An Analysis of the Relative Efficiency of Freeway Congestion Mitigation as an Emissions Reduction Strategy

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ABSTRACT

In order to move toward better understanding of freeway congestion mitigation and emissions reduction strategies, this paper explores the effects of traffic speeds, freeway capacity, travel demand, and alternative efficiency strategies on freeway emissions. Emissions from a homogenous freeway section with typical fleet and traffic characteristics are modeled and analyzed utilizing widely established emission models and macroscopic speed-flow relationships. Assuming an *inelastic* travel demand function, it is observed that the potential for marginal emissions rate reductions through average travel speed adjustments between 30 and 65 mph is small – though larger rate reductions are possible by moderating speeds that are outside this range. If *elastic* travel demands functions are assumed, then it is observed that capacity expansions that reduce marginal emissions rates by increasing travel speeds are likely to increase total emissions for initial Level of Service E or above. Finally, it is also shown that alternative emissions reduction strategies that do not rely on increasing freeway speed or capacity may be more effective, even assuming an inelastic demand function.

Keywords: congestion mitigation, emissions reduction, speed-flow relationships, emissions models

INTRODUCTION

Transportation's role in decreasing urban air quality (*1*) and increasing atmospheric greenhouse gases (*2*) through motor vehicle emissions is a global concern. Concurrent with increasing emissions of greenhouse gases, freeway congestion continues to increase in the U.S. and abroad with varying economic, social, and environmental costs (*3*-*5*). But the full effects of congestion on emissions are still not well quantified because of interactions and impacts on many scales, from vehicle maintenance to land uses. Despite a lack of consensus on the congestion-emissions relationship, policy-makers, researchers, and activists often assume that congestion reductions inevitably lead to reduced vehicle emissions. In many cases, emissions reductions are cited as an implicit benefit of congestion mitigation without proper justification or quantification of the benefits. For example, the Congestion Mitigation and Air Quality (CMAQ) Improvement Program suggests a clear relation between the two. CMAQ has provided over $14 billion in funding for transportation projects to reduce congestion and improve air quality (*6*) – much of it for traffic flow improvement projects (*7*).

We need better understanding of total congestion impacts on motor vehicle emissions for system performance assessment and emissions reduction strategy development. Toward that goal, this paper presents a modeling study to explore the relationships among freeway emissions, travel speeds, freeway capacity, and travel demand. Vehicle emissions rates of several pollutants are modeled as functions of average travel speed to assess travel efficiency, and then total emissions related to travel demand. In addition, this paper discusses how emissions-traffic relations can help inform congestion and emissions mitigation strategies on homogenous freeway sections. Finally, alternative emissions reduction strategies such as shorter average commutes, vehicle fleet fuel efficiency improvements, reduced fuel carbon intensity, and electric vehicle adoption are discussed and compared.

BACKGROUND

The increasing intensity and extent of congestion on the roadway network is documented elsewhere (*3*,*4*). Additionally, attempts have been made to quantify some of the negative impacts of congestion (*5*,*8*). These attempts suffer from challenges such as estimating the extent of higher-order, indirect effects (e.g. congestion impacts on land use) and quantifying intangibles (e.g. traveler stress levels). Congestion studies are inhibited by inconsistent definitions and thresholds of congestion. A 'congestion-free' scenario is typically used as a benchmark for estimating congestion effects, but the attributes of this hypothetical situation are not manifest. Probably the most common benchmarking approach is to simply compare congested speeds to free-flow or threshold speeds (e.g. (*3*,*8*,*9*) – see also (*4*,*10*)). The hypothetical system change, then, is limitless supply, with all existing transport demand serviced without impedance – and suppressed demand ignored. The European Conference of Ministers of Transport (ECMT) criticizes a free-flow speed benchmark as suggestive of 'unattainable' policy outcomes. Furthermore free-flow, unhindered driving can be characterized from real-world measurements or simulated as constant-speed steady-state traffic flow; hypothetical steady speed driving generates lower emissions rates than real-world driving at constant speeds (*11*-*13*). Hence, congestion indicators and cost estimates need more clear and consistent benchmarking to be comparable and realistic: benchmarks that fully represent uncongested roadways. For example, uncongested comparisons should use true free-flow travel speeds (not posted limits), unimpeded travel demand (which includes accounting for suppressed demand), and transient drive patterns (not steady-state speeds) (*4*).

Direct Congestion Effects on Emissions

The emissions effects of individual facets of congestion have been studied in varying detail. A recent analysis by the U.S. DOT (*5*) estimates emissions as a minor component of total congestion costs, and asserts that the total impact can be beneficial or detrimental, depending on the context. The most salient, direct impact of congestion is an increase in travel times (decrease in average travel speed), which increases emissions rates per mile of travel when speeds are very low (*11*,*12*,*14*,*15*). This emissions rate increase is partly due to increased engine loads from higher acceleration intensity and frequency during unsteady traffic (*9*,*11*,*12*,*16*). However, studies have also shown that moderate travel speed reductions from excessive speeds can reduce emissions rates per mile of travel (*11*,*12*,*14*,*17*,*18*).

Indirect Congestion Effects on Emissions

Longer travel times can suppress travel demand (just as flow improvements induce demand), and so offset emissions rate increases (per vehicle-mile). Fewer miles traveled decreases total emissions, but travel behavior changes in response to congestion depend on the road network and other factors, and research is still needed in this area (*4*,*5*,*10*,*19*-*25*).

Travel time unreliability due to congestion has been demonstrated and is seen as a poor performance indicator for a roadway (*3*,*4*). The demand-suppressing (and thus emissions-reducing) effects of the disutility of unreliable travel times are not known – though Goodwin (*10*) presumes they could exceed average travel speed effects on demand. The emissions impacts of other facets of unreliability (direct effects related to driving behavior or traffic characteristics of nonrecurrent congestion, or indirect effects related to routing, departure time, etc.) have not been quantified. Emissions aspects of other congestion impacts are not well known, including rerouting, departure time shifts, mode shift, freight operations, etc.

Capacity Based Strategies (CBS) for Congestion Mitigation and Emissions Reductions

The direct impacts of congestion on motor vehicle emissions (particularly the increased marginal emissions rates) have prompted suggestions of congestion mitigation strategies targeting emissions reductions (e.g. (*12*)). Assessment of mitigation strategies suffers the same limitations as estimates of congestion impacts and costs. Traffic flow improvement that increases freeway capacity and so increases travel speed is a common approach to congestion mitigation (*7*). The primary emissions benefit is more efficient travel at higher average speeds. Travel demand effects are important considerations in assessing these mitigation strategies because traffic flow improvements can induce travel that cancels out any short-term emissions reductions (*19*,*20*). An NCHRP report by Dowling (*21*) used travel demand modeling to estimate air quality effects of traffic flow improvements but yielded very large uncertainties (*19*). The conclusion of the report was that more research is needed "to better understand the conditions under which traffic-flow improvements contribute to an overall net increase or decrease in vehicle emissions."

