A Study of the Emissions Benefits of Commercial Vehicle Lane Management Strategies

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Submitted for publication in the Transportation Research Record

(Revised February 2013)

7,499 Words [5,499 + 6 figure x 250 + 2 tables x 250]

ABSTRACT
Traffic congestion mitigation has been proposed as a strategy to help attain air quality goals. A better understanding of the full impacts of congestion on heavy-duty (HD) vehicles is needed because HD vehicles contribute a large share of on-road emissions and are more sensitive to speed than light-duty (LD) vehicles. This research shows that the estimated emissions effects of congestion mitigation vary greatly by pollutant and are sensitive to the assumed travel demand elasticity, initial congestion level, and lane management strategy. Analysis of four different managed lane scenarios shows that vehicle class-segregated facilities tend to out-perform general-purpose lane strategies in terms of emissions reductions. Although potentially controversial, from an emissions perspective, conversion of a general purpose lane to a truck-only lane may produce more emissions benefits than adding either a truck-only lane or a general purpose lane. Furthermore, the expected emissions benefits from truck-only lane conversion are robust to uncertainty in travel demand elasticity. This research demonstrates the emissions trade-offs inherent in congestion management between emissions rates and travel volumes by vehicle class, and presents a concise methodological framework that can be readily applied in other contexts for sketch-level analysis of emissions impacts from vehicle class-targeted congestion management.

Keywords: vehicle emissions, traffic congestion, heavy-duty vehicles, truck-only lanes, lane management

INTRODUCTION

Pollution emissions from motorized vehicles degrade air quality in urban areas and contribute to the build-up of atmospheric greenhouse gases. Quantification of the full effects of traffic congestion on motor vehicle emissions is difficult because of interactions and impacts on many scales. Most literature related to traffic congestion and emissions has focused on the impacts of the more numerous light-duty (LD) vehicles, mostly passenger cars. This paper investigates the impacts of heavy-duty (HD) vehicles, which are mostly commercial vehicles (predominantly trucks, and a small fraction of buses).

A better understanding of the full impacts of congestion on HD vehicle emissions is needed because HD vehicles contribute a large share of on-road emissions, although they are a minority of vehicles in the fleet. Recent research has shown that when induced demand is taken into account there are many plausible scenarios where total vehicle emissions increase with congestion mitigation (1). However, the specific impacts of HD vehicles and vehicle class-specific lane management strategies were not considered.

This research first examines the sensitivity of LD and HD vehicle emissions to average travel speed and the contribution of each to total emissions. Given their distinct characteristics, we go on to investigate the potential for emissions reductions through vehicle class-targeted congestion mitigation using four different freeway lane management scenarios. The next section describes the relevant literature, followed by the emissions modeling methodology, emissions modeling results, managed lane analysis framework and results, and finally conclusions.

LITERATURE REVIEW

Although much work has been done in the field of motor vehicle emissions estimation, our understanding of the full impacts of congestion on emissions is still limited. Generally, congestion decreases vehicle efficiency and increases emissions rates per mile (2, 3), but it also suppresses travel demand (4) – and the balance of these two effects is not well quantified. Many estimates of congestion costs consider efficiency changes but neglect variable demand effects. When variable demand is considered, the total emissions effects of congestion are highly uncertain (5–7).

For heavy-duty (HD) vehicles (primarily commercial movements), congestion can increase freight operating costs, with complex potential supply chain or operations responses. Slower speeds in congestion are associated with higher emissions rates (8), but congestion mitigation can increase freight vehicle travel demand (9), offsetting lower emissions rates. Figliozzi (10) showed that the impacts of congestion on truck emissions per route can be significant and complex, depending on depot/customer relative locations, routing constraints, and congestion levels.

Travel responses to changing congestion levels are typically assessed using travel demand elasticity to travel time or speed. General vehicle travel demand volume elasticity to travel speed is expected to be between 0.2 and 1.0, depending on the context (11–13). For road freight vehicles, complex relationships exist between travel time and travel demand because time costs must be viewed in the context of supply chains, labor, and market costs (9). For intercity or regional travel, road/truck freight elasticity to travel speed has been reported from 0.0 to 1.0 (14–16). The freight elasticities, however, are based on much fewer studies than passenger vehicle travel demand elasticities, and so are more uncertain (12). Time costs are a smaller portion of total travel costs for freight than for personal travel, so freight travel demand could be less sensitive to travel time, though this has yet to be established (12, 15). In fact, Figliozzi (10, 17) showed that more congestion can increase commercial vehicle trips because of shorter and less efficient routes. Hence, for certain trucking sectors such as LTL (less than truckload delivery or service routes), commercial vehicle travel demand could increase at lower traffic speeds (i.e. negative demand elasticity to speed).

The distinct emissions characteristics of LD and HD vehicle classes has spurred interest in vehicle class-targeted emissions reduction strategies. Truck-only lanes (TOL) are roadway facilities that provide exclusive right-of-way and prioritized mobility for HD (commercial) vehicles. The impacts of TOL on traffic flow and travel demand vary with operation strategy, lane configuration, and tolling strategy, if any (18–20). Typically, TOL are pursued for economic, safety, and operational efficiency reasons, with air quality as a potential co-benefit (21–23). Air quality benefits from TOL come with the caveat that TOL may increase truck travel demand by increasing travel speeds (24), which can lead to increased total emissions.

In their analysis of the emissions impacts of tolled TOL in Atlanta, Chu and Meyer (25) estimate net emissions reductions of 3% to 6% for hydrocarbons and 61% to 62% for carbon dioxide (depending on implementation). They estimate net emissions increases of 2% to 5% for carbon monoxide and 1% to 18% for nitrogen oxides, with total travel demand volume changes of -3% to 1%. The details of the demand model, tolls, and speed estimates for the studied scenarios are not described in the paper, so the implied travel demand elasticity cannot be compared with this analysis.

In summary, despite a large body of research on HD or commercial vehicle lane management and emissions estimation there is still much uncertainty about the full impacts of congestion management on total emissions. The distinct emissions and travel demand characteristics of LD and HD vehicle classes suggest the need to disaggregate congestion-emissions relationships by vehicle class and lane management strategy type; that need is the purview of this research. The next section describes the notation and equations used to investigate trade-offs among travel speed, travel volume, and total emissions by vehicle class.

METHODOLOGY

Methodological Framework

This paper extends a previously developed methodological framework to assess aggregate emissions effects of congestion (1). For vehicles of class j (in the mutually exclusive and exhaustive set of vehicle classes J), the average emissions rate in mass per unit distance of vehicle travel is e_j and the travel demand volume is q_j. The fraction of on-road vehicles that are of class j (by distance traveled) is f_j, so that $f_j = \frac{q_j}{q}$ where q is the total travel demand volume. Vehicle class-total emissions are $E_j = q_j \cdot e_j = q \cdot f_j \cdot e_j$.

The elasticity of average emissions rate, e_j, to average travel speed, v_j, is expressed $\varepsilon_{e_j}^{v_j} = \frac{v_j}{e_j} \cdot \frac{\partial e_j}{\partial v_j}$. The long-term elasticity of travel demand volume q_j to v_j is expressed $\eta_{q_j}^{v_j} = \frac{v_j}{q_j} \cdot \frac{\partial q_j}{\partial v_j}$. The value of $\eta_{q_j}^{v_j}$ represents the percentage change in class-j vehicle miles traveled (VMT) with a one percent v_j change on a roadway of arbitrary length. The elasticity of E_j to v_j is

$$\varepsilon_{E_j}^{v_j} = \frac{v_j}{E_j} \cdot \frac{\partial E_j}{\partial v_j} = \eta_{q_j}^{v_j} + \varepsilon_{e_j}^{v_j}, \quad (1)$$

so the elasticity of total emissions to average travel speed is the combined effects of changes in travel demand volume and emission rate. Generally, demand elasticity to speed $\eta_{q_j}^{v_j}$ is expected to be positive and emissions rate elasticity to speed $\varepsilon_{e_j}^{v_j}$ is expected to be negative, so at lower average speeds total emissions are influenced up by e_j and down by q_j.

The total emissions from on-road vehicles of all classes in J, in mass per unit length of road per unit of time, is $E = \sum_{j\in J} E_j = q \cdot \sum_{j\in J}(f_j \cdot e_j) = q \cdot \bar{e}$, with average emissions rate $\bar{e}$. The average travel speed on the roadway is $\bar{v}$ in distance traveled per unit time. The elasticity of total emissions E to average speed $\bar{v}$, assuming that speed changes proportionally for all vehicle classes $\frac{\partial v_j}{\partial \bar{v}} = \frac{v_j}{\bar{v}}\ \forall\, j \in J$, is

$$\varepsilon_E^{\bar{v}} = \frac{\bar{v}}{E} \cdot \frac{\partial E}{\partial \bar{v}} = \frac{1}{\bar{e}} \cdot \sum_{j\in J}\left[e_j \cdot f_j \cdot \varepsilon_{E_j}^{v_j}\right] = \sum_{j\in J}\left[\frac{E_j}{E} \cdot \varepsilon_{E_j}^{v_j}\right]. \qquad (2)$$

From Equation 2, emissions break-even conditions exist when decreased emissions from one vehicle class offset increased emissions from another, in addition to the general (trivial) case where each vehicle class's total emissions elasticity to speed is zero, $\varepsilon_{E_j}^{v_j} = 0\ \forall\, j \in J$.

For a LD/HD vehicle class dichotomy the set of vehicle types is $J = \{l, h\}$, where $j = l$ denotes LD vehicles and $j = h$ denotes HD vehicles. These two vehicle classes are expected to have different intensity of emissions (e_l and e_h), different sensitivity of emissions to speed ($\varepsilon_{e_l}^{v_l}$ and $\varepsilon_{e_h}^{v_h}$), and potentially different demand elasticity to speed ($\eta_{q_l}^{v_l}$ and $\eta_{q_h}^{v_h}$). Passenger-car equivalence (PCE) is used to adjust for different occupation of road capacity by vehicles of different classes (26). Considering PCE, the effective traffic volume q' in passenger cars per hour per lane (pcphpl) is calculated as $q' = q \cdot \sum_{j\in J}(PCE_j \cdot f_j)$, where PCE_j is the passenger-car equivalence of each vehicle in class j. Assuming $PCE_l = 1$, the effective volume of vehicle travel in PCE with $J = \{l, h\}$ is

$$q' = q\left(1 + f_h(PCE_h - 1)\right). \qquad (3)$$

Total emissions from the vehicle fleet where $J = \{l, h\}$ are

$$E = E_l + E_h = q[(1 - f_h)e_l + f_h e_h]. \qquad (4)$$

A fleet with the same vehicle volume q but composed entirely of LD vehicles ($f_h = 0$) would have total emissions of $E_{f_h=0} = e_l \cdot q$. Comparing these, the ratio of total emissions from a mixed LD/HD fleet to total emissions from an LD-only fleet with the same traffic volume (assuming the same v_l) is

$$\frac{E_{f_h=f_h}}{E_{f_h=0}} = 1 + f_h\left(\frac{e_h}{e_l} - 1\right). \qquad (5)$$

With the ratio $\frac{E_{f_h=f_h}}{E_{f_h=0}}$, Equation 5 demonstrates the impact of the presence of heavy-duty vehicles on total emissions; note that this ratio is independent of total vehicle volume q.

Emissions Modeling

Following previous research on how emissions rates vary with average speed and congestion level (2, 27), the functional form for emissions rates e_j as a function of speed v_j is an exponentiated polynomial

$$e_j(v_j) = \exp\left(\sum_{i=0}^{4}\left[a_{i,j} \cdot {v_j}^i\right]\right), \qquad (6)$$

where $a_{i,j}$ are fitted parameters. Differentiating Equation 6, the elasticity of e_j to v_j is

$$\varepsilon_{e_j}^{v_j} = \sum_{i=1}^{4}\left(i a_{i,j} v_j{}^{i}\right) . \quad (7)$$

Note that $\varepsilon_{e_j}^{v_j}$ is independent of volume q as long as emissions rates are only a function of speed, $e_j = f(v_j)$.

In order to generate data for fitting $a_{i,j}$ in Equation 6, the EPA's Motor Vehicle Emissions Simulator (MOVES) model (28) is used for estimates of emissions rates e_j. The modeled pollutants are CO_2e (GHG 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). The average-speed emissions modeling approach employed by MOVES uses facility-specific dynamic driving patterns (speed profiles) to represent typical congested traffic conditions (29, 30).

Emissions rates (in grams per vehicle-mile) are modeled using an estimated on-road vehicle fleet from the I-5 freeway in Portland, Oregon for 2010, segmented into LD and HD vehicles. The LD vehicle fleet includes 7 MOVES Source Type ID's below 40: motorcycles, passenger cars, passenger trucks, and single-unit two-axle light-duty commercial trucks under 19,500 lbs. Gross Vehicle Weight Rating (GVWR). The HD vehicle fleet includes 10 MOVES Source Type ID's above 40: buses, combination trucks, and other heavy-duty trucks over 19,500 lbs. GVWR.

The MOVES model generates discrete emissions rate estimates in 16 average-speed bins (5 mph increments) for each emissions Source Type on urban freeway (restricted) facilities. The modeled emissions are running exhaust and evaporative emissions. National average and county-specific (Multnomah County, Oregon) values are used for other model inputs (meteorology, vehicle inspection and maintenance program, fuel formulation, vehicle age distributions, etc.).

From the MOVES-generated emissions rate-average speed (e_j, v_j) data points, the parameters $a_{i,j}$ in Equation 6 are estimated using a least-squares fit for all five pollutants and each vehicle class, obtaining $R^2 > 0.96$ for all ten curves. The fitted parameters for the LD ($a_{i,l}$) and HD ($a_{i,h}$) portions of the vehicle fleet are shown in TABLE 1 for afternoon peak periods on freeways in April 2010. Emissions rate estimates for other time periods were also generated, but were not sufficiently different to include in this paper.

EMISSION CURVES BY VEHICLE CLASS AND POLLUTANT

Using the emissions rate parameters shown in TABLE 1, emissions rate differences for LD and HD vehicles vary with both pollutant type and average speed. The largest emissions rate ratio between the two vehicle classes, $\frac{e_h}{e_l}$, is for $PM_{2.5}$, which ranges from about 30 at 60 mph up to 60 at 20 mph. In other words, HD vehicle emissions rates per mile can be up to 60 times greater than LD vehicle emissions rates. NO_x has the next highest emissions rate ratio, about 15 at 60 mph and 25 at 20 mph. CO_2e emissions rates are about 4 times greater for HD vehicles, and HC emissions rate ratios range from about 4 at 60 mph to 8 at 20 mph. Only CO emissions rates are somewhat similar between the two vehicle classes (a $\frac{e_h}{e_l}$ ratio of 1 to 2, depending on the speed). The emissions rate ratio $\frac{e_h}{e_l}$ trends downward with increasing speed, indicating that HD vehicle emissions rates are proportionally higher in congestion – i.e. $\varepsilon_{e_h}^{v_h} < \varepsilon_{e_l}^{v_l} < 0$.

Assuming 10% HD vehicles ($f_h = 0.1$), HD vehicle emissions (E_h) dominate total emissions E for $PM_{2.5}$ and NO_x (around 80% and 65% of E, respectively). LD vehicle emissions (E_l) dominate total per-mile CO and CO_2e emissions with about 85% and 70% of E, respectively. HC emissions are more evenly divided, with about 40% from HD vehicles. As with the emissions rate ratio $\frac{e_h}{e_l}$, the fraction of total per-mile emissions from HD vehicles, $\frac{E_h}{E}$, trends downward with increasing speed because HD vehicles are more sensitive to congestion.

FIGURE 1 illustrates the effects of HD vehicles in the traffic stream. Using Equation 5, FIGURE 1 shows the ratio of total emissions from a mixed fleet to those from an LD-only fleet with the same volume $\left(\frac{E_{f_h=0.1}}{E_{f_h=0}}\right)$ versus average speed $\bar{v}$, assuming equivalent speeds for all vehicles ($v_l = v_h = \bar{v}$). For the same volume q, HD vehicles in the fleet lead to 7 times greater per-mile emissions of $PM_{2.5}$ and more than 3 times greater emissions of NO_x compared to a LD-only fleet. Per-mile CO emissions are almost unaffected by the substitution of HD vehicles for LD vehicles.

Equation 3 can be used to adjust for PCE differences and compare mixed LD/HD and LD-only fleet emissions with equivalent q' by assuming $PCE_h = 1.5$ (for level terrain from the Highway Capacity Manual (26)). The effect of the PCE_h adjustment would be a 5% reduction in the impact of HD vehicles in FIGURE 1. In other words, for the same PCE-adjusted volume q', the impact of HD vehicles' consistently higher emissions rates $\left(\frac{e_h}{e_l} > 1\right)$ is partially mitigated because HD vehicles occupy more roadway capacity than LD vehicles.

MANAGED LANE STRATEGY FRAMEWORK

The large contribution to total emissions from a small number of HD vehicles (and their emissions rate sensitivity to congestion) makes them likely targets for more focused emissions and congestion mitigation strategies. Vehicle class-segregated lane management strategies aim to improve safety and reduce congestion effects by separating vehicles with dissimilar operating characteristics. In order to explore the potential emissions effects of vehicle class-targeted congestion management, four different managed lane scenarios are assessed, including vehicle class segregation through TOL. The four lane management scenarios are:

I. Adding capacity
   - Ia. Add a TOL
   - Ib. Add a General Purpose (GP) lane

II. Managing existing capacity
   - IIa. Convert one of the GP lanes to a TOL
   - IIb. Remove a GP lane (i.e. decrease existing capacity)

Tolling is not explicitly considered, though some of its effects can be simulated by studying different demand elasticity values. An explicit consideration of tolling is left as a subject for future research.

The assumed volume-speed relationship is the well-known Bureau of Public Roads (BPR) function, which estimates the average travel rate, $\bar{t}$, in time per unit distance, as a function of the effective demand volume, q', from Equation (3) in passenger cars per hour per lane (pcphpl), as

$$\bar{t} = t_o\left(1 + \alpha\left({q'}/{c}\right)^{\beta}\right) \tag{8}$$

where t_o is the free-flow travel rate, c is the roadway capacity in pcphpl, and α and β are dimensionless parameters. The average travel speed, $\bar{v}$, is the inverse of average travel rate, $\bar{v} = {}^{1}/_{\bar{t}}$. From Horowitz (31), assumed BPR parameters are $\alpha = 0.83$ and $\beta = 5.5$. The BPR model scale aligns with the average-speed emissions modeling approach of MOVES; both consider space-averaged properties of traffic over a corridor or segment of road. The BPR model and the assumed parameter values are used illustratively, recognizing that the selection of a volume-speed relationship can have a significant impact on total emissions calculations (32).

To estimate changes in traffic volume per vehicle class with travel speed changes, arc demand elasticities are used. If the initial demand volume and speed for vehicles of class j are q_{j_1} and v_{j_1}, respectively, the new demand volume q_{j_2} is calculated from the initial conditions and the new speed, v_{j_2}, using

$$\eta_{q_j}^{v_j} = \frac{\left(v_{j_2}+v_{j_1}\right)\left(q_{j_2}-q_{j_1}\right)}{\left(q_{j_2}+q_{j_1}\right)\left(v_{j_2}-v_{j_1}\right)} \text{ or}$$

$$q_{j_2} = q_{j_1}\frac{v_{j_1}+v_{j_2}+\eta_{q_j}^{v_j}\left(v_{j_2}-v_{j_1}\right)}{v_{j_1}+v_{j_2}-\eta_{q_j}^{v_j}\left(v_{j_2}-v_{j_1}\right)} . \tag{9}$$

The impact of the additional volume, $q_{j_2} - q_{j_1}$, on the final speed, v_{j_2}, must also be considered. If q'_2 is the final volume in PCE, then using Equation 8, $v_{j_2} = \frac{1}{t_o\left(1+\alpha\left({}^{q'_2}/_{c}\right)^{\beta}\right)}$. Rearranging Equation 9 and substituting for v_{j_2} obtains

$$q_{j_2}\left[q'^{\beta}_2 v_{j_1} t_o \alpha c^{-\beta}\left(1+\eta_{q_j}^{v_j}\right) + v_{j_1} t_o\left(1+\eta_{q_j}^{v_j}\right) + 1 - \eta_{q_j}^{v_j}\right] + q'^{\beta}_2 q_{j_1} v_{j_1} t_o \alpha c^{-\beta}\left(1-\eta_{q_j}^{v_j}\right) = q_{j_1} v_{j_1} t_o\left(1-\eta_{q_j}^{v_j}\right) + q_{j_1}\left(1+\eta_{q_j}^{v_j}\right) . \tag{10}$$

Combining vehicle classes, the total volume in PCE is

$$q'_2 = \sum_{j\in J} q_{j_2} \cdot PCE_j . \tag{11}$$

Thus, for two vehicle classes (LD and HD) $J = \{l, h\}$, Equations 10 and 11 represent a system of three equations with three unknowns: q_{l_2}, q_{h_2}, and q'_2 (Equation 10 is repeated for each vehicle class). All other variables are parameters or initial conditions. These equations are simultaneously solved to find the final volumes and speeds for each vehicle class, which satisfy both the demand elasticity $\eta_{q_j}^{v_j}$ and the theoretical volume/speed relationship (BPR). This method assumes that all VMT changes from variable demand are reflected in changing q.

MANAGED LANE RESULTS

This section presents estimated volume, speed, and emissions changes for four different lane management scenarios for a 3-lane congested freeway: Ia. Add a TOL, Ib. Add a GP lane, IIa. Convert one GP lane to a TOL, and IIb. Remove a GP lane (i.e. decrease existing capacity). The analysis context aims to replicate a typical congested urban freeway. Base conditions assume a 3-lane freeway corridor of arbitrary length – all GP lanes – with the following characteristics:

1. 10% HD vehicles ($f_h = 0.1$) with $PCE_h = 1.5$ for level terrain (26)

2. Travel demand volume elasticity to speed of 0.3 for both HD and LD vehicles $\left(\eta_{q_l}^{v_l} = \eta_{q_h}^{v_h} = 0.3\right)$
3. Roadway capacity of $c = 2{,}200$ pcphpl and free-flow speed of 60 mph
4. Initial volume of $q = 1{,}800$ vphpl (vehicles per hour, per lane); 86% of capacity, considering PCE.

The assumed travel demand elasticity is based on values found in the literature (see Section 0). Sensitivity of the results to the assumed demand elasticity is examined below, as is sensitivity analysis for the fraction of HD vehicles, f_h. The analysis makes the further assumptions:

1. An even distribution of travel demand volume among all available travel lanes
2. On mixed LD/HD facilities (i.e. GP lanes), LD and HD vehicles travel at the same average speed ($v_l = v_h = \bar{v}$); a scaling of v_h with respect to v_l in mixed GP lanes was also considered, though results were largely unchanged
3. When TOL exist, they are mandatory and exclusive for all HD vehicles – meaning there are no mixed LD/HD flow lanes when TOL exist.

FIGURE 2 shows the total emissions results of this analysis for all five pollutants as the percent change in total emissions E from base conditions for each strategy. The largest percent emissions savings can be obtained for $PM_{2.5}$ emissions, as hinted at by FIGURE 1. From the MOVES-generated emissions-speed curves represented by Equation 6 and TABLE 1, $PM_{2.5}$ and HC are more sensitive to speed/congestion changes than the other pollutants; this leads to greater reductions in $PM_{2.5}$ and HC for the added-capacity scenarios (Ia and Ib) and increased emissions for the capacity-removal scenario (IIb). Because $PM_{2.5}$ is disproportionally emitted by HD vehicles, it is reduced more from the TOL conversion than HC, though both decrease. Even considering potential LD vehicle traffic diversion effects, a reduction of $PM_{2.5}$ is highly likely with a TOL conversion.

CO responds similarly to CO_2e in each scenario, as does NO_x (although NO_x increases in Ib because it is less sensitive to speed). Of the TOL strategies in FIGURE 2 (Ia and IIa), TOL conversion outperforms lane addition from an emissions perspective for all pollutants except HC. Of the additional capacity scenarios (Ia and Ib), adding a TOL produces lower total emissions than adding a GP lane for all pollutants. GP lane removal (IIb) has mixed effects: it generates the greatest reduction in NO_x and near-best reduction in CO and CO2e, but $PM_{2.5}$ and HC emissions both increase.

Because the effects of each pollutant are different, the value of a 1% change for different pollutants is not directly comparable. For strategies where one pollutant is expected to increase while another decreases (Ib and IIb), consideration of the marginal benefits of reducing each pollutant is needed. That comparison is beyond the scope of this paper, but an important topic for further research.

More detailed results for CO_2e emissions are shown in TABLE 2. TABLE 2 shows results for base conditions and all four lane scenarios, with absolute values and percent changes from base conditions for class-specific volumes, speeds, and CO_2e emissions. Percent changes in TABLE 2 are calculated with respect to base conditions (i.e. $\frac{x_2 - x_1}{x_1}$), whereas arc elasticities for $\eta_{q_j}^{v_j}$ are calculated with respect to midpoints (i.e. $\frac{x_2 - x_1}{(x_2 + x_1)/2}$). The highest per-lane volume is 2,295 vphpl (IIb): a volume/capacity ratio of 1.10, including the PCE adjustment. Both TOL scenarios (Ia and IIa) reduce HD vehicle emissions, E_h, by 9%, but the lane conversion (IIa) also reduces LD vehicle speed (v_l) enough to suppress LD vehicle volume (q_l) by 9% and reduce LD vehicle emissions, E_l, by 6%. A TOL as additional capacity (Ia) produces a slight increase in E_l, with decreased emissions rates e_l but a 4% increase in volume q_l at the higher speed v_l. The 9% increase in HD vehicle volume q_h with the TOL is not enough to offset the increased efficiency for HD vehicles at higher speed v_h. The emissions benefits are greater for the strategies that manage existing capacity (IIa and IIb) than those that add new capacity (Ia and Ib). Furthermore, whether adding a lane or not, the TOL strategies reduce emissions more than similar GP-only lane management.

An important assumption in this analysis is that all VMT changes from variable demand are reflected in changing demand volume q (Section 0). The value of demand elasticity to speed $\eta_{q_j}^{v_j}$ captures net changes in VMT, but explicit network effects or traffic diversions (i.e. redistribution of VMT) are not considered. For example, if removing a GP lane shifts VMT onto already congested parallel arterials or local streets, this could result in higher total emissions – especially because arterials are more sensitive to emissions increases in congestion (1) . A TOL conversion that is accompanied by Bus Rapid Transit (BRT) or increased public transportation service on the corridor can diminish traffic diversion effects by providing alternative responses to increased GP lane travel time costs. Adding capacity can also have traffic diversion effects by shifting VMT to the study corridor – especially if the parallel facility is already congested. Some potential impacts of traffic diversion are examined below by varying travel demand elasticity.

To better understand the volume and speed changes that generate TABLE 2, FIGURE 3 illustrates the vehicle class-specific initial and final speed-volume points (v_j, q_j) for each lane management strategy (with volume in passenger cars per hour). The markers “L1”, “H1”, and “A1” refer to the LD vehicle, HD vehicle, and all-vehicle speed-volume points under base conditions. “L2”, “H2”, and “A2” refer to the final speed-volume points for LD vehicles, HD vehicles and all vehicles, respectively. FIGURE 3 includes downward-sloping dark lines for the BPR curves and upward-sloping grey lines for the demand elasticity curves. The LD and HD vehicle volumes sum to the all-vehicle volumes, which are located on GP lane BPR curves. For TOL strategies (Ia and IIa), “H2” is located on the TOL BPR curve and “L2” is located on the Final GP lane BPR curve. For GP strategies (Ib and IIb), “A2” is located on the Final BPR curve. The final volumes are found by following each vehicle class’s demand elasticity curve to its intersection with the final BPR curve (for GP strategies this is constrained so that “A2”, “L2”, and “H2” are at the same equilibrium speed).

The importance of demand elasticity $\eta_{q_j}^{v_j}$ can be seen in FIGURE 3: more elastic demand would lead to steeper demand elasticity curves and greater changes in volume before intersecting the new BPR curves. The greater change in volume would also be accompanied by smaller changes in speed (and in emissions rates). Thus, more elastic demand would increase E for the added capacity scenarios (Ia and Ib), but reduce E for the capacity management scenarios (IIa and IIb, though there are E_l and E_h trade-offs in IIa). These effects can also be seen in Equations 1 and 2. Similarly, the slope of the BPR curves (intensity of congestion changes with volume changes, or sensitivity of v_j to q_j) will influence the location of the final (v_j, q_j) points for each strategy.

To connect the changes in FIGURE 3 with the emissions effects in FIGURE 2 and TABLE 2, FIGURE 4 plots total emissions elasticity $\varepsilon_{E_j}^{v_j}$ versus speed v_j for each vehicle class, with the base condition speed ($v_l = v_h = 44$ mph) indicated by a vertical line. Using the assumed demand elasticity $\eta_{q_l}^{v_l} = \eta_{q_h}^{v_h} = 0.3$, total emissions elasticity $\varepsilon_{E_j}^{v_j}$ is directly calculated using Equations 1 and 7. For a speed increase from base conditions, the class-total emissions E_j increase if $\varepsilon_{E_j}^{v_j} > 0$ and decrease if $\varepsilon_{E_j}^{v_j} < 0$ – and *vice versa* if v_j decreases. Thus, shaded on FIGURE 4 are four regions, two of which lead to total emissions increases (grey), and two of which lead to total emissions decreases (white).

At the initial speed, $\varepsilon_{E_l}^{v_l} > 0$ and $\varepsilon_{E_h}^{v_h} < 0$; thus, where v_j increases from L1 to L2 or H1 to H2 in FIGURE 3, E_l increases and E_h decreases (agreeing with TABLE 2). Initially, the opposite is true when v_j decreases: E_l decreases and E_h increases. However, an exception occurs when $\varepsilon_{E_j}^{v_j}$ crosses the horizontal axis (changes sign) on the way to the new equilibrium point; then, the net area under the curve determines the change in E_j. For HD vehicles in scenario IIb, this means that despite an initial $\varepsilon_{E_h}^{v_h} < 0$ at $v_h = 44$ mph, E_h is lower at the final speed of $v_h = 25$ mph because $\varepsilon_{E_h}^{v_h} > 0$ for most of the traversed speed range from 44 to 25 mph.

FIGURE 4 shows emissions changes using emissions elasticity $\varepsilon_{E_j}^{v_j}$ for CO_2e only. For pollutants that are more sensitive to speed (i.e. more negative emissions rate elasticity to speed $\varepsilon_{e_j}^{v_j}$), $\varepsilon_{E_j}^{v_j}$ will be lower and more of the curve will see total emissions E_j decrease at higher speeds and increase at lower speeds. This is the case for HC and $PM_{2.5}$, which have lower $\varepsilon_{e_j}^{v_j}$ based on the values in TABLE 1. These pollutants see total emissions increase in the lower-speed capacity reduction scenario (IIb) and greater benefits from the speed increases in added-capacity scenarios (Ia and Ib).

We next explore the sensitivity of these results to several key characteristