, arterial access management, and freeway HOV lanes. The HOV lane effects methodology includes varying capacity effects which obfuscate the constant-capacity operations impact, and so it is excluded from application here.

The percentage delay reduction estimates in the UMR study differentiate some strategies by deployment types (for example, signal coordination on arterials with traffic signal density over/under 3 signals per mile). In addition to percent delay reductions for each strategy at each congestion level, the UMR operations study provides estimates of existing deployment (in percent coverage of lane-miles or DVMT), delay savings at existing deployment, and delay savings at maximum/full deployment (all three aggregated by urban area size). The challenge in applying these data for GreenSTEP is that the existing deployment and the existing/maximum delay savings data are aggregated by urban area size and not provided by congestion level or for disaggregated urban areas. Additionally, the unspecified roadway network in GreenSTEP does not distinguish some deployment types (specified traffic signal density, for example). Thus, we cannot apply the reported delay reductions and deployments directly to estimate delay reductions in GreenSTEP.

The chosen strategy is to use regression to estimate the fractional delay reductions (with respect to total delay) at each congestion level, for each operations strategy, using the UMR data tables. We beginning with the expected delay reduction impacts by congestion level presented in the UMR operations study methodology. We then scale these base values to minimize the sum of square difference between: 1) the potential operations effects by urban area size at full deployment presented in the UMR study, and 2) the calculated operations delay reductions at full coverage for each urban area. Mathematically, if DR_s is the potential reduction in delay due to an operations strategy for urban areas of size category s (from the UMR study), then we estimate the fractional delay reduction at each congestion level, λ_c, for which

$$\min \sum_{u \epsilon U} \left(\sum_{c \epsilon C} \left(\lambda_c \cdot D_{c,u} \right) - DR_{s_u} \right)^2$$

where $D_{c,u}$ is the base delay at congestion level c in the set of congestion levels C for urban area u in the set of urban areas U, and s_u is the size category of urban area u. The result is estimates of fractional delay reductions for each operations strategy and each congestion level (λ_c) on a scale relative to full deployment (full coverage of all delay).

This approach gets the overall size of potential delay reductions consistent with the UMR study, while keeping a reasonable distribution of the delay effects by congestion level and not specifying the deployment conditions. We follow the UMR operations study methodology in estimating cumulative impacts from these four strategies as additive (where overlaps exist). Table 3 summarizes the scope of impact of each strategy. The results of the investigation described here are presented in Section 5.

Table 3. Summary of Operations Delay Impacts from UMR Operations Study

Operations Strategy	Facility Type	Delay Type
Ramp Metering	Freeway	Recurring & Non-recurring
Incident Management	Freeway	Non-recurring
Signal Coordination	Arterial	Recurring
Access Management	Arterial	Recurring & Non-recurring

3.4.2 Estimation of Speed-Smoothing Impacts

Insufficient eco-driving or "smoothed" driving schedules are available to estimate a new set of "smoothed" fuel-speed curves. Instead, we use the constant-speed fuel consumption modeling from Task 1 (see *Final Report for Refining GreenSTEP, Task 1*) to estimate upper-bounds on eco-driving fuel economy (with respect to existing fuel-speed curves). Then, fuel-speed curves are scaled up toward this bound in proportion to a reasonable estimate of attainable speed-smoothing effects (based on values published in the literature).

3.4.3 Estimation of Other Impacts

Operations strategies for which insufficient aggregate performance data are available (variable speed limits, truck-only lanes, etc.) or miscellaneous, unspecified operations improvements can also be incorporated directly through adjustments in GreenSTEP. This is done by adjusting the efficacy estimates for the five presumed traffic operations effects. For example, although variable speed limit impacts on vehicular delay are unclear, if we choose to assume that there will be a recurring delay reduction then that reduction can be reflected in the efficacy estimates directly. This is discussed further in Section 6.

3.5 Baseline Deployments

Baseline traffic operations deployments included in the observed speed data can be estimated from the UMR data tables. The baseline levels of deployment are represented as the fraction of total potential delay savings from each operations strategy that are captured by existing deployments. These values are estimated in the UMR operations study, aggregated by urban area size. If EDR_s is the existing delay reduction from an operations improvement for urban areas of size s, then the deployment level for that size category is simply $\frac{EDR_s}{DR_s}$. Then, the baseline fractional delay reduction for each congestion level (for each strategy) is $\frac{EDR_s}{DR_s}\lambda_c$. The results from these calculations are presented in Section 5.

Since existing average speeds by congestion level are provided for each urban area in the UMR data tables, we can use the existing delay reduction estimates to calculate a base speed for each congestion level, averaged over urban areas, which is expected to exist without these operations impacts. Then, operations delay reductions are applied to these base speeds in order to calculate the revised average speed for each congestion level in each city (also for each vehicle type) – based on assumed deployment levels.

The following results sections present first the analysis of different types of delay adjustments in GreenSTEP. Then, estimations of operations strategy impacts are presented, followed by an explanation of the proposed implementation in GreenSTEP.

4 Results – Adjustments in GreenSTEP

In this section we investigate the fuel economy impacts of different methods of adjustment in GreenSTEP. This will help selection of the most appropriate tools from Section 3.3, and inform the final implementation strategy. Note that this investigation is based on the version of GreenSTEP extant in the spring of 2011. An updated model version now splits metropolitan DVMT between facility types using an iterative function that accounts for congested speeds (Gregor, 2011).

4.1 Speed and Delay Adjustments

This section shows the fuel economy impacts of varying average speeds by congestion level, varying the distribution of DVMT by congestion level, and adjusting the lane-mile roadway supply for freeways and arterials (during congestion adjustments) in GreenSTEP. All of these adjustments change the average-speed distribution of DVMT in slightly different ways.

Figure 3 shows the sensitivity of fuel economy to delay adjustments in GreenSTEP, based on adjusting **(a)** the distribution of DVMT by congestion level, **(b)** the average speed at each congestion level, and **(c)** the lane-mile supply of freeway and arterial roadways (during congestion calculations). These plots are based on the existing fuel-speed curve values in GreenSTEP. The figure shows how fuel economy (as miles per gallon, MPG) and delay values vary with respect to existing base conditions in Portland, Oregon based on data from the 2009 UMR (for the year 2007). MPG fractional changes are shown separately for autos (solid lines) and trucks (dashed lines), and separately for freeway adjustments (black lines), and arterial adjustments (grey lines). For **(a)** and **(b)** the proportional change (in DVMT or speed) is the same for all levels of congestion.

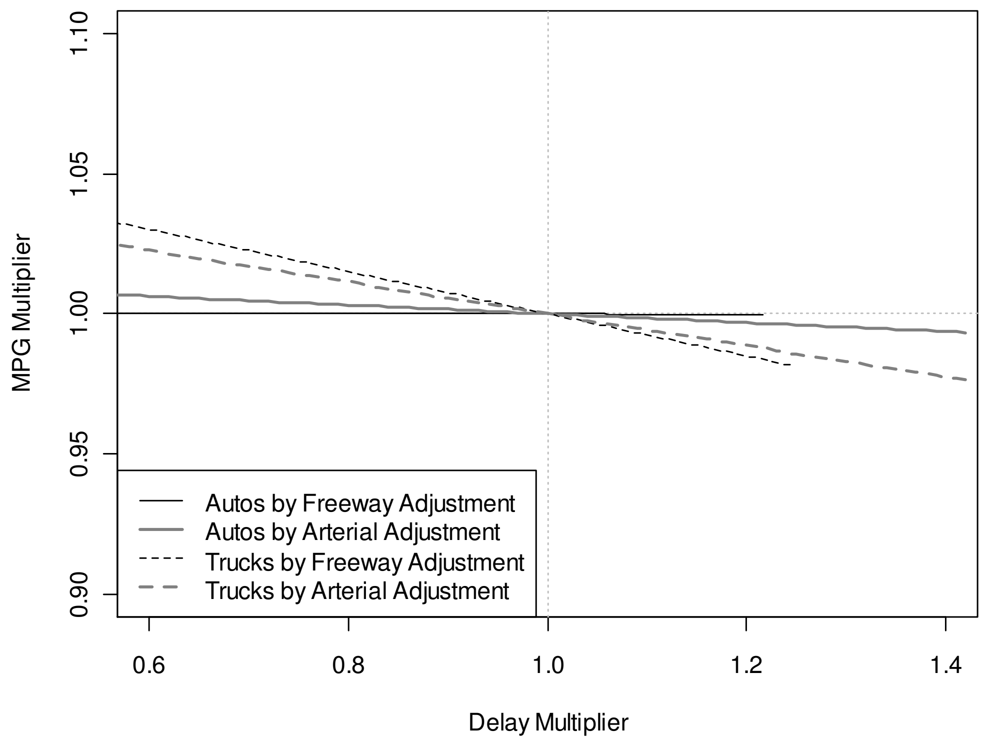

Figure 3a. Fuel Economy Sensitivity to Delay Adjustments through DVMT Distribution by Congestion Level for Portland

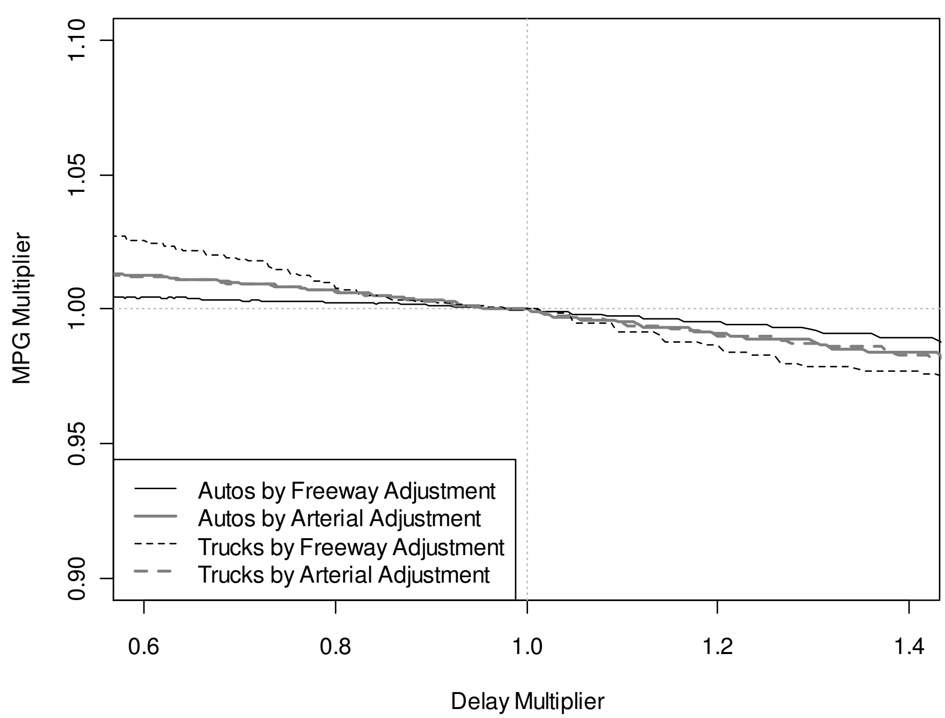

Figure 3b. Fuel Economy Sensitivity to Delay Adjustments through Congested Speeds for Portland