Non-Capacity Based Strategies (NCBS) for Emissions Reductions

NCBS aim to reduce emissions by increasing travel efficiency without increasing freeway capacity – an approach which has been suggested in order to avoid the negative impacts of induced demand (*26*). As an example, Barth and Boriboonsomsin show that more efficient driving on freeways can reduce greenhouse gas emissions by 10-20% without a significant change in travel time, with more benefits at higher levels of congestion (*16*). Some commonly suggested freeway NCBS include "eco-driving" (*16*,*27*), congestion or road pricing (*15*,*28*,*29*), high-occupancy vehicle lanes (*30*,*31*), and speed-smoothing/steadying traffic management techniques such as variable speed limits and intelligent speed adaptation (*12*,*32*,*33*). Much of the research in this area needs more consideration of indirect impacts and/or more detailed modeling of the congested traffic flow characteristics. The different emissions characteristics of light- and heavy-duty vehicles suggest opportunities for strategic emissions reductions using vehicle class-segregated facilities (*34*,*35*). These different vehicle classes likely have different demand responses to travel time and travel time reliability changes, which require consideration for emissions impacts. NCBS can also target emissions generation directly through vehicle efficiency and alternative fuel approaches (*36*,*37*) – these can also have indirect demand effects because of changing travel costs.

MODELING METHODOLOGY

The macroscopic modeling in this study is designed to advance our understanding of the relationships between traffic characteristics and vehicle emissions on freeways. The models and assumptions use homogenous freeway sections with typical fleet and traffic characteristics, as detailed in this section.

Emissions Rate Modeling

Average vehicle emissions rates are estimated using MOVES 2010, the latest average-speed emissions model from the U.S. Environmental Protection Agency (*38*). Emissions rates (per vehicle-mile) are modeled using estimated on-road vehicle fleets for freeways in the Portland, Oregon metropolitan region for the years 2000, 2010, and 2020. The modeled gases are CO_2e (greenhouse gases in carbon dioxide equivalent units), CO (carbon monoxide), NO_x (nitrogen oxides), $PM_{2.5}$ (particulate matter smaller than 2.5 microns), and HC (hydrocarbons). Where available, county-specific inputs are used (meteorology, vehicle inspection and maintenance program, fuel formulation), and national averages are used for other model inputs (vehicle age distributions).

The MOVES model outputs emissions rates in 16 average-speed bins for 18 vehicle types (combinations of 14 vehicle classes and gas or diesel fuels) for 4 different seasons and 24 hours of the day. In addition to vehicle class emissions rates, the vehicle types were combined into light duty (LD), heavy duty (HD), and full fleet combinations during the analysis. The vehicle type makeup of each of these fleet combinations was based on expected national average (default) allocations for 2010 from MOBILE6.2, the EPA predecessor to MOVES. Therefore, composite fleet emissions rate comparisons between years reflect emissions characteristic changes of vehicles within each category, but not potential changes in on-road vehicle type distributions. The estimates are for freeway travel only, and the modeled emissions are running exhaust and evaporative emissions; refueling, brake/tire wear, and start emissions are not included. Particulate resuspension is not modeled by MOVES.

The average-speed emissions modeling approach estimates emissions for average travel speeds using facility-specific driving patterns (speed profiles). These driving patterns (also called “drive cycles” or “drive schedules”) are composed of measured, archetypal combinations of acceleration, deceleration, cruise, and idle behavior at various average travel speeds on specific facilities, collected on-road in various U.S. cities (see MOVES documentation for details). Drive patterns effectively represent typical congested conditions for emissions modeling, as long as they are representative of real-world driving (*39*). They generally do not represent unique microscopic traffic characteristics and so cannot be used to model individual features in congestion (e.g. weaving sections), but they are appropriate for a macroscopic analysis such as performed here. For robustness, comparison analysis is also done using emissions rates published by Boulter et al. (*40*) and Barth & Boriboonsomsin (*12*).

Traffic Modeling

Travel demand modelers use demand flow-speed (or volume-speed) relationships to estimate the average speed over a road section (with respect to the traveler) based on demand flow and road capacity. In this study volume-speed relationships are used to calculate the total emissions over a peak period – including the emissions from queued or delayed vehicles. This analysis employs the well-known Bureau of Public Roads (BPR) model for macroscopic volume-speed relations (*41*), with α=0.15 and β=7 (from Hansen et al. (*42*)). It is used illustratively, while recognizing that the selection of a volume-speed relationship can have a significant impact on emissions calculations (*43*).

RESULTS ASSUMING INELASTIC DEMAND

Emissions rates and emissions rate gradients per vehicle-mile and average travel speed

Spatial marginal emissions rates (mass per vehicle-mile) have relationships with average travel speed that describe how traffic speed affects a single vehicle’s emissions over distance. These emissions-speed curves (ESC) also represent freeway efficiency, in terms of emissions per vehicle, per mile of freeway. ESC have been described and discussed often in the literature, e.g. (*11*,*12*,*14*,*44*-*46*), particularly in relation to minima or optimal travel speeds.

In the short-term for a given section of freeway, these marginal rates only reflect total freeway emissions effects if flows are not related to traffic speed – which runs counter to basic traffic flow theory (*47*). Similarly, the marginal rates would reflect long-term total emissions per vehicle-mile traveled (VMT) if travel demand were insensitive to speed or travel time – which runs counter to the concept of induced demand (*22*). When we see potential savings from average speed changes based on ESC, they are reductions in *marginal rates*, and do not account for inevitable flow changes, both short term (because of traffic state relationships) and long term (because of demand-travel time relationships).

Plots of spatial marginal emissions versus average travel speed are shown in Figure 1 for CO_2e, CO, $PM_{2.5}$, and NO_x. In addition to the ESC generated by MOVES for a 2010 Portland on-road fleet, comparison curves are plotted based on research by Boulter et al. (*40*) and Barth & Boriboonsomsin (*12*). The Boulter curves are for EU vehicles, with an approximately equivalent mix of vehicle types as the Portland 2010 modeled fleet. The Boulter curves are only drawn over their valid speed range. The Barth curve is for CO_2 only, for a typical LD vehicle fleet from Southern California in 2005. As a qualitative reference, level-of-service (LOS) indicators are included from the well-known Highway Capacity Manual (HCM), using basic freeway sections (*48*). LOS A+ through F- are based on traffic density thresholds where LOS F is fully congested. Figure 1 displays dashed vertical lines marking average speeds for various freeway LOS, based on Barth et al. (*11*).

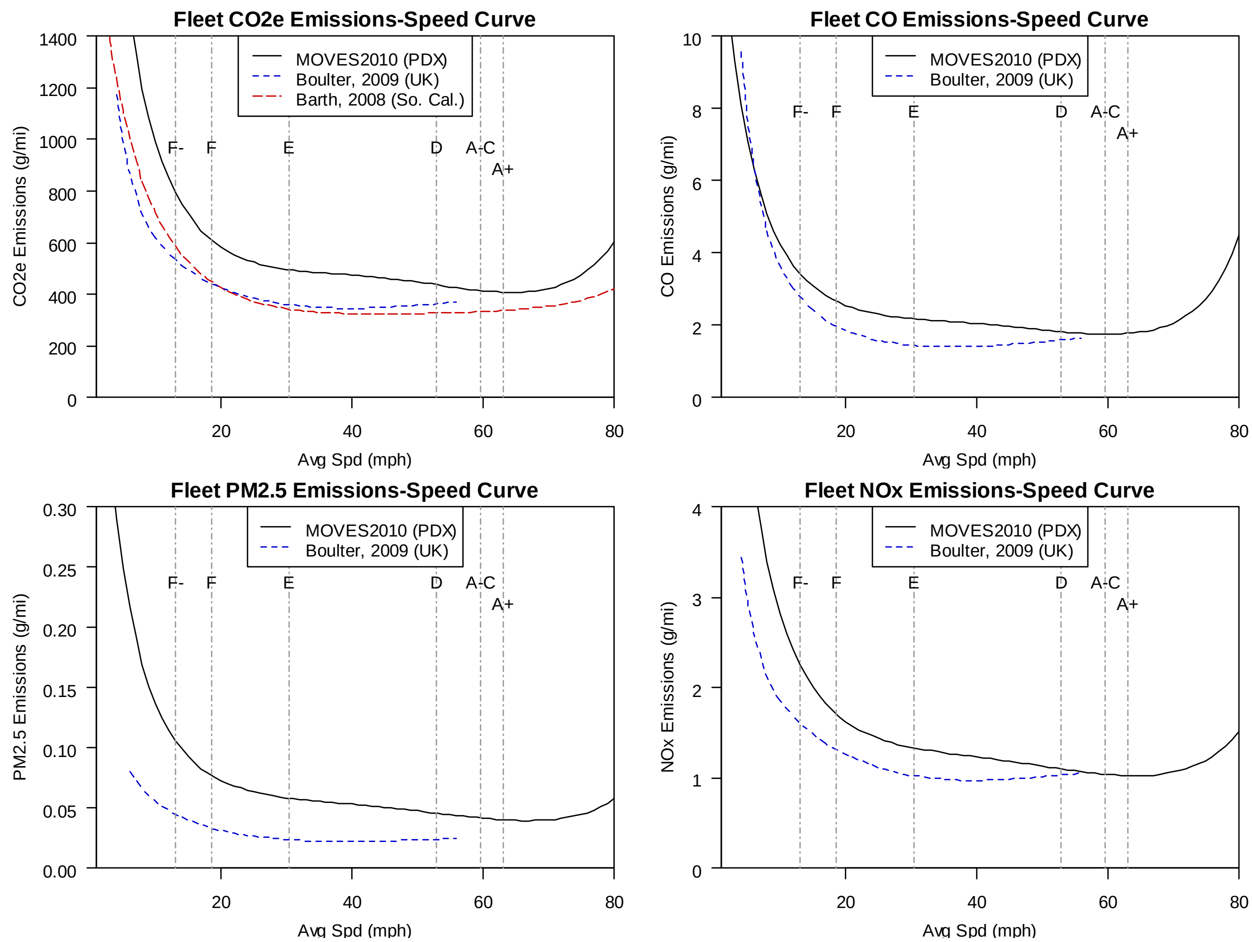

Figure 1. Full fleet emissions rate vs. average speed for CO_2e, CO, $PM_{2.5}$, and NO_x, with LOS

The three curve sources in Figure 1 are based on different vehicles, emissions data, and assumptions, and so not surprisingly do not agree on absolute emissions rates. The key to observe in these figures is that emissions rates per vehicle-mile do not have a monotonic relation with travel speed, and there are potential emissions *rate* reductions from moderating speeds from both directions. For most gases, there is also a relatively flat area in the middle of the curve – where emissions rate sensitivity to travel speed is slight. This sensitivity is easily seen in Figure 2, which shows the marginal emissions rate gradients versus average travel speed for the same gases and models. The plots show gradients as the percentage change in marginal emissions rate per 1 mph speed increase. The optimal emissions rate is when the gradient curve crosses the speed (x) axis.

The gradients have low absolute values around 30-65 mph (where much freeway travel occurs) – meaning speed changes over this range have a small effect on marginal emissions. Increasing speeds above LOS E provides small emissions benefits, and above LOS A can start to have an emissions-intensifying impact. While the ESC and ESC gradients differ by gas, vehicle type, and emissions model, the emissions gradients are consistently small at moderate speeds. As such, few emissions efficiency gains are to be found outside of heavily congested (or extremely high speed) freeway sections. Below 20 mph, however, increasing average travel speeds greatly improves emissions efficiency per vehicle-mile.

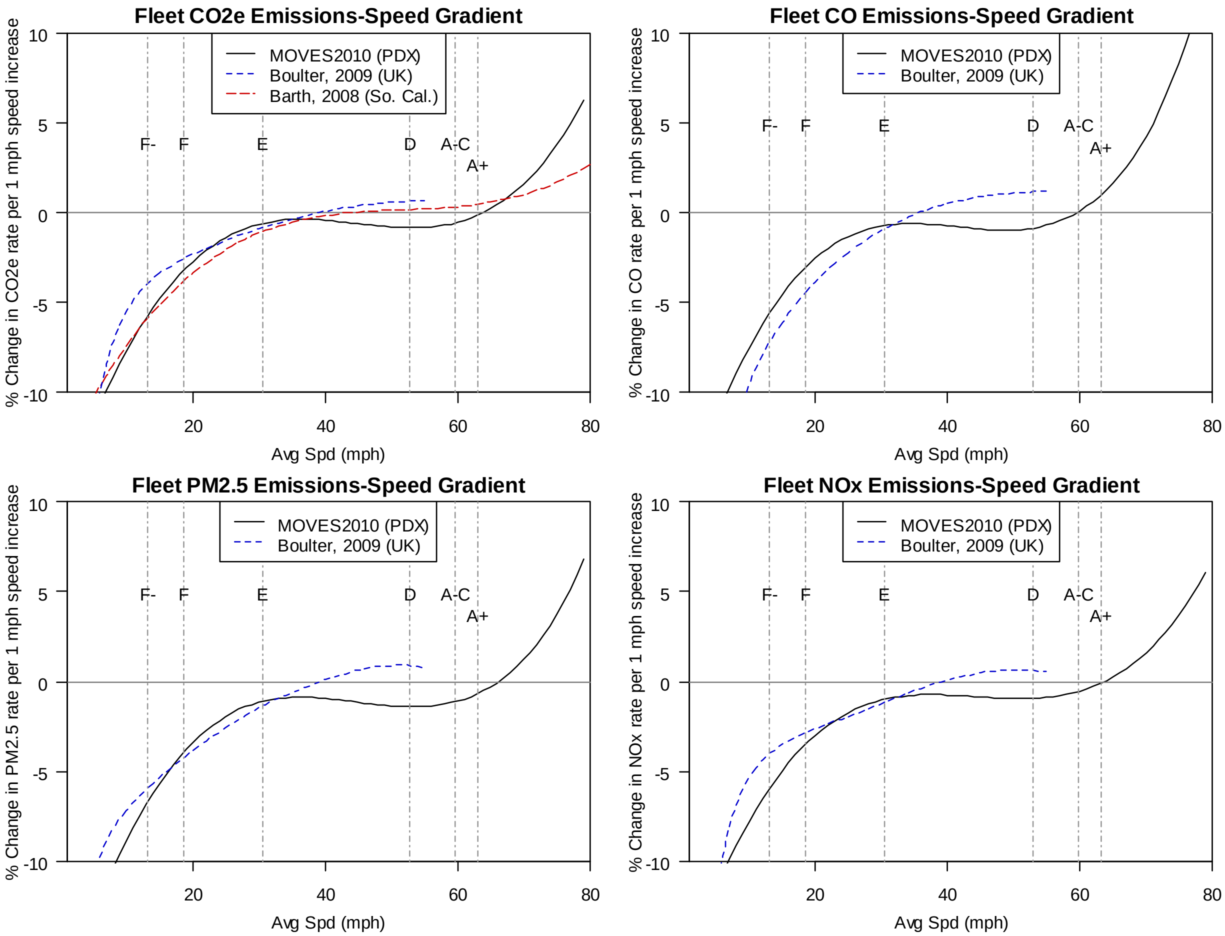

Figure 2. Fleet emissions rate gradients vs. average speed for CO_2, CO, $PM_{2.5}$ and NO_x, with LOS

The potential emissions rate reductions at different initial travel speeds are shown in Figure 3 as percent emissions rate reduced per mph speed increase for five pollutants using the Portland MOVES modeling. Again, there are large emissions rate reductions for very heavy congestion, but above 25 mph the emissions savings are minimal. These figures show that emissions rate increases during congestion are mostly relevant for very poor levels of service (F and F-).

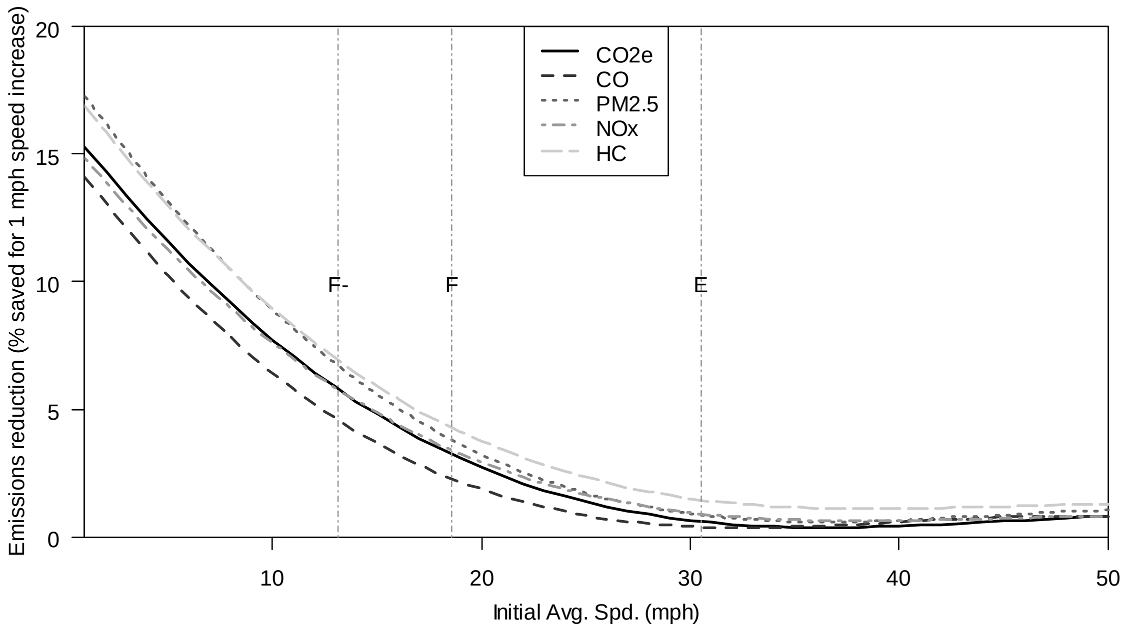

Figure 3. Potential emissions reductions and initial average speed, with LOS

Emissions Rate Sensitivities

Light duty and heavy duty vehicles have distinct emissions characteristics, so their combination in the total fleet affects the fleet-wide emissions curves. Figure 4 shows the sensitivity to percent HD vehicles of fleet emissions rates and emissions rate gradients versus average travel speed curves for CO_2e and NO_x. As expected, more HD vehicles increase the fleet emissions rate (seen in the top two panels). Fleet emissions rate sensitivity to speed also increases slightly with percentage HD (seen in the higher absolute value of the gradient). Interestingly, the optimal speed also increases slightly with more HD in the fleet – shown by the gradient crossing the speed axis at slightly higher values with higher percentage HD. This shows that traffic streams with more HD vehicles potentially have greater benefits from increasing average travel speeds – and that LD and HD vehicles could be targeted differently for congestion mitigation with air quality objectives.

Changing emissions and engine technologies in the vehicle fleet also affect the emissions rate relationships with average travel speed. Figure 5 illustrates changes in fleet-wide CO and NO_x emissions rates for on-road vehicles from 2000, 2010, and 2020 (based on MOVES modeling and projections). Again, these plots show the emissions rate and emissions rate gradient versus average travel speed. The changes from 2000 to 2020 are only for changing vehicle characteristics within vehicle classes, and do not reflect changes in fleet composition over time (they use a static fleet mix of vehicle types).

With better technologies the emissions rates are falling, but the gradients are not very sensitive to the changing engines. The optimal speeds for CO decrease slightly, as does the emissions rate sensitivity at moderate speeds. The NO_x gradients are practically unchanged. It is worth noting that this could be an artifact of the emissions modeling methodology, as future vehicle technologies are difficult to predict and are often modeled on current performance. This modeling suggests that potential savings in emissions rates from speed increases (congestion mitigation) are diminishing or unchanging with cleaner fleets. For some pollutants (HC and CO), optimal speeds are falling and sensitivity decreasing for LD vehicles and the fleet overall. For the HD fleet, optimal speeds increase slightly for CO and NOx, while speed sensitivity is still lower (plots omitted for space efficiency). Similar air toxics modeling by Timoshek et al. (*49*) suggests that emissions rate sensitivity to average speed is decreasing over time with cleaner vehicles.

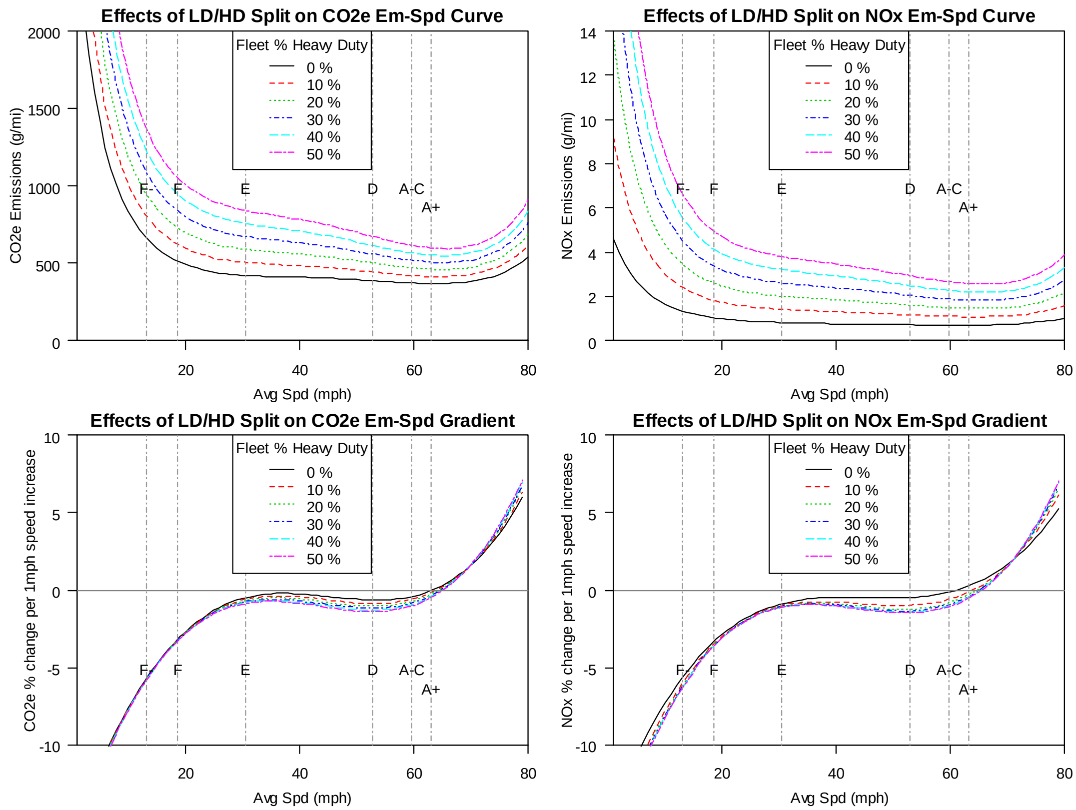

Figure 4. Fleet emissions sensitivity to LD/HD mix, with LOS

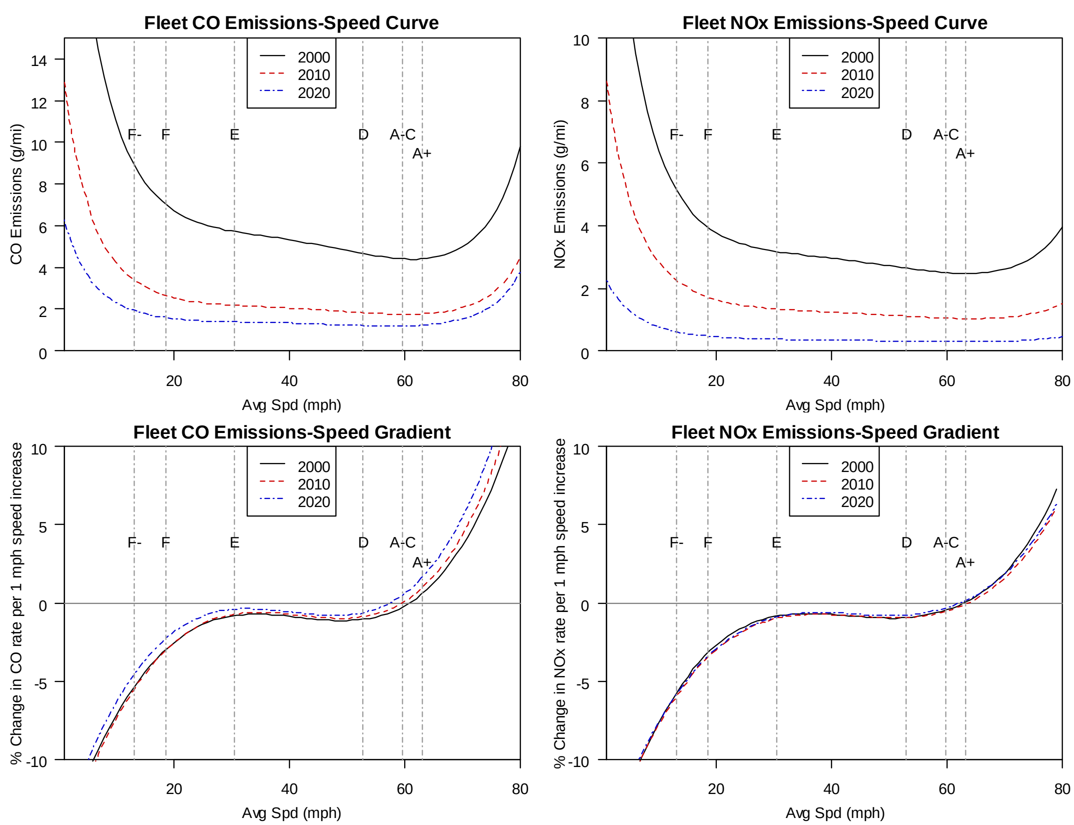

Figure 5. CO ESC sensitivity to changing vehicle technologies, with LOS

By various models and for various fleets, the consistent pattern appears of stagnant emissions rates per vehicle-mile over a wide range of moderate speeds. At the more extreme speeds (below 20 and above 70 mph) emissions efficiency degrades rapidly. A final note on the sensitivity of these curves is that they are based on driving patterns and average-speed modeling; changes in microscopic traffic characteristics over time (behavioral, technological, or operational) will also affect the shapes of the ESC.

RESULTS ASSUMING ELASTIC DEMAND

Emissions rates per vehicle-hour

Temporal marginal emissions rates (per vehicle-hour of travel) are simply related to spatial rates by average speed, *v*, as follows:

$$E_{temporal} = E_{spatial} \cdot v \tag{1}$$

Hence, temporal marginal emissions rates can similarly be modeled as a function of travel speed. These curves describe how the average travel speed affects a single vehicle's emissions rate per *hour* of operation. For assessing long-term total emissions characteristics, temporal rate curves would be indicative of the total emissions-speed relationship if travel demand were fully elastic with travel time (i.e. total travel time is fixed).

This scenario has been suggested by Metz (*23*), who claims that in the long run average travelers adjust their travel behavior by modifying their access choices while maintaining a fairly constant travel time budget. This approach differs greatly from the application of spatial emissions rates for total emissions-speed relationships, which implies fixed travel demand insensitive to travel time constraints. In other words, using temporal rates for total emissions implies a travel volume adjustment for every travel speed change to maintain total travel time, while using spatial rates implies that travel volume is maintained, unaffected by travel speed.

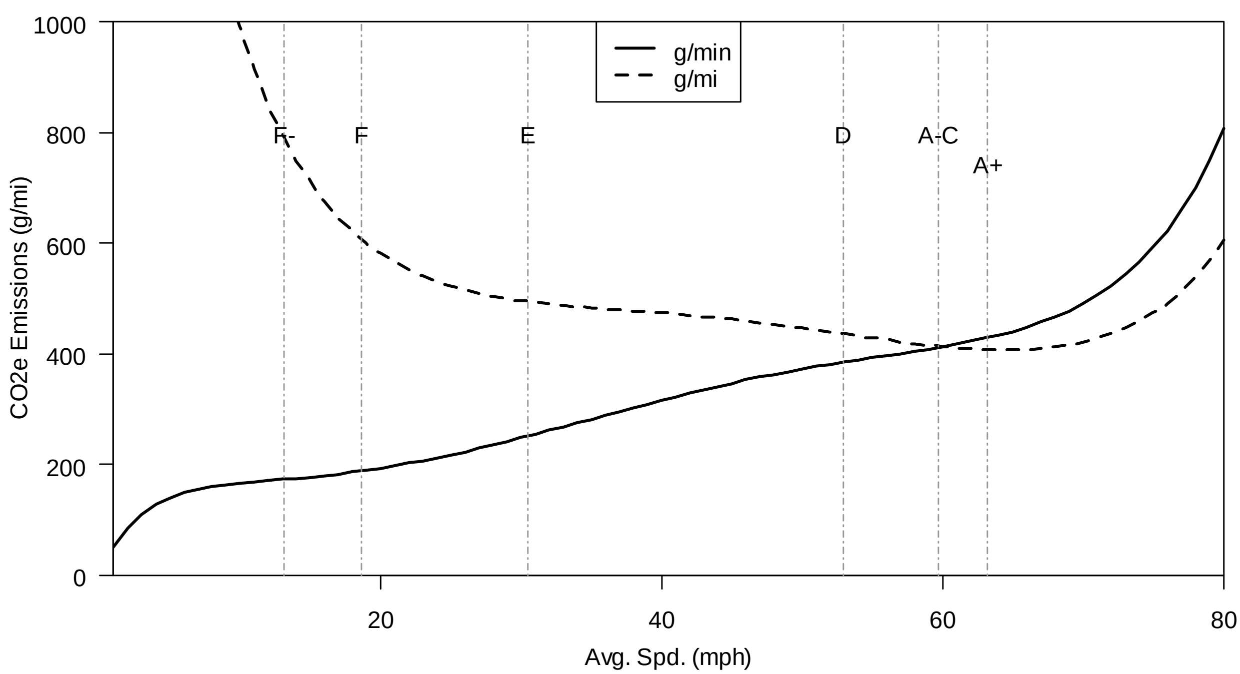

Figure 6. Spatial and Temporal fleet CO_2e emissions rates for Portland 2010, with LOS

An illustrative comparison of marginal fleet CO_2e emissions rates for Portland 2010 in grams per vehicle-minute and per vehicle-mile is shown in Figure 6 versus average travel speed. These curves meet at 60mph where the travel rate is 1 min/mi. At low speeds the curves display diverging behavior. For a fixed travel distance the spatial emissions rates increase at low speeds because of inefficient driving, but after adjusting for shorter travel distances (to maintain travel time) the temporal emissions rates decrease at lower speeds. From the opposite perspective, for a fixed travel time the temporal emissions rates decrease at low speeds because of lower engine loads, but after adjusting for longer travel times (to maintain travel distance) the spatial emissions rates increase at lower speeds.

The long-term reality of total emissions is probably somewhere in between the perfectly inelastic and elastic projections. If we assume that in the long-run travelers are not fixed to an absolute travel distance or time, but make trade-offs depending on the utility of each, then the most representative shape is somewhere in between these curves. As such, the long-term emissions inefficiencies of low travel speeds are not as great as they appear to be from the spatial emissions rate curves in preceding Figures. This further illustrates one of the dangers of employing fixed-demand free-flow speed benchmarks for congestion cost estimates.

Capacity Based Congestion Mitigation

Relationships between emissions rates and traffic characteristics can assist with mitigation strategy development and assessment, targeting both congestion and vehicle emissions. For example, Barth & Boriboonsomsin (*12*), Woensel et al. (*14*), and others have demonstrated emissions benefits of increasing congested vehicle speeds. But the impacts of induced travel demand illustrated by the two curves in Figure 6 show that capacity-based strategies (CBS) for congestion mitigation must also assess traffic volume when estimating emissions effects due to speed improvements.

In the long term, travel time changes will affect travel demand, as has been shown and discussed in the literature (*22*). While increasing congested travel speeds will often reduce the average vehicle's marginal emissions, it will also induce more travel and so increase the travel demand volume. Other researchers have shown how traffic flow improvements can increase emissions using microsimulation (*19*,*20*); we perform a similar but simplified analysis here using macroscopic traffic characteristics to illustrate the emissions impacts of freeway capacity changes to reduce congestion.

Figure 7 shows total CO_2e emissions contours (kg/hr/lane-mi) on the travel rate – demand flow plane, with two BPR-derived curves using freeway capacities of 2,200 (solid line) and 2,420 veh/hr/lane (dashed line – a 10% increase). As an illustration, consider an initially congested demand state of 3,000 veh/hr during a peak period, with an initial emissions rate of 1,397 kg/hr/ln-mi. If the capacity were to increase by 10%, travel time would decrease by 28% and the total emissions would decrease by 6% – *at a fixed demand flow* of 3,000 veh/hr. If, alternatively, the travel rate were fixed (i.e. the constant travel time budget scenario suggest by Metz (*23*)), the new demand flow would be 3,300 veh/hr, with a total emissions *increase* of 10%. The time required to move from the initial demand of 3,000 veh/hr up to the higher demand rate would depend on the evolving elasticity of travel demand to travel time. The most likely outcome is some induced demand and some travel time savings, ending up on the new curve somewhere between these two extremes (the green arrow in the figure between the two white arrows).

To estimate a break-even induced demand flow from an emissions perspective, we can use the slope of the total emissions contour lines on the travel rate vs. demand flow plane. Following an emissions contour line down from the first (solid line) curve to the second (dashed line) curve arrives at an equivalent induced demand that would cancel marginal speed benefits. For the example here, the original emissions rate is found on the second curve at a flow of 3,136 – which corresponds to a 4.5% increase in flow and 17% decrease in travel time. The corresponding break-even elasticity of demand volume to travel time is -0.266. Compared to other values from the literature – Noland and Quddus (*19*) cite a range of -0.2 to -1.0 for short to long term elasticity – this is a fairly low number, which implies that the increased capacity will likely increase total emissions from induced demand.

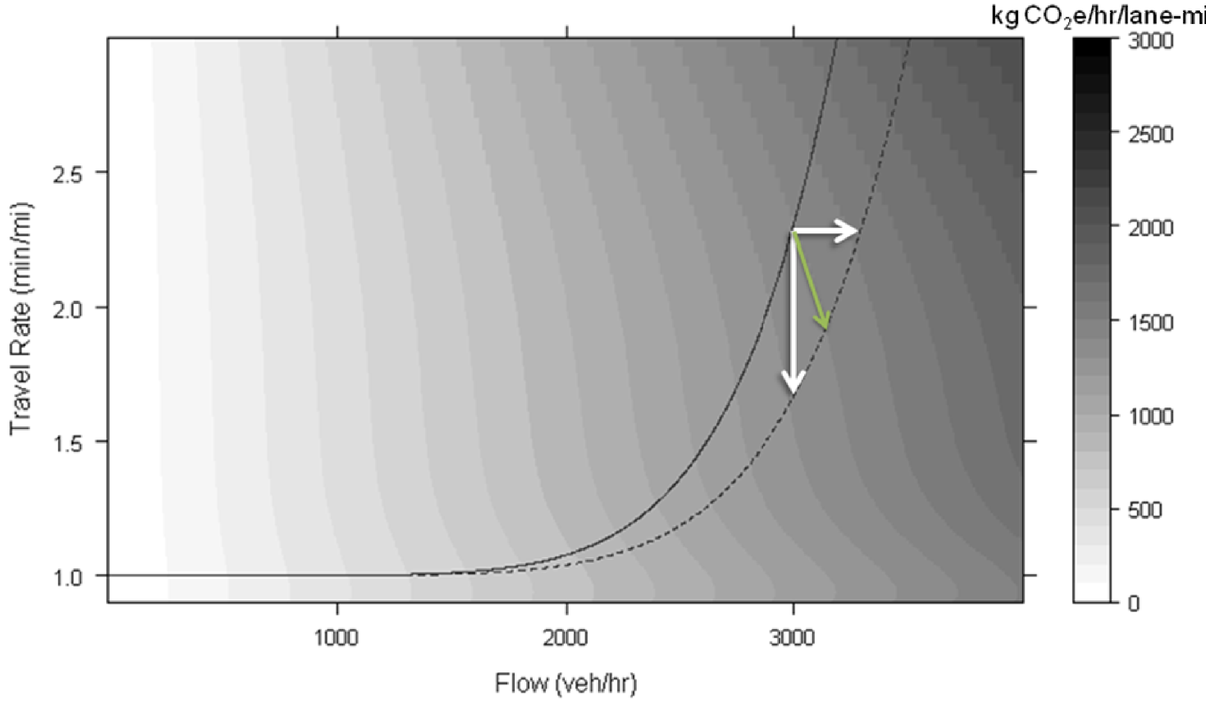

Figure 7. Capacity enhancement and total emissions;
BPR curves at 2200 veh/hr/lane capacity (solid line) and 2420 veh/hr/lane capacity (dashed line)

This method of estimating break-even elasticities from total emissions contour slopes was applied for a range of initial average speeds, as illustrated in Figure 8. The break-even elasticities were calculated for three different macroscopic fleet CO_2 models (MOVES, Barth, and Boulter – as described above). Figure 8 presents the results from the three CO_2 models along with lines for LOS. Although the speed-flow relationship illustrated in Figure 7 can vary greatly by volume-speed model, the slope of the emissions contour line at any given travel rate (when expressed as an elasticity) does not vary with flow. In other words, the shapes of the curves in Figure 8 do not depend on volume-speed model.

The results are highly intuitive in light of the preceding analysis. By all three emission models, only in heavily congested conditions with LOS below E is it possible to reduce total emissions assuming a moderate elasticity greater than -0.5. Break-even elasticities above zero in Figure 8 indicate that the capacity increase immediately increases emissions rates because of higher speeds. Hence, to break even in the Barth and Boulter models speed would have to decrease if capacity increases and the initial speed is over 45mph. The MOVES CO_2 model produces elasticities notably different from the other two models. This is particularly true for higher initial speeds because emissions rates decrease with speed for speeds around free-flow (60mph) in the MOVES model, but increase with speed in this range by the other two models (see Figure 2). In the case of the MOVES model, any elasticity that is greater than -0.4 would increase total emissions for capacity expansions with initial speed over 25mph.

Although the break-even elasticities vary by CO_2 model and initial speed, all values here are within the Noland and Quddus range of expected short or long term demand elasticity to travel time. Elasticity values closer to zero are more feasibly reached on short time scales – which is the case for moderate initial speeds around LOS E. For lower initial speeds below 20mph, the marginal emissions rate benefits of speed increases are greater, so the break-even elasticity is lower. Figure 8 shows that it is likely CBS will increase emissions in the long-run by the induced demand effect, though the time required for induced demand to cancel marginal emissions rate benefits would be longer for heavier initial congestion.

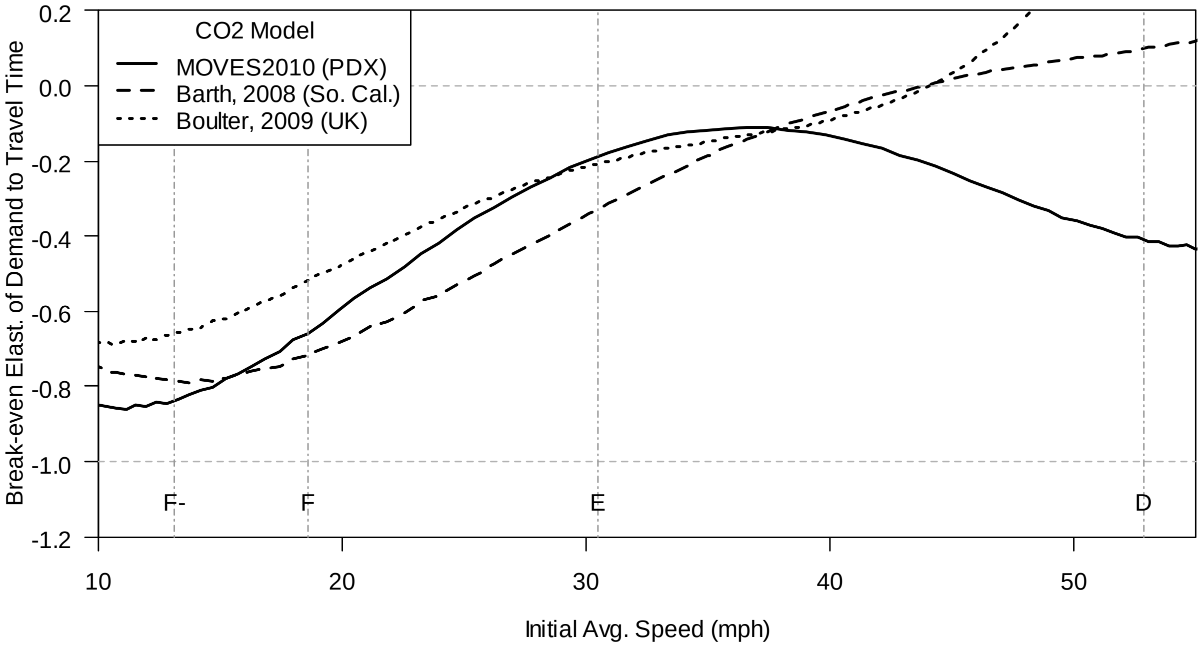

Figure 8. Emissions break-even elasticities of demand volume to travel time versus initial average speed, using 3 different CO_2 models, with LOS

EFFICIENCY OF NON-CAPACITY BASED EMISSIONS STRATEGIES

As a final consideration, we put marginal emissions changes from speed into context by rough comparison to a set of alternative NCBS for efficiency improvements. This analysis employs a broad set of assumptions about the U.S. commuting fleet to make comparisons of NCBS to freeway CBS that increase speeds as indicated by improving LOS from F to E, from E to D, and from D to the A-C range (again, LOS average speeds are from Barth et al. (*11*)).

The alternative strategies considered are shorter commutes (made possible by denser, more mixed land use), vehicle fleet fuel efficiency improvements (by lighter vehicles or less power-intensive engines), reduced fuel carbon intensity (by alternative fuels such as biodiesel or less energy-intensive production and delivery methods), and replacement of light-duty vehicles in the fleet with electric vehicles (EV). These alternative strategies do not increase capacity and therefore there is no induced demand generated by their application. However, increasing fuel efficiency leads to reduced operational costs and there is potential for indirect long-term effects. This is not the case for cleaner fuel or EV alternatives.

To compare the efficiency of NCBS we assume an average daily commute on primary facilities of 16.6 miles (average of 439 U.S. urban areas in 2007 from Schrank and Lomax (*3*)), fleet fuel efficiency of 21.1 mi/gal (for the U.S. light-duty vehicle fleet, model year 2009, from the EPA (*36*)), average fuel carbon intensity of 8.9 kgCO_2e/gal (calculated from (*36*)), and electric vehicle carbon intensity of travel of 0.216 kgCO_2e/mi (from the supplementary material of Samaras & Meisterling (*37*)). This EV carbon intensity of travel is based on life-cycle assessment (LCA), while upstream emissions are not included in the roadway emissions estimates for petroleum vehicles. In order to make an equivalent comparison with the on-road emissions, an additional estimate is made using zero emissions for EV's.

For each hypothetical LOS improvement the increased average speeds and reduced commute emissions are shown in the first two rows of Table 1. These assume that the LOS change applies to the entire primary-road commute and exclude induced demand. The table results also assume independence of strategies – in other words changes to commute distance or vehicle efficiency do not affect travel speeds. The final five rows in Table 1 show the changes that would be required to generate the same commute emissions savings from each alternative strategy.

As expected from the previous modeling in this paper, the LOS change from F to E generates the greatest marginal benefits, which require the greatest alternative efficiency improvements to match. The greatest relative difference in the emissions reduction efficiency is observed in the central column. A 73% increase in freeway speed renders a meager 10% in terms of emissions reductions. Similar reductions can be achieved by increasing fleet fuel efficiency by 2.3mpg or reducing commutes by less than a mile in each direction. Furthermore, some alternative strategies (such as EV's and fuel efficiency) have the potential for net cost savings, as opposed to most capital improvement projects such as urban freeway widening that run between $7.9 to $11 million per lane-mile.

The values in Table 1 are based on the MOVES-modeled emissions rates. A similar table based on the Barth model is similar for LOS F to E, but the efficiency gains from LOS E to D are much less (4% emissions savings, which can be matched by 4% shorter commutes or 5% more efficient vehicles). For an improvement from LOS D to the A-C range the Barth model predicts net emissions *increases* because of the inefficiency of high-speed travel.

Table 1. Comparison of Equivalent Emissions Efficiency Strategies

	LOS F to LOS E	LOS E to LOS D	LOS D to LOS A-C
Avg. speed increase (mph)	11.9 (64%)	22.4 (73%)	6.8 (13%)
Emissions savings (gCO_2e/commuter-day)	1,705 (19%)	759 (10%)	317 (5%)
Alternative Efficiency Strategy			
Shorter commutes (miles/commuter-day)	3.1 (19%)	1.7 (10%)	0.8 (5%)
Vehicle efficiency improvement (mpg)	3.7 (23%)	2.3 (11%)	1.1 (5%)
Fuel carbon intensity reduction (kg CO_2e/gallon)	1.7 (19%)	0.9 (10%)	0.4 (5%)
Elec. vehicle penetration by LCA (% of commuting fleet)	31%	20%	10%
Elec. vehicle penetration by zero-emissions (% of commuting fleet)	19%	10%	5%

For CBS improvements above LOS E the large speed increases generate only small emissions savings, which are more easily attained by other means. By assuming the LOS changes apply to the full commute and *neglecting induced demand, the alternative strategy equivalents are conservative*: in reality the freeway efficiency improvements are even more easily achieved by alternative strategies because the net long-term emissions savings from CBS would be less. Broadly, freeway CBS for emissions reductions are not likely to be the most cost-effective approach for emissions rate reductions, and are susceptible to self-defeating behavior responses through induced travel.

CONCLUSIONS

In order to move toward better understanding of freeway congestion mitigation and emissions reduction strategies, this paper explores the effects of traffic speeds, freeway capacity, travel demand, and alternative efficiency strategies on freeway emissions. Marginal emissions rates are modeled as functions of average travel speed, and then total emissions related to travel demand. The exact relationships among emissions, traffic speed, and travel demand vary with the model, pollutant, and vehicle fleet applied – but several consistent features and trends arise from this study. The central conclusion from the emissions-speed relations is that the potential for marginal emissions rate reductions through average travel speed adjustments between 30 and 65 mph is small– though larger rate reductions are possible by moderating speeds that are outside this range.

When considering total freeway emissions, marginal emissions rates per vehicle-mile provide an incomplete picture. Accounting for trade-offs between travel distance and travel time, the effects of travel speed on total emissions are better represented by the combined shapes of the spatial and temporal marginal emissions rate curves (per vehicle-mile and per vehicle-hour). Induced or suppressed travel demand due to these trade-offs are critical considerations when assessing the emissions effects of capacity-based congestion mitigation strategies. Capacity expansions that reduce marginal emissions rates by increasing travel speeds are likely to increase total emissions in the long run through induced demand. Even neglecting induced demand, freeway efficiency projects that increase freeway speeds above LOS E have small emissions benefits that are more easily and cost-effectively attained by other strategies. In summary, capacity based strategies to mitigate congestion in homogenous freeway sections can lead to higher overall emissions in the long-run, though this outcome is less probable for sections with heavier initial congestion (LOS F).

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