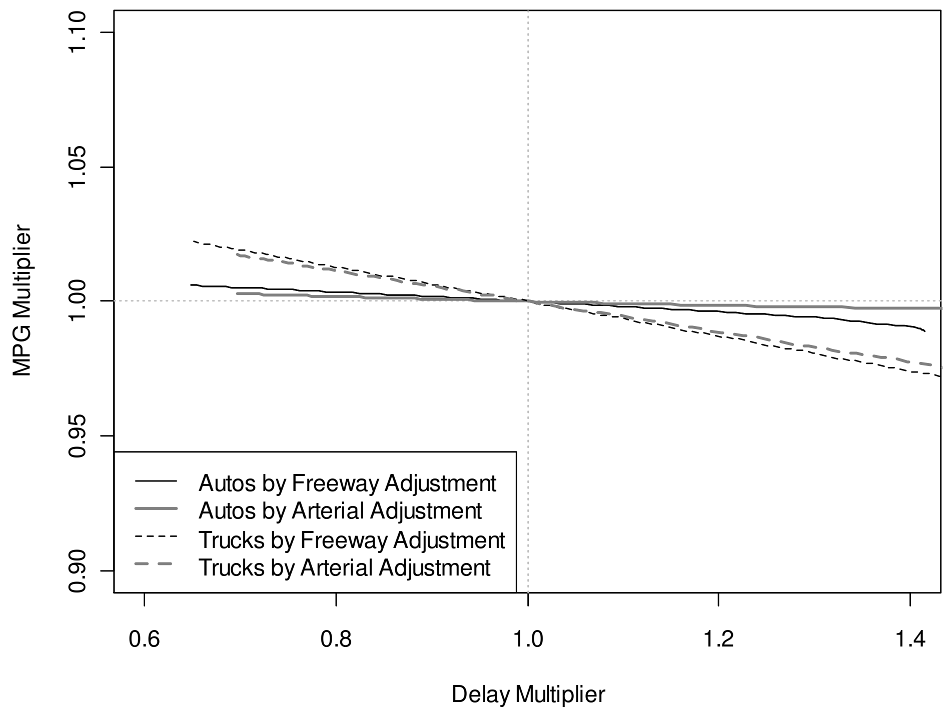

Figure 3c. Fuel Economy Sensitivity to Delay Adjustments through the Roadway Lane-Mile Supply for Portland (During Congestion Calculation Only)

Figure 3 shows the largest fuel economy effects for trucks on freeways. In all cases, the proportional MPG change is much smaller than the proportional delay change. The largest MPG change is a 3% increase in fuel economy for 40% delay savings for trucks on Portland-area freeways – an absolute value of elasticity smaller than 0.1. Most MPG changes are much smaller – particularly for autos on the freeway. This means that even fairly large delay reductions are expected to have only minor effects on fuel economy.

Figure 3 also shows that the different methods of delay adjustment have similar impacts on fuel economy. Although the speed distribution of DVMT is impacted in different ways by each adjustment, the net impact on fuel economy is consistent. The lane-mile adjustment (c) has a slightly different effect from (a) or (b) because it impacts not only the distribution of DVMT by congestion level, but also the DVMT split by facility type. Using the revised GreenSTEP method that adjusts DVMT distribution on freeways and arterials using congested speeds, the delay-only adjustments in (a) and (b) will more closely resemble the DVMT adjustment in (c). A similar investigation of smaller cities (Eugene and Salem) revealed the same effects, though with even smaller MPG changes because of lower existing levels of congestion.

Using the proposed fuel-speed curves from Task 1 with moderate assumed portions of advanced vehicles and median congestion effects curves (see the *Final Report for Refining GreenSTEP, Task 1*), the impact of delay adjustments is even smaller (plots not shown here). The conventional auto fuel economy in the median proposed curves is slightly more sensitive to congestion than in the existing GreenSTEP FSC, but the advanced vehicle fuel economy is much less sensitive – and has some beneficial effects in this speed range. With the proposed FSC from Task 1, the different delay-related congestion adjustments still have similar fuel efficiency effects.

Given the consistency of fuel economy adjustments across methods (and the small overall impact on fuel economy), we will implement delay effects by adjusting average speeds at each congestion level. This is most directly calculable from existing aggregate operations impacts data, and most readily integrated into the existing GreenSTEP model.

4.1.1 Roadway Supply and Travel Demand

As noted above, total travel demand in GreenSTEP is not sensitive to changes in travel time. Travel demand can be impacted by delay adjustments through changing fuel costs, but as shown in the previous section the impacts of operations on fuel economy is small (particularly with respect to the impacts on delay). Facility-specific travel demand is impacted by the DVMT split equilibrium function in the revised GreenSTEP model, which is sensitive to delay.

Adjusting the metropolitan area lane-mile supply of roadway before simulating household decision making is the other possible way to reflect operations strategies in total travel demand. This would impact both vehicle ownership decisions and household DVMT production. However, this method is not undertaken here for two reasons. First, the empirical data used to develop the vehicle ownership and DVMT models in GreenSTEP use physical lane-miles of roadway, implicitly including various influences on roadway capacity such as existing roadway management, grades, etc. Adjusting the lane-mile supply for *effective* roadway capacity could have unintended effects if it truly is the physical lane-miles of roadway that is the causal variable and not the lane-mile (vehicle throughput) capacity. Second, only freeway lane-mile supply is used in the household decision making process and so adjustments to arterial lane-mile supply will not influence vehicle ownership or household DVMT production. The insensitivity of DVMT production to arterial lane-mile supply means that only the effects of freeway operations improvements could be represented by changes in effective lane-mile supply. We leave the topic of effective lane-mile supplies for freeways as a subject for future research.

4.1.2 Free-Speed Reduction

The proposed fuel-speed curves from Task 1 extend beyond 70 mph. This allows for estimation of the fuel impacts of varying high-speed freeway driving speeds. The freeway free-flow speed can be set higher than the existing 60 mph value to reflect potential high-speed driving, or lower to represent lower speed limits, stricter speed enforcement, or traffic management such as variable speed limits. With the exception of some hybrid electric autos and heavy trucks which are particularly sensitive to congestion, fuel sensitivity to speed is generally low in the range of 60-70 mph – see the *Final Report for Refining GreenSTEP, Task 1*. Thus, the effect of including higher free-flow speeds (or high speed-reducing operations strategies) will be small.

4.2 Eco-Driving and Low Rolling Resistance Tires

Eco-driving and low rolling resistance tires are currently included in GreenSTEP as a scalar adjustment of average fuel economy. This is a speed- and congestion-independent adjustment. But as was pointed out in Section 2.6, eco-driving is expected to have more of an impact in heavier congestion. Similarly, comparing constant-speed driving to the fuel-speed curves reveals a greater proportional difference in fuel economy at lower speeds (again, see the *Final Report for Refining GreenSTEP, Task 1*). For this reason, we recommend to incorporate eco-driving and speed-smoothing traffic operations improvements as adjustments to fuel-speed curves and not a scaling of average fuel economy.

Low rolling-resistance tires have the effect of reducing the road load coefficients (RLC) in the vehicle power equation (see the *Final Report for Refining GreenSTEP, Task 1*). As discussed in that report, reducing the RLC *decreases* the relative fuel efficiency in congestion as compared to free-flow conditions, since it provides more of a fuel economy benefit at higher speeds. To account for this, the application of low rolling-resistance tires can be reflected using the current scaling in GreenSTEP, combined with a slight *reduction* in the assumed Congestion Efficiency value described in the Task 1 documentation.

5 Results - Traffic Operations Impacts

In this section we describe the results of calculations to estimate the delay-reducing impacts of the four traffic operations strategies included in the UMR operations study. Additionally, speed-smoothing and eco-driving effects on fuel-speed curves are described.

5.1 Freeway Ramp Metering

Figure 4 shows the percent delay reductions by urban area size due to ramp metering at full implementation and existing deployments. The paired bars compare the calculated mean reductions and the UMR operations study estimate for each urban area size category. "Very Large" indicates populations above 3 million, "Large" is 1-3 million, "Medium" is 0.5-1 million, and "Small" (not included) is under 0.5 million. Small urban areas are excluded from the freeway traffic operations impacts calculations due to too little freeway delay.

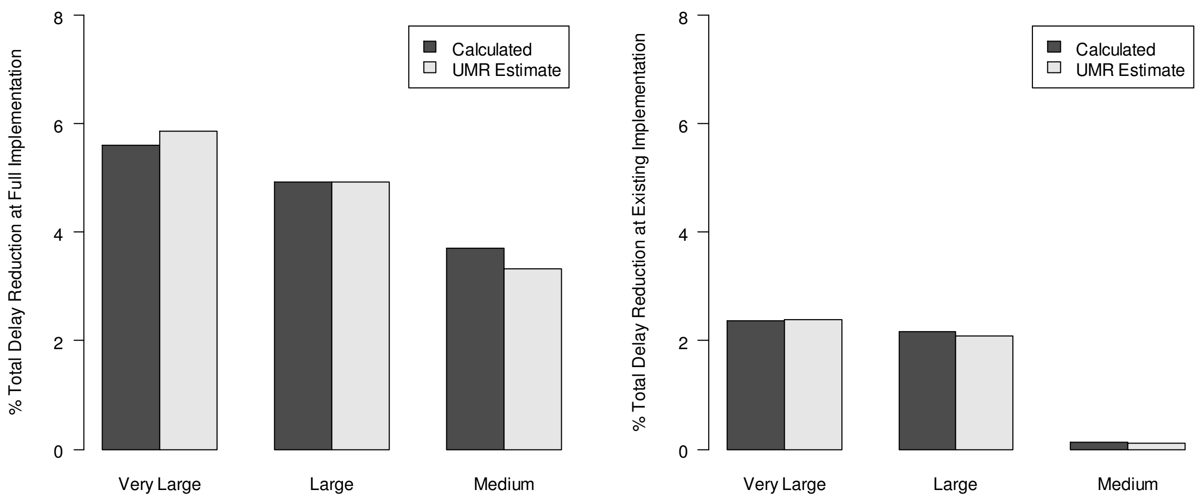

Figure 4. Percent Freeway Delay Reduction due to Ramp Metering at Full Implementation (left) and Existing Deployments (right), by Urban Area Size

These calculated aggregate delay reductions are based on a percent reduction of total recurring and non-recurring freeway delay by congestion level as indicated in Table 4. The deployment levels for each urban area size category (as a fraction of full implementation and full delay reductions) are as shown in Table 5. As an example, the average existing deployment of ramp metering in Large urban areas is 0.43 (1 is the maximum possible), which results in an Extreme freeway congestion delay reduction of $0.43 \times 6.3\% = 2.1\%$.

Table 4. Full Implementation Ramp Metering Delay Reduction by Congestion Level

Congestion Level	Recurring and Non-recurring Freeway Delay Reduction (%)
None	0.0
Moderate	0.0
Heavy	2.8
Severe	5.6
Extreme	6.3

Table 5. Ramp Metering Fractional Deployment by Urban Area Size

Urban Area Size	Fractional Deployment
Small	0.00
Medium	0.03
Large	0.43
Very Large	0.41

Figure 5 shows freeway delay reductions from ramp metering for existing and full-deployment conditions for the 90 urban areas in the UMR data tables, segregated by size category, versus the Travel Time Index (TTI). The TTI is a congestion measure used in the UMR to indicate the amount of distance-normalized delay; it is calculated as the ratio of the average travel time (in congestion) to the free-flow travel time. The horizontal lines indicate UMR operations study delay reduction values for each size category.

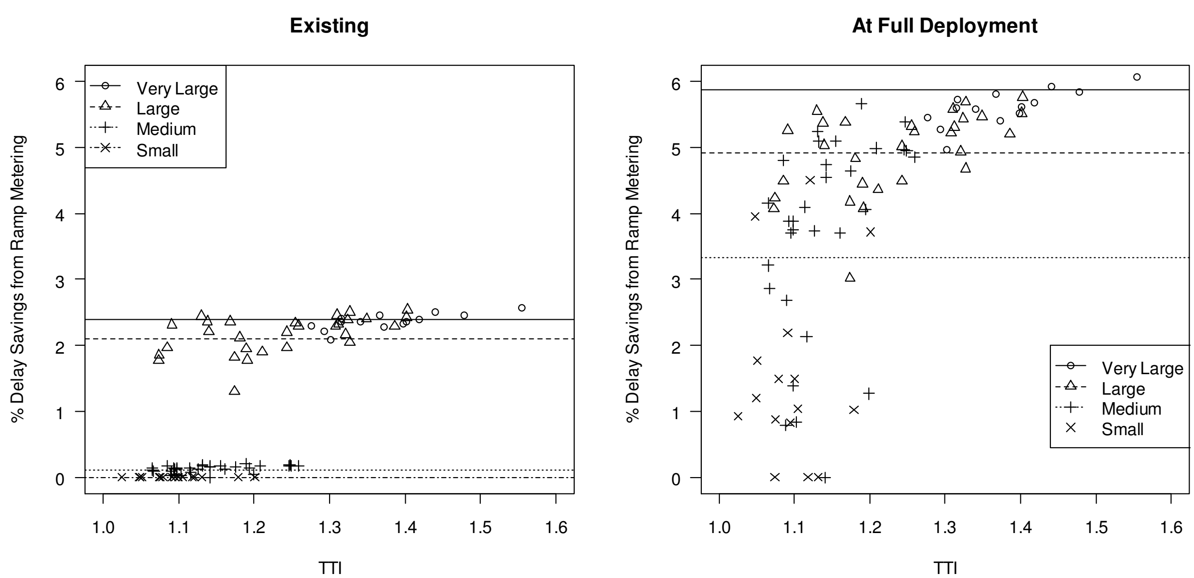

Figure 5. Ramp Metering Freeway Delay Reductions versus Travel Time Index

Only urban areas with Heavy, Severe, and Extreme freeway congestion can benefit from ramp metering by this method. Figure 5 shows that Large and Very Large urban areas have similar delay reductions from existing ramp metering, though there is more potential for reductions in the Very Large Areas. The largest two size categories are utilizing somewhat less than half of their ramp metering potential. Medium sized urban areas have very little ramp metering deployed, and moderate potential gains at full deployment. Particularly for Small and Medium urban areas, there is a wide variation in potential percent delay reductions at full deployment (depending on the congestion level distribution of DVMT). The potential delay reductions trend up with the TTI, since there is more DVMT at heavier levels of congestion (and ramp metering is more effective in heavier congestion – see Table 4).

This methodology, based on the UMR analysis, assumes ramp metering impacts can be represented by freeway delay alone. By impeding access to the freeway, ramp metering could potentially divert some short-distance freeway traffic to a parallel arterial. At the same time, improvements in freeway traffic flow will make freeway travel more attractive, partially or fully offsetting the diverted traffic to the arterial. For existing deployments this is not an issue, since the empirical freeway/arterial DVMT split will include any such diversions from existing ramp metering. For varying deployments, we assume that the revised GreenSTEP freeway/arterial DVMT distribution method – which is sensitive to congested speeds – will reflect any net freeway/arterial diversion that could result from a ramp metering system.

5.2 Freeway Incident Management

Figure 6 shows the percent freeway delay reductions by urban area size due to incident management at full implementation and existing deployments. The paired bars compare the calculated mean reductions and the UMR operations study estimate for each urban area size category. Again, small urban areas were excluded from the freeway operations impacts calculations due to too little freeway delay.

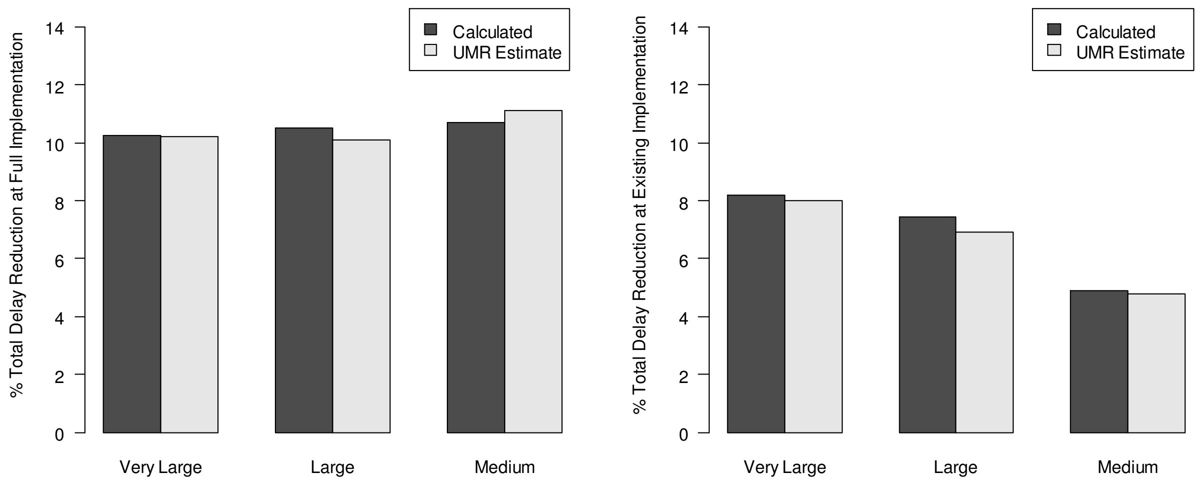

Figure 6. Percent Freeway Delay Reduction from Incident Management at Full Implementation (left) and Existing Deployments (right), by Urban Area Size

The calculated aggregate delay reductions are based on a percent reduction of non-recurring freeway delay by congestion level as indicated in Table 6. The deployment levels for each urban area size category (as a fraction of full implementation and full delay reductions) are as shown in Table 7. Incident management has the potential for large percentage delay reductions for all levels of congestion, though only for non-recurring delay. The opportunity for delay reductions is actually slightly greater in Medium areas than in larger urban areas, since incident-related (non-recurring) delay is a larger portion of total delay at lighter levels of congestion than at heavier levels (see Table 2).

Table 6. Full Implementation Incident Management Delay Reduction by Congestion Level

Congestion Level	Non-recurring Freeway Delay Reduction (%)
None	0.0
Moderate	13.2
Heavy	14.9
Severe	16.5
Extreme	18.9

Table 7. Incident Management Fractional Deployment by Urban Area Size

Urban Area Size	Fractional Deployment
Small	0.67
Medium	0.43
Large	0.69
Very Large	0.78

Figure 7 shows freeway delay reductions from incident management for existing and full-deployment conditions for the 90 urban areas in the UMR data tables, segregated by size category, versus the Travel Time Index (TTI). The horizontal lines indicate UMR operations study delay reduction values for each size category. Incident management effects do not trend with the TTI. This is because increasing levels of congestion do not indicate greater potential for a proportional impact from incident management: the percentage delay reductions are fairly steady across congestion levels (see Table 6).

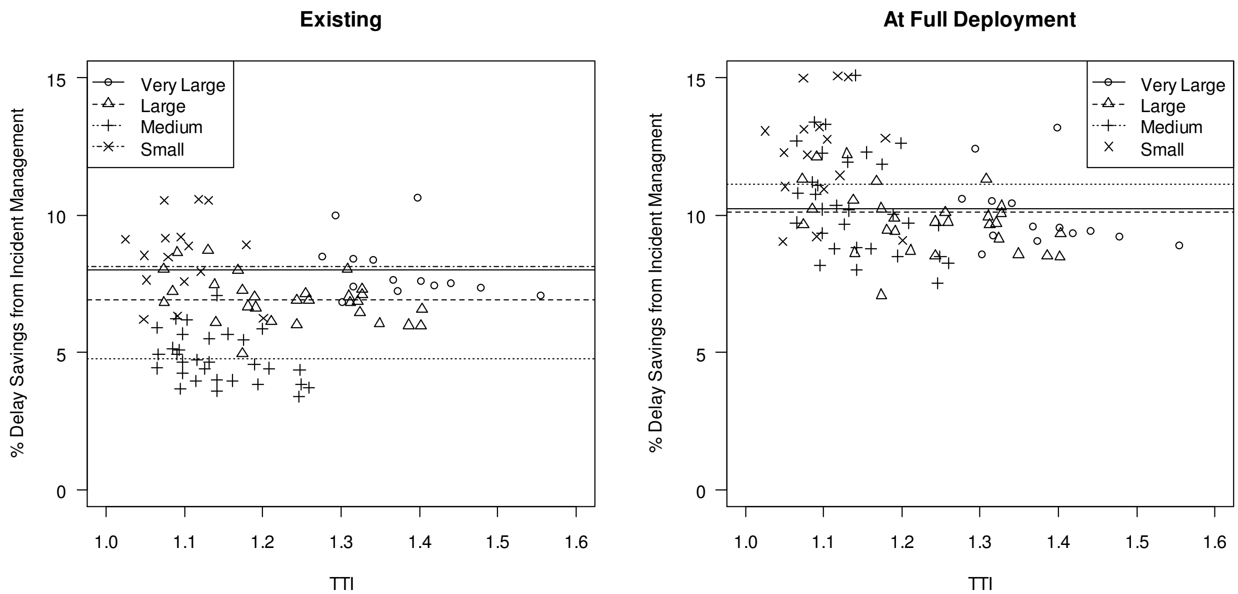

Figure 7. Incident Managment Freeway Delay Reductions versus Travel Time Index

5.3 Arterial Traffic Signal Coordination

Figure 8 shows the percent arterial delay reductions by urban area size due to traffic signal coordination at full implementation and existing deployments. The paired bars compare the calculated mean reductions and the UMR operations study estimate for each urban area size category. This operations strategy is more consistent across urban area size than the freeway strategies, both in potential and existing effects.

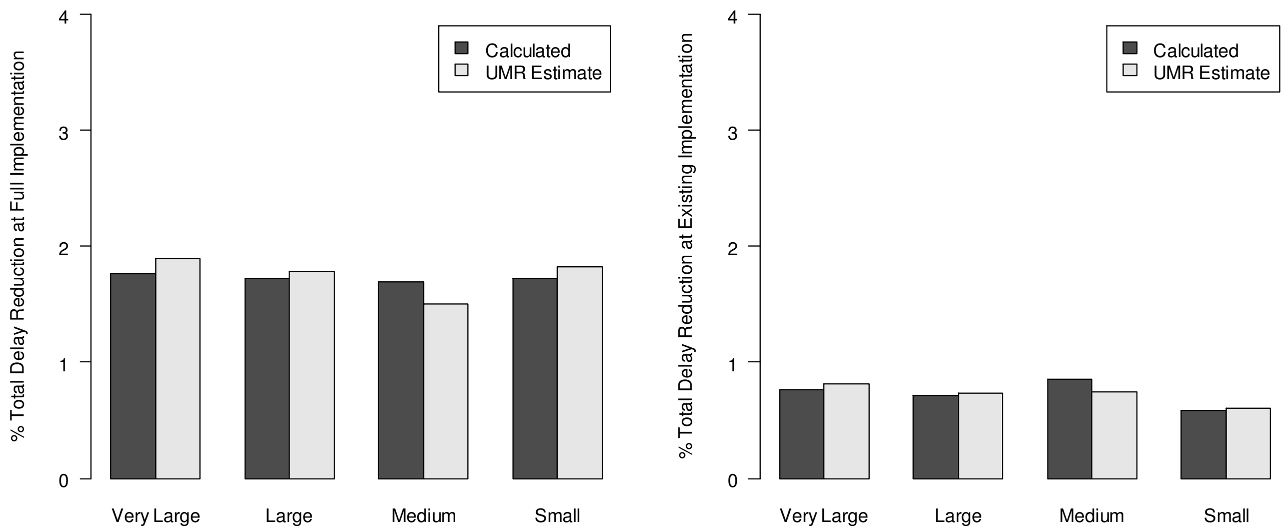

Figure 8. Percent Arterial Delay Reduction from Traffic Signal Coordination at Full Implementation (left) and Existing Deployments (right), by Urban Area Size

The calculated aggregate delay reductions are based on a percent reduction of recurring arterial delay by congestion level as indicated in Table 8. The deployment levels for each urban area size category (as a fraction of full implementation and full delay reductions) are as shown in Table 9. Traffic signal coordination has greater potential percentage delay reductions at lighter levels of congestion, and is only for recurring delay. The larger urban area size categories have similar levels of deployment, with somewhat more and less in the Medium and Small urban areas, respectively. The larger areas have heavier levels of congestion, for which signal coordination is less effective in reducing recurring delay. At the same time, heavier congestion has larger shares of recurring congestion – though arterials in general have a larger portion of non-recurring congestion than freeways, as seen in Table 2.

Table 8. Full Implementation of Signal Coordination Delay Reduction by Congestion Level

Congestion Level	Recurring Arterial Delay Reduction (%)
None	0.0
Moderate	10.3
Heavy	10.1
Severe	7.7
Extreme	5.2

Table 9. Traffic Signal Coordination Fractional Deployment by Urban Area Size

Urban Area Size	Fractional Deployment
Small	0.33
Medium	0.50
Large	0.41
Very Large	0.43

Figure 9 shows arterial delay reductions from traffic signal coordination for existing and full-deployment conditions for the 90 urban areas in the UMR data tables, segregated by size category, versus the Travel Time Index (TTI). The horizontal lines indicate UMR operations study delay reduction values for each size category. The potential for percent arterial delay reductions is small (less than 2%). Signal coordination effects also do not trend up or down with the TTI: the percentage delay reductions decrease in heavier congestion (Table 8) while the share of recurring delay increases (Table 2), with offsetting effects.

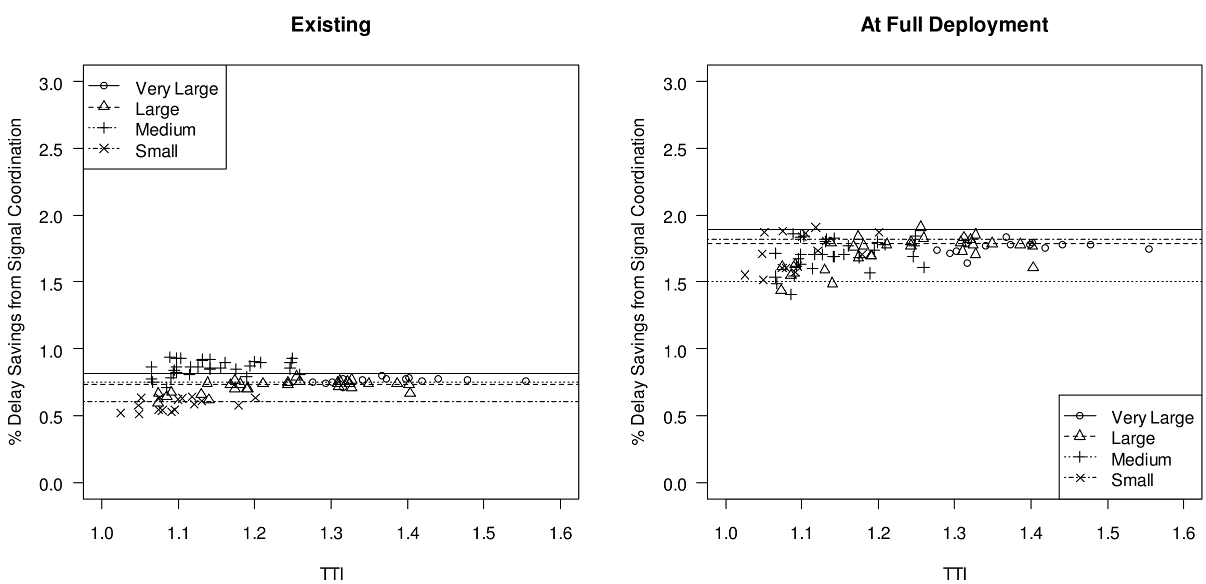

Figure 9. Signal Coordination Arterial Delay Reductions versus Travel Time Index

5.4 Arterial Access Management

Figure 10 shows the percent arterial delay reductions by urban area size due to traffic signal coordination at full implementation and existing deployments. The paired bars compare the calculated mean reductions and the UMR operations study estimate for each urban area size category. This operations strategy is consistent across urban area sizes in terms of potential effects, though the larger urban areas have somewhat larger existing effects.

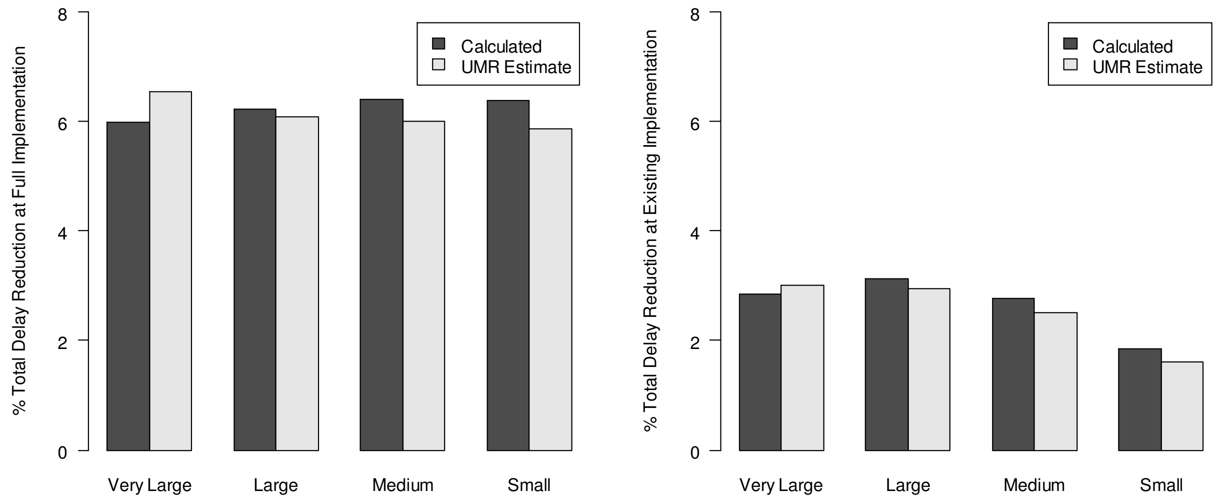

Figure 10. Percent Arterial Delay Reduction from Access Management at Full Implementation (left) and Existing Deployments (right), by Urban Area Size

The calculated aggregate delay reductions are based on a percent reduction of arterial delay by congestion level as indicated in Table 10. This shows an expected decrease in non-recurring delay but an *increase* in recurring delay (negative reduction), as explained in Section 2.5. The combined recurring/non-recurring delay effects lead to a net delay reduction because the percent decrease is greater (for non-recurring delay in Table 10), and the portion of non-recurring delay is greater than recurring delay on arterials (Table 2). The deployment levels for each urban area size category (as a fraction of full implementation and full delay reductions) are shown in Table 11.

Table 10. Full Implementation Access Management Delay Reduction by Congestion Level

Congestion Level	Recurring Arterial Delay Reduction (%)	Non-recurring Arterial Delay Reduction (%)
None	0.0	0.0
Moderate	0.0	8.0
Heavy	-2.2	8.0
Severe	-4.5	9.8
Extreme	-6.7	9.8

Table 11. Access Management Fractional Deployment by Urban Area Size

Urban Area Size	Fractional Deployment
Small	0.28
Medium	0.42
Large	0.49
Very Large	0.46

Figure 11 shows arterial delay reductions from access management for existing and full-deployment conditions for the 90 urban areas in the UMR data tables, segregated by size category, versus the Travel Time Index (TTI). The horizontal lines indicate UMR operations study delay reduction values for each size category. The potential effects trend downward slightly with TTI, since increasing levels of congestion have more recurring delay increases (and similar non-recurring delay decreases).

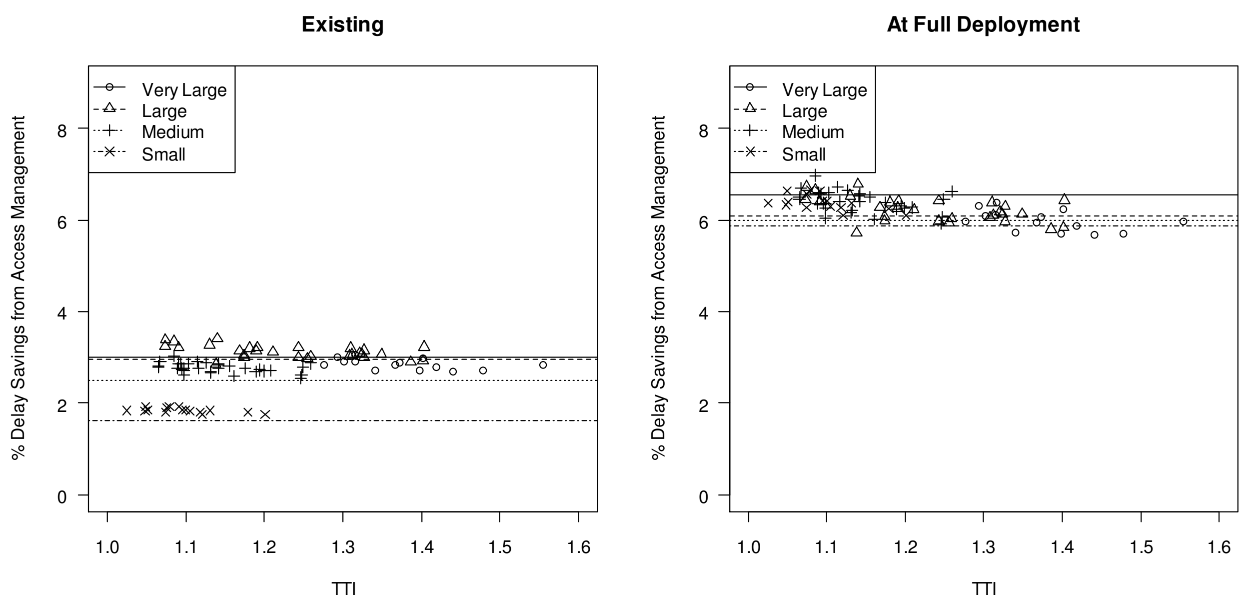

Figure 11. Access Management Arterial Delay Reductions versus Travel Time Index

5.5 Combined Delay Impacts of Traffic Operations

In this section we look at the combined impacts of these four delay-related operations strategies. We estimate the base speeds without these operations improvements and the potential and existing delay savings of the combined strategies.

5.5.1 Base Speeds – without Operations

Using the values above we can calculate the base recurring and non-recurring freeway and arterial speeds (without operations) for each urban area in the UMR data tables – using observed speeds from the UMR data and operations deployments by urban area size. Figure 12 shows the calculated base speeds averaged for all urban areas and the existing average speeds by congestion level. The top plots include both recurring and nonrecurring delay, while the bottom plots include only recurrent delay. The differences between the bars in Figure 12 are small, reflecting the small existing impact of operations strategies on average speed. The calculated base speeds are also shown in Table 12.

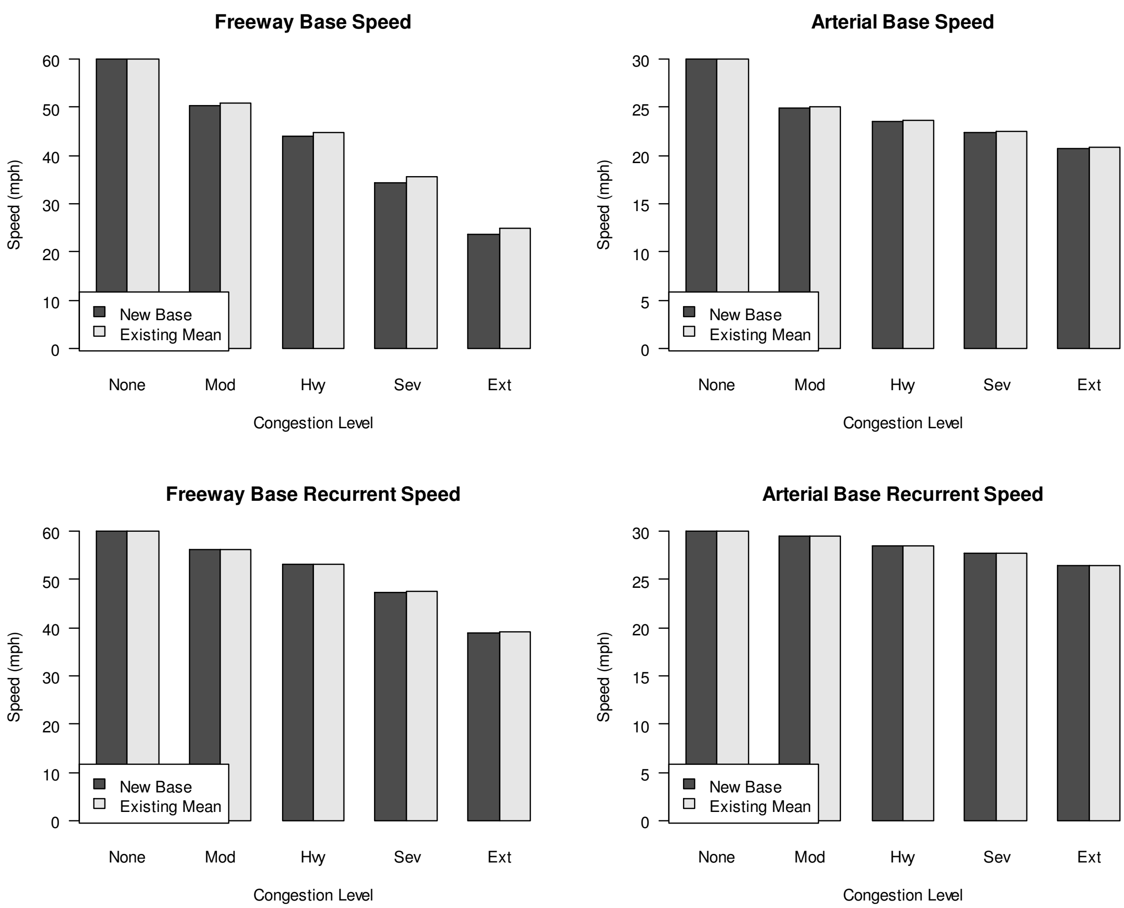

Figure 12. Calculated Base Speeds by Congestion Level, Compared with Existing Speeds

Table 12. Base Speeds (in mph) without Traffic Operations Strategies

Congestion Level	Freeways – with incidents	Freeways – without incidents	Arterials –with incidents	Arterials – without incidents
None	60.0	60.0	30.0	30.0
Moderate	50.4	56.2	24.9	29.4
Heavy	44.0	53.2	23.5	28.5
Severe	34.3	47.4	22.3	27.7
Extreme	23.5	38.8	20.6	26.4

5.5.2 Existing Delay Reductions

The calculated existing speed for each congestion level in each urban area depend on the level of operations deployments. Average existing deployments by urban area size are shown in Figure 13. These indicate the fraction of potential delay reduction which is achieved for each operation strategy (for the relevant delay types).

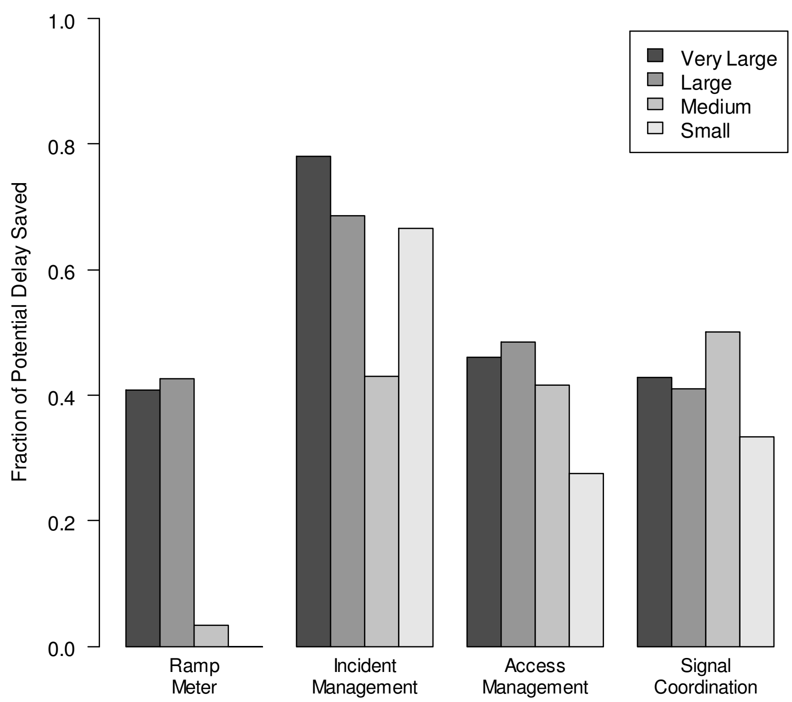

Figure 13. Existing Operations Deployments by Urban Area Size

Figure 14 shows the total percent freeway delay reduction for existing deployments, segmented by urban area size and congestion level. Larger areas generally have larger reductions, although small areas have a larger proportional reduction from incident management than medium areas (as indicated in Figure 13). Figure 15 shows the same data, but presented as a normalized delay reduction (in minutes per mile). Here we see that because heavier levels of congestion have more delay, they dominate the total delay reduction in absolute numbers.

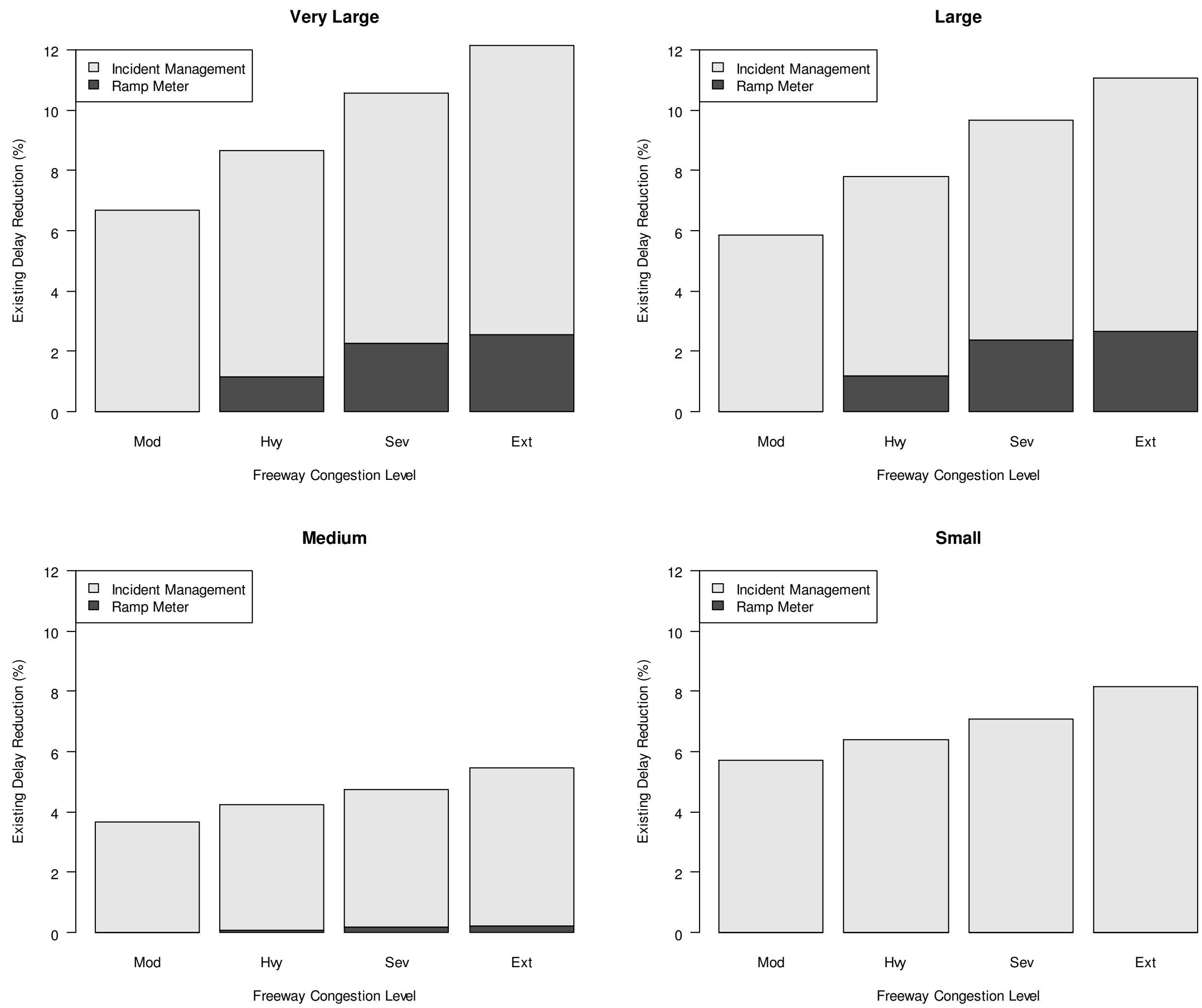

Figure 14. Percent Delay Reduction on Freeways with Existing Deployments

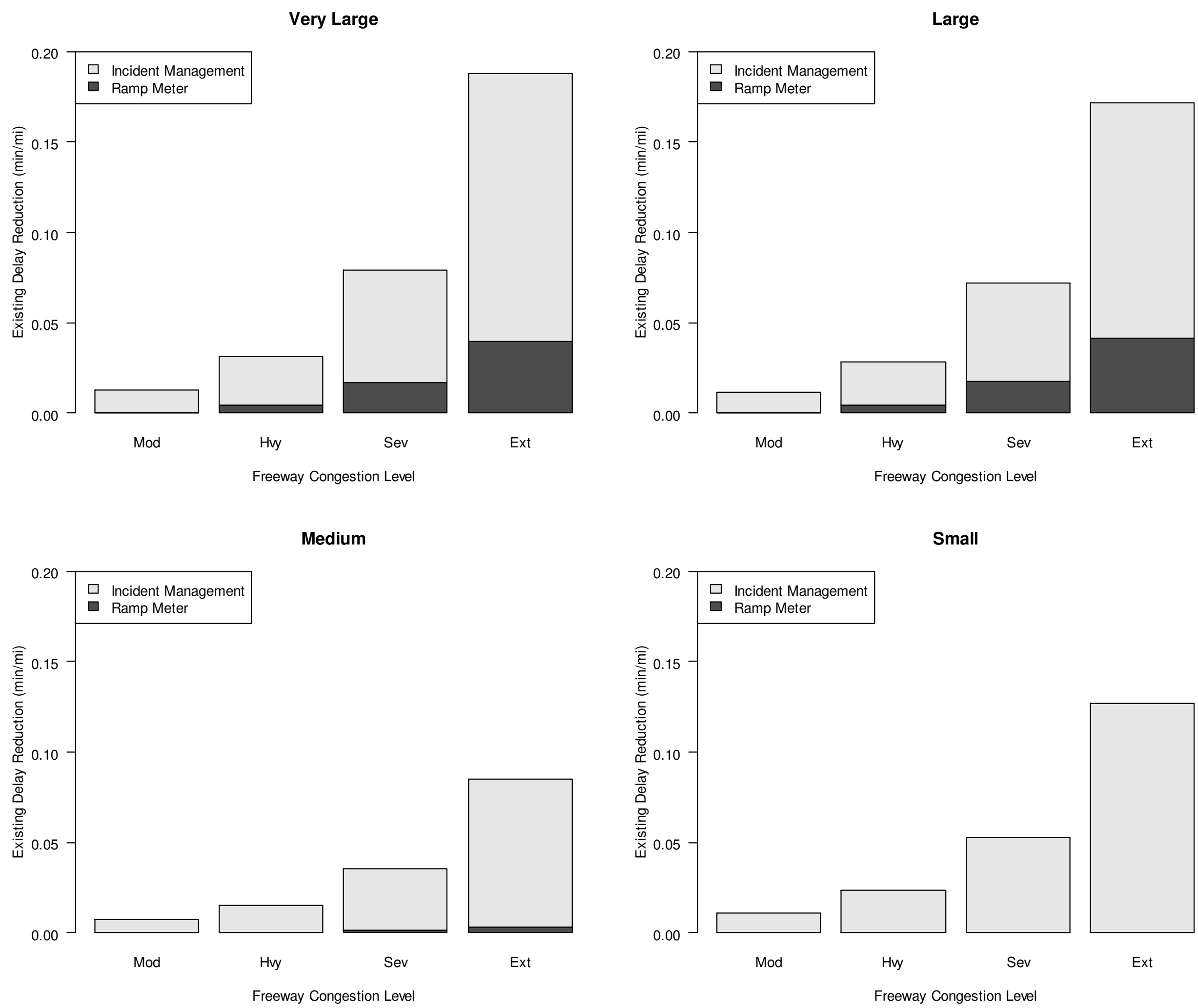

Figure 15. Absolute Delay Reduction on Freeways with Existing Deployments

Figure 16 shows a similar comparison for arterials, with both percent and absolute delay reductions segmented by congestion level (but only for Very Large and Medium urban areas). Here the percent reductions are smaller for heavier congestion, so the absolute delay reduction is more consistent across congestion levels. Also, urban areas of different sizes have more similar arterial delay reductions than freeway delay reductions (though only two are shown).

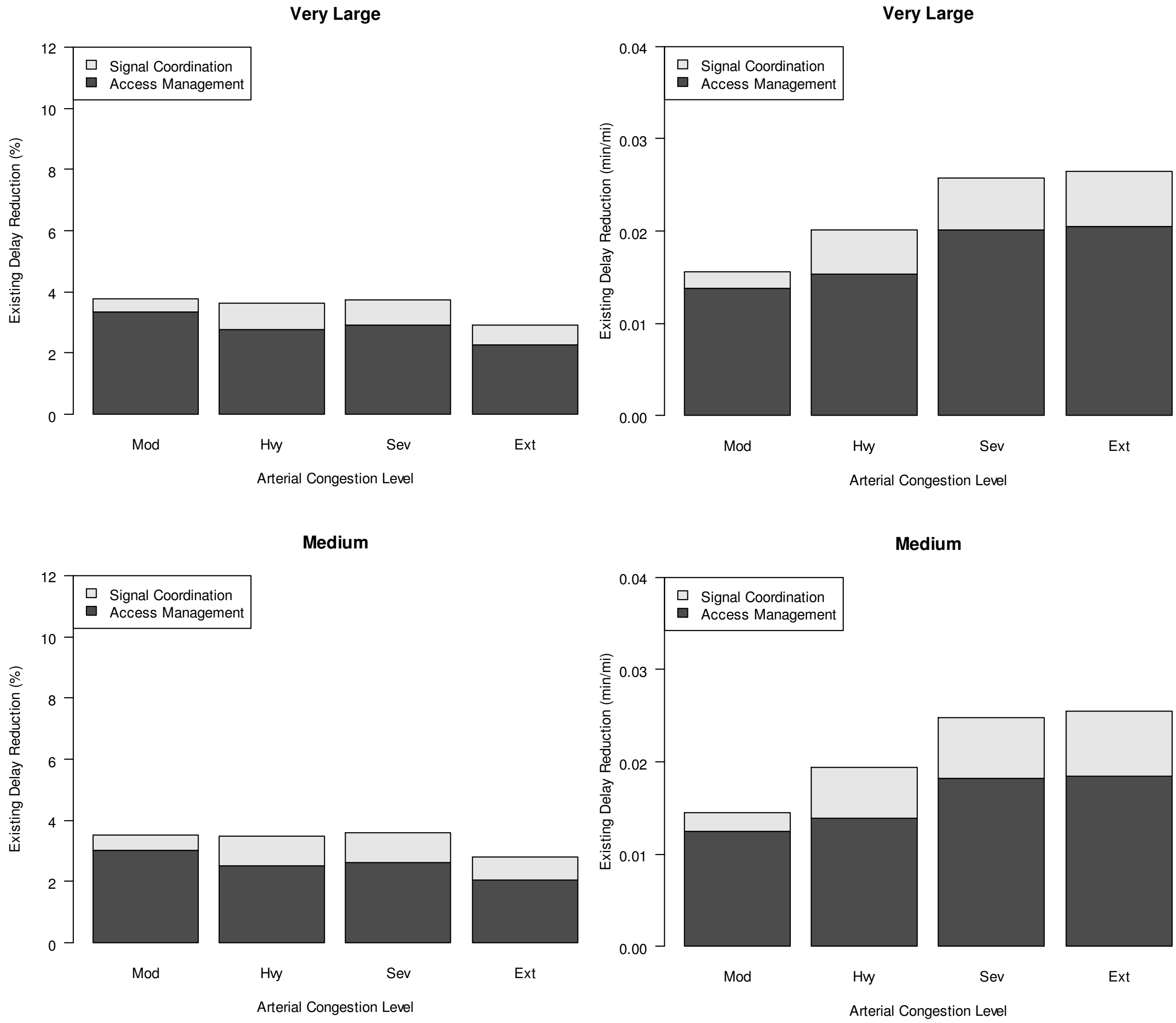

Figure 16. Delay Reductions (Percent and Absolute) on Arterials for Existing Deployments

5.5.3 Full Operations Deployment Speeds

Figure 17 shows the base speed and maximum speed at full operations deployments for each congestion level on freeways and arterials. Similar to Figure 12, the potential for speed increases through operations improvements is moderate to small. The largest potential is for heavily congestion freeways. The maximum speeds are also presented in Table 13.

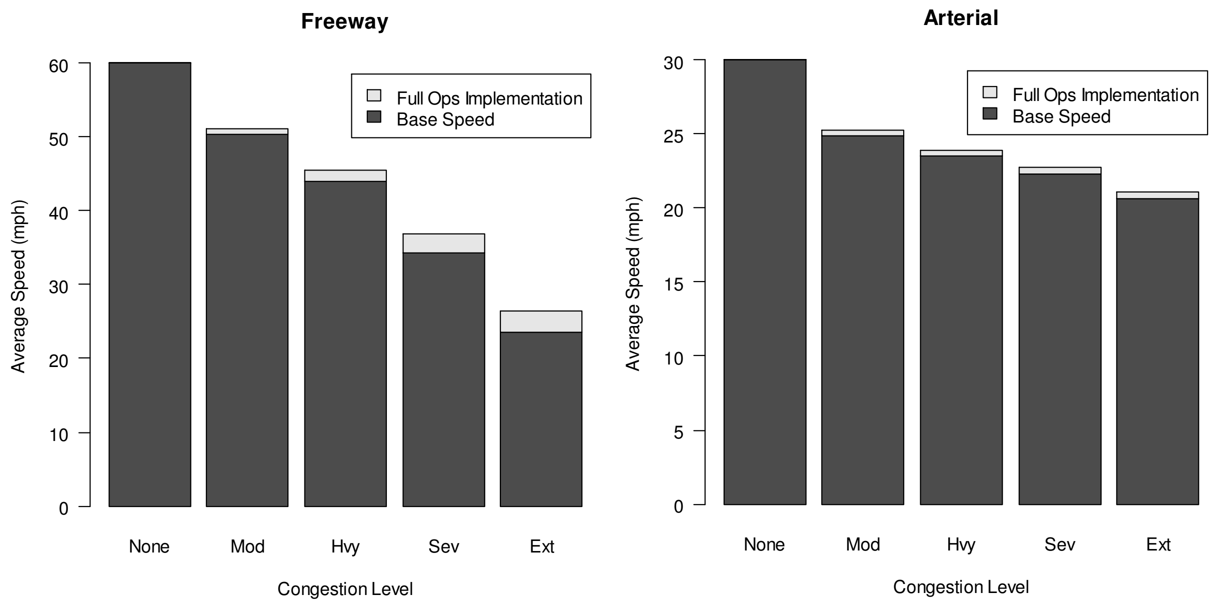

Figure 17. Base Speed and Maximum Speed at Full Operations Deployments

Table 13. Maximum Speeds (in mph) at Full Deployment of Operations Strategies

Congestion Level	Freeways – with incidents	Freeways – without incidents	Arterials –with incidents	Arterials – without incidents
None	60.0	60.0	30.0	30.0
Moderate	51.1	56.2	25.2	29.5
Heavy	45.5	53.3	23.9	28.6
Severe	36.9	47.9	22.8	27.7
Extreme	26.5	39.7	21.1	26.4

Separating the effects of different strategies, Figure 18 shows maximal delay reductions (percentage and absolute) for full deployments of each operations strategy by congestion level. Here we see that the absolute delay reductions on arterials are very small, which is consistent with Figure 17. The freeway delay reductions are mostly due to incident management, while the arterial delay reductions are primarily access management (and for both, the principal effect is on incident-related delay).

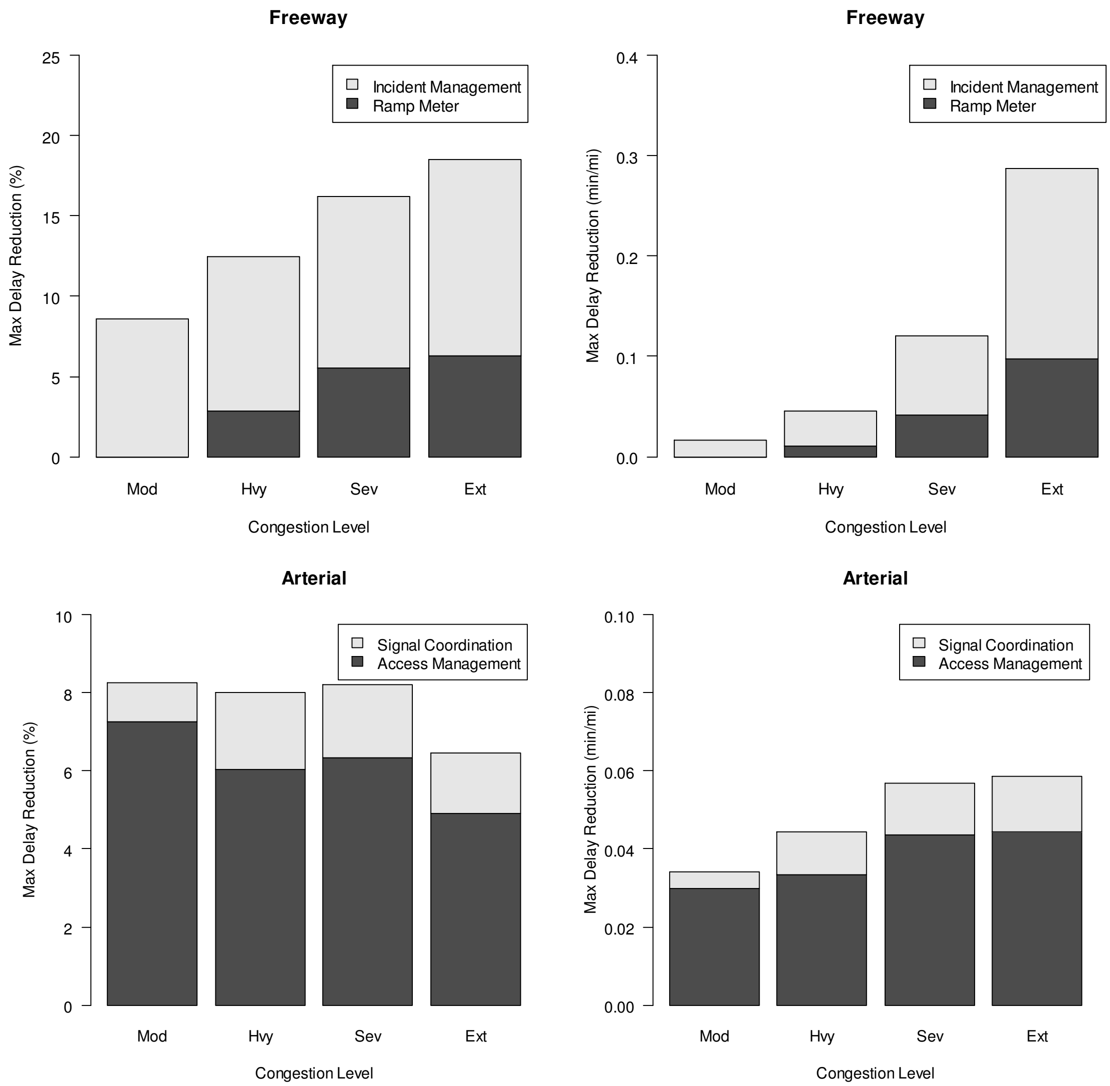

Figure 18. Maximum Delay Reductions at Full Deployment for Operations Strategies

5.6 Speed-Smoothing/Eco-Driving

The potential effects of eco-driving or speed-smoothing traffic management are estimated using constant-speed fuel-speed curves. These represent steady-state driving and the upper bound of fuel economy at a given speed. Constant-speed modeling was executed in PERE at speeds of 20, 30, 40, 50, and 60 mph for high and low congestion efficiency vehicles (see *Final Report for Refining GreenSTEP, Task 1*).

Figure 19 shows constant-speed fuel economy in proportion to drive schedule-based fuel economy for the selected light-duty (LD) and heavy-duty (HD) internal combustion engine (ICE) vehicles. For LD vehicles, a constant-speed curve is also included based on research by Barth and Boriboonsomsin (2008). These plots show fuel economy benefits of up to 70% for LD vehicles and 120% for HD vehicles. The largest benefits are for speeds of 20-30 mph, while the potential savings near freeway free-flow speed are smaller. A sensitivity analysis shows more potential speed-smoothing benefits for vehicles without regenerative braking, with flat-efficiency powertrains (non-ICE), and with low accessory loads (since accessory loads are unaffected by driving schedule).

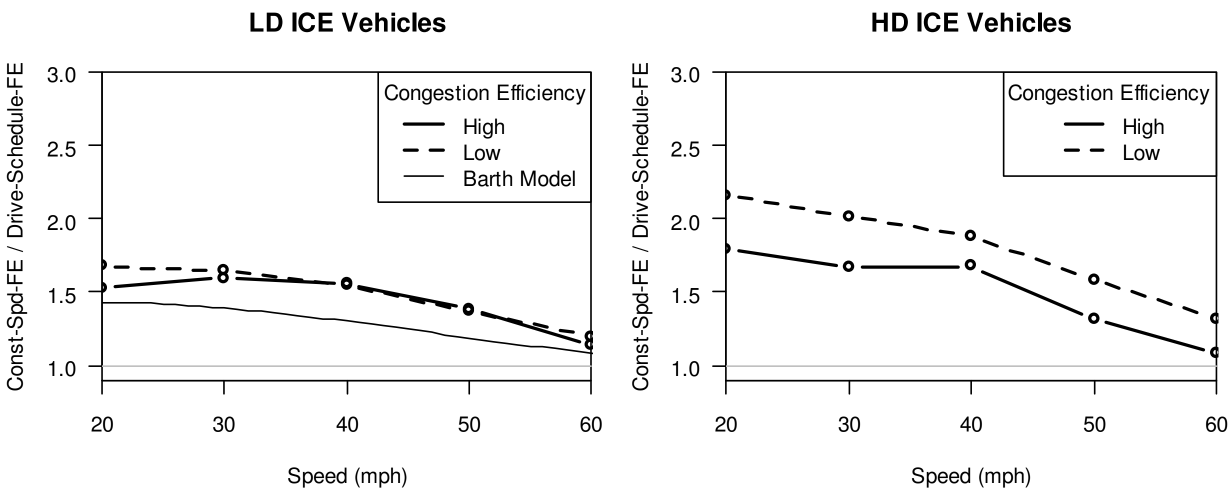

Figure 19. Constant-Speed Fuel Economy with Respect to Drive Schedule-Based Fuel Economy

The maximum percent fuel economy improvements from speed smoothing, based on the mean values between these curves, are shown in Table 14. Again, these are upper-bound estimates not realistically attained by any operational improvement. As a realistic point of reference, a recent paper by Barth and Boriboonsomsin (2009) on freeway eco-driving for passenger vehicles found fuel savings of up to 20% for mixed eco-driving fleets – with larger savings in heavier congestion. This would imply potential real-world improvements at 1/3rd the values shown in Table 14. A similar study on arterials found 12% fuel savings with eco-driving simulation runs (Barth, Mandava, Boriboonsomsin, & Xia, 2011). Potential implementations will vary widely in effects, but based on the literature, 50% of the values in Table 14 is a reasonable estimate for the maximum real-world attainable speed smoothing and eco-driving benefits.

Table 14. Upper-Bound Percent Fuel Economy Improvement from Speed Smoothing

Speed (mph)	Passenger Vehicles (% FE Improvement)	Trucks (% FE Improvement)
20	51	97
30	57	84
40	55	78
50	38	45
60	16	20

6 Implementation in GreenSTEP

The above results for traffic operations impacts and congestion adjustments in GreenSTEP are used here for a proposed method to incorporate traffic operations into GreenSTEP. Figure 20 illustrates the proposed strategy – a revision of Figure 2 – with the first three operations effects all being represented by average speed adjustments in GreenSTEP. The remaining components needed to implement this strategy are an efficacy estimator tool and coding to integrate the operations effects into GreenSTEP. These are each discussed in the following sections.

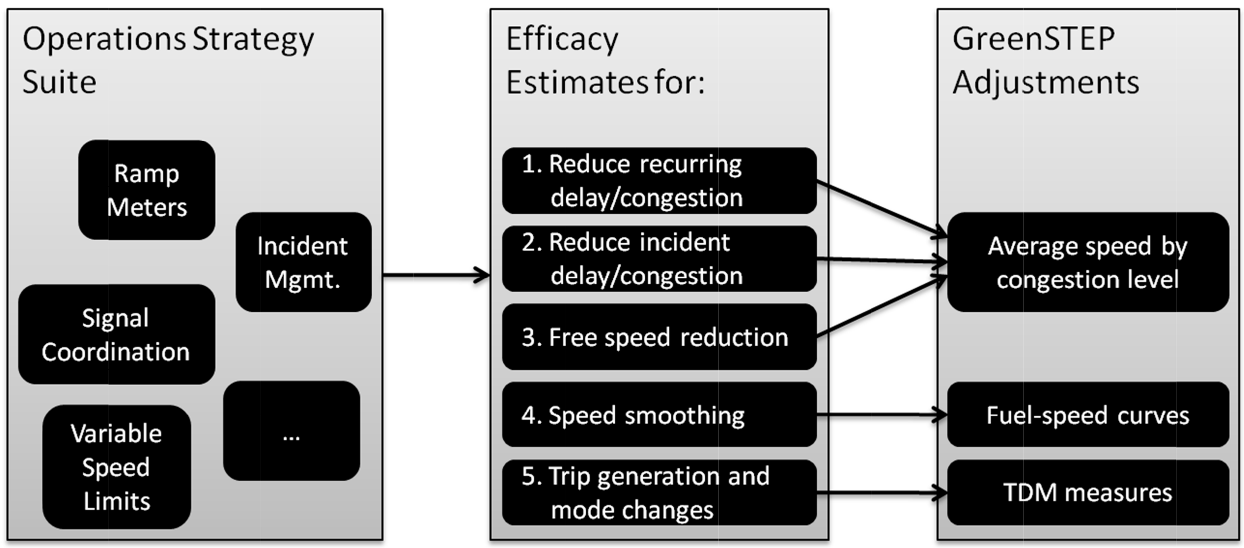

Figure 20. Final Diagram of Traffic Operations Incorporation in GreenSTEP

6.1 Efficacy Estimates

The efficacy estimates tool provides an interface to generate cumulative operations effects from a set of deployments (from the first to second column in Figure 20). These estimates are then used to adjust components of the GreenSTEP congestion model (moving to the third column in Figure 20). Rather than using physical details about the operations improvements, this tool is based on relative deployments with respect to maximum, minimum, and reference-city values.

6.1.1 Speed Estimates and Delay Adjustments

For each metropolitan area, deployments of ramp metering, incident management, signal coordination, and access management are indicated by a scalar value of 0 to 1. A value of 0 indicates no operational improvement, 1 is the maximum possible deployment (and delay reduction), and 0.5 is the typical deployment for urban areas of similar size (by category).

Delay reductions are estimated from the deployment level based on the results in Section 5. Additionally, the tool allows manual input of delay reductions for each combination of vehicle type, facility type, and congestion level. This allows for exploratory estimation of fuel impacts from operations strategies for which insufficient data are available to predict the effects with certainty. These additional delay reductions are input as a percent reduction, which is compounded with the delay reductions estimated for the established four traffic operations strategies. Then, base speed is adjusted up for the delay reduction values to produce estimates of average speed by facility type and congestion level for each urban area, year, and vehicle type. Additionally, input values for freeway free-flow speeds by vehicle type (passenger vehicle and truck) are applied directly for the revised uncongested freeway speeds.

6.1.2 Fuel-Speed Curve Adjustments

Eco-driving and speed-smoothing are also indicated by metropolitan area and year. Speed smoothing traffic management is represented by a scalar value from 0 to 1, separately for freeways and arterials, where 0 implies the standard fuel-speed curves and 1 scales the fuel economy up to 50% of the values in Table 14. For eco-driving (passive or active), the input is the fraction of vehicles utilizing eco-driving, separately for passenger vehicles and trucks. We then assume freeway eco-drivers achieve 33% of the fuel economy benefits in Table 14 and arterial eco-drivers achieve 21% (based on values from the literature – see Section 5.6), with no impact on other vehicles. The speed-smoothing traffic management applies only to non-eco-driving vehicles, unless the speed-smoothing benefit exceeds the eco-driving benefit, in which case eco-driving is masked and speed-smoothing traffic management applies to all vehicles. Scaling the values in Table 14 produces factors for adjusting the FSC in the GreenSTEP congestion model.

6.1.3 Efficacy Estimates Tool

In this section we describe the Efficacy Estimates Tool calculations in more detail. The Efficacy Estimates Tool performs the efficacy calculations to convert scenario metropolitan-level operations improvements to new input data for the GreenSTEP congestion model. Inputs are:

- Fractional deployments of four operations strategies (freeway ramp metering, freeway incident management, arterial access management, and arterial traffic signal coordination) – where 0 is no deployment, 1 is the full potential delay savings, and 0.5 is the average delay savings for similar-sized cities

- Fractional deployment of speed smoothing traffic management for freeways and arterials, separately – where 0 is no deployment and 1 is the full potential fuel savings
- Eco-driving penetration for passenger vehicles and trucks, separately – the fraction of vehicles from 0 to 1
- Freeway free-flow speeds for passenger vehicles and trucks – in mph
- Percent delay reductions for other (unspecified) operations strategies, segmented by congestion level, facility type (freeway, arterial), and vehicle type (passenger vehicles, trucks)
- Metropolitan population – to determine the city's size category

From these inputs, the Efficacy Estimates Tool then produces average speeds by congestion level (none, moderate, heavy, severe, extreme), facility type (freeway, arterial), and vehicle type (passenger vehicles, trucks), as well as fuel economy adjustments versus average speed curves for passenger vehicles and trucks on freeways and arterials (four curves in total).

The recurring and non-recurring base speeds (without operations improvements) for each congestion level and facility type are $BSR_{C,F}$ and $BSNR_{C,F}$, respectively. These values are shown in Table 12, where recurring is without incidents and nonrecurring is with incidents. The recurring base delay is then $\frac{1}{BSR_{C,F}} - \frac{1}{FFS_F}$, where FFS_F is the base free-flow speed for facility type F (60 mph for freeways and 30 mph for arterials). Similarly, the nonrecurring base delay is $\frac{1}{BSNR_{C,F}} - \frac{1}{BSNR_{C,F}}$.

Let the relative level of deployment for operations strategy S for each metropolitan area for each year be θ_S, where $0 \leq \theta_S \leq 1$; this is with respect to similar-sized cities. Further, let $\vartheta_{C,V,F}$ be the input fractional delay reduction from unspecified operations strategies for congestion level C, vehicle type V, and facility type F. The metropolitan population is used to identify the city size category (see Section 5). The city size category determines the *reference* deployment levels (with respect to the potential delay savings) for each operations strategy S, as shown in Table 5, Table 7, Table 9, and Table 11. The scenario deployment levels are then interpolated using θ_S. A value of $\theta_S = 0.5$ yields the reference deployment level. For $0 \leq \theta_S <$

0.5, the deployment is interpolated between 0 and the reference deployment. For $0.5 \leq \theta_S \leq 1$, the deployment is interpolated between the reference deployment and 1. Let this deployment level (fraction of potential delay savings) for operations strategy S be γ_S.

The potential delay savings at full deployment for each congestion level by each operations strategy are shown in Table 4, Table 6, Table 8, and Table 10. Let these potential delay savings be represented $\delta_{C,S}$. Then the delay reductions for each C and F can be calculated:

$\sum_S \left[\gamma_S \delta_{C,S} \left(\frac{1}{BSR_{C,F}} - \frac{1}{FFS_F}\right)\right]$ for recurring delay and

$\sum_S \left[\gamma_S \delta_{C,S} \left(\frac{1}{BSNR_{C,F}} - \frac{1}{BSR_{C,F}}\right)\right]$ for non-recurring delay, as appropriate.

The total delay reduction for each C and F is the sum of these two effects. Delay is further reduced by subtracting $\vartheta_{C,V,F}$ for each V. The remaining delay is converted back into speed using the same free-flow speeds as above. Final speeds for uncongested freeways are taken from the input value for each V, and final arterial uncongested speeds are 30 mph. The result is 20 average-speed estimates after operations improvements – one for each combination of F, V, and C.

For speed smoothing, upper-bound percent fuel economy improvements are shown in Table 14. If the speed-smoothing traffic management input is set above 33% of potential fuel benefits for freeways or above 21% of potential benefits for arterials, then eco-driving is masked for that facility. If eco-driving is *not* masked, the fraction of vehicles engaged in eco-driving is multiplied by the assumed eco-driving benefits (33% and 21% of potential fuel economy improvement for freeways and arterials, respectively), to estimate the fraction of potential speed-smoothing savings from eco-driving for each F and V.

If eco-driving is masked, the fraction of speed-smoothing traffic management as an input is multiplied by 0.5 to estimate the fraction of potential fuel economy improvement achieved from speed-smoothing traffic management (for each F). If eco-driving is *not* masked, then this value is further multiplied by the fraction of vehicles *not* engaged in eco-driving (for each F and V). The combined speed-smoothing effects of traffic management and eco-driving is simply the sum of the two effects (for each F and V), multiplied by the upper-bound percent fuel economy improvements shown in Table 14. These produce fractional fuel economy improvements at different speeds for each combination of F and V.

6.2 Revisions to GreenSTEP

The efficacy estimates tool generates two output data tables: 1) average speeds at each congestion level by facility type, vehicle type, urban area, and year, and 2) scalar adjustments to the fuel-speed curves at 10 mph increments from 20 mph to 60 mph, by facility type and vehicle type. These data are fed directly into the GreenSTEP congestion adjustment function and model object.

The average speed estimates replace the existing speeds by congestion level in the "CongModel_" data object. The FSC adjustment factors are applied using a revised "calcCongestion" function in GreenSTEP (provided with the Task 1 documentation). Other traffic operations adjustments that are to be reflected by travel demand management (such as HOV lane effects on ECO programs or transit priority impacts on transit quality of service) can be applied in the scenario input data files.

The efficacy estimate tool calculations were initially implemented in spreadsheet format, in a file attached to the draft version of this report. The efficacy calculation and adjustment processes are now integrated into the GreenSTEP model through revised GreenSTEP model code for the "calcCongestion" function and "CongModel_" objects, as well as new input files.

7 Conclusions

This report describes analysis undertaken to establish a method for incorporating traffic operations and ITS strategies into the GreenSTEP model. We first discuss operations impacts on fuel economy and delay from the literature. Then, an investigation of delay adjustments in GreenSTEP shows that different methods of representing delay changes lead to similar impacts on fuel economy. From this result we establish average speed adjustment by congestion level as the preferred method for incorporating delay effects.

Next, an investigation of aggregate traffic operations impacts produces estimates of base speeds without operations improvements, maximum speeds with full operational improvements, and existing deployments by city size for each congestion level. This is calculated for ramp metering, incident management, traffic signal coordination, and access management. Additionally, a comparison of constant-speed and drive schedule-based fuel-speed curves generates estimates of potential fuel benefits from eco-driving and speed-smoothing traffic management. These operations impacts estimates are used to provide guidance for estimates of operations efficacy in delay reductions and speed smoothing. The cumulative impact of delay-based operations strategies on fuel economy is small, though speed-smoothing effects can be large.

The proposed implementation strategy includes an efficacy estimates tool for the net effects of operations strategies, and locations in the model where those effects can be included. Traffic operations impacts on travel demand must be separately applied as travel demand management inputs to the existing GreenSTEP model. Efficacy estimates were originally provided in spreadsheet format, and are now implemented in revised scripts in GreenSTEP for congestion calculations that integrate operations improvements.

The proposed method for incorporating traffic operations improvements into GreenSTEP is based on a limited quantity of available data for aggregate operations impacts on fuel economy. Ideally, more diverse strategies would be included, but the body of knowledge is insufficient at this time. Various long-term research projects are underway to establish the role that ITS can play in meeting our climate and energy goals (such as AERIS at the U.S. Department of Transportation, http://www.its.dot.gov/aeris). Until those are complete, the proposed method provides expected impacts from several established operations strategies and the flexibility to accommodate the assumed effects of as-yet undetermined strategies.

Future work which would be of particular value is incorporation of delay impacts or time budgeting into GreenSTEP. Although the fuel impacts of varying operations strategies is relatively small, the delay impacts can be large – which would impact traveler behavior responsive to time constraints.

8 References

Allaby, P., Hellinga, B., & Bullock, M. (2006). Variable speed limits: safety and operational impacts of a candidate control strategy for an urban freeway. *Intelligent Transportation Systems Conference, 2006. ITSC'06. IEEE* (pp. 897–902).

Barth, M., & Boriboonsomsin, K. (2008). Real-World Carbon Dioxide Impacts of Traffic Congestion. *Transportation Research Record: Journal of the Transportation Research Board*, *2058*, 163–171.

Barth, M., & Boriboonsomsin, K. (2009). Energy and emissions impacts of a freeway-based dynamic eco-driving system. *Transportation Research Part D: Transport and Environment*, *14*(6), 400-410. doi:10.1016/j.trd.2009.01.004

Barth, M., Mandava, S., Boriboonsomsin, K., & Xia, H. (2011). Dynamic ECO-Driving for Arterial Corridors. Presented at the 2011 IEEE Forum on Integrated and Sustainable Transportation Systems, Vienna, Austria.

Boriboonsomsin, K., & Barth, M. (2007). Evaluating Air Quality Benefits of Freeway High-Occupancy Vehicle Lanes in Southern California. *Transportation Research Record: Journal of the Transportation Research Board*, *2011*, 137-147. doi:10.3141/2011-15

Boriboonsomsin, K., & Barth, M. (2008). Impacts of freeway high-occupancy vehicle lane configuration on vehicle emissions. *Transportation Research Part D: Transport and Environment*, *13*(2), 112-125. doi:10.1016/j.trd.2008.01.001

Cascetta, E., Punzo, V., & Sorvillo, R. (2010). Impact on vehicle speeds and pollutant emissions of a fully automated section speed control scheme on the Naples urban motorway. *89th Annual Meeting of the Transportation Research Board*. Presented at the 89th Annual Meeting of the Transportation Research Board, Washington, D.C.

Cassidy, M. J., Daganzo, C. F., Jang, K., & Chung, K. (2006). *Empirical reassessment of traffic operations: Freeway bottlenecks and the case for HOV lanes*. Institute of Transportation Studies, U.C. Berkeley.

Chen, C., Varaiya, P., & Kwon, J. (2005). An empirical assessment of traffic operations. *Proceedings, International Symposium on Transportation and Traffic Theory* (pp. 19–21).

Chu, H.-C., & Meyer, M. D. (2009). Methodology for assessing emission reduction of truck-only toll lanes. *Energy Policy*, *37*(8), 3287-3294. doi:10.1016/j.enpol.2009.03.058

Dahlgren, J. (1998). High occupancy vehicle lanes: Not always more effective than general purpose lanes. *Transportation Research Part A: Policy and Practice*, *32*(2), 99-114. doi:10.1016/S0965-8564(97)00021-9

Dion, F., Rakha, H., & Zhang, Y. (2004). Evaluation of Potential Transit Signal Priority Benefits along a Fixed-Time Signalized Arterial. *Journal of Transportation Engineering*, *130*(3), 294-303. doi:10.1061/(ASCE)0733-947X(2004)130:3(294)

Eisele, B., & Lomax, T. (2004). *ODOT Operations Performance Measures Final Report*. Oregon Department of Transportation.

Federal Highway Administration. (2002). *Highway Economic Requirements System - State Version*. U.S. Department of Transportation.

Federal Highway Administration. (2007). *Active Traffic Management: The Next Step in Congestion Management* (No. FHWA-PL-07-012). Washington, D.C.: Federal Highway Administration.

Gregor, B. (2011). *A Revised Congestion Emissions Model for GreenSTEP* (Draft). Oregon Department of Transportation.

Keller, J., Andreani-Aksoyoglu, S., Tinguely, M., Flemming, J., Heldstab, J., Keller, M., Zbinden, R., et al. (2008). The impact of reducing the maximum speed limit on motorways in Switzerland to 80 km h-1 on emissions and peak ozone. *Environmental Modelling & Software*, *23*(3), 322-332. doi:10.1016/j.envsoft.2007.04.008

Lee, C., Hellinga, B., & Saccomanno, F. (2004). Assessing safety benefits of variable speed limits. *Transportation Research Record: Journal of the Transportation Research Board*, *1897*(-1), 183–190.

Menendez, M., & Daganzo, C. F. (2007). Effects of HOV lanes on freeway bottlenecks. *Transportation Research Part B: Methodological*, *41*(8), 809-822. doi:10.1016/j.trb.2007.03.001

Papageorgiou, M., Kosmatopoulos, E., & Papamichail, I. (2008). Effects of variable speed limits on motorway traffic flow. *Transportation Research Record: Journal of the Transportation Research Board*, *2047*(-1), 37–48.

Roorda, M., Hain, M., Amirjamshidi, G., Cavalcante, R., Abdulhai, B., & Woudsma, C. (2010). Exclusive Truck Facilities in the Toronto Area: Analysis of Truck and Automobile Demand. *89th Annual Meeting of the Transportation Research Board*. Washington, D.C.

Schrank, D., & Lomax, T. (2009a). *The 2009 Urban Mobility Report*. College Station, TX: Texas Transportation Institute.

Schrank, D., & Lomax, T. (2009b). *Six Congestion Reduction Strategies and Their Effects on Mobility*. Texas Transportation Institute.

Servin, O., Boriboonsomsin, K., & Barth, M. (2006). An energy and emissions impact evaluation of intelligent speed adaptation. *Intelligent Transportation Systems Conference, 2006. ITSC '06. IEEE* (pp. 1257-1262). Presented at the Intelligent Transportation Systems Conference, 2006. ITSC '06. IEEE. doi:10.1109/ITSC.2006.1707395

U.S. Environmental Protection Agency. (1998). *Assessing the Emissions and Fuel Consumption Impacts of Intelligent Transportation Systems (ITS)* (No. EPA-231-R-98-007). Washington, D.C.

Unal, A., Rouphail, N. M., & Frey, H. C. (2003). Effect of arterial signalization and level of service on measured vehicle emissions. *Transportation Research Record: Journal of the Transportation Research Board*, *1842*(-1), 47–56.

Zegeye, S. K., De Schutter, B., Hellendoorn, J., & Breunesse, E. (2010). Variable Speed Limits for Area-Wide Reduction of Emissions. Presented at the 13th International IEEE Conference on ITS, Madeira Island, Portugal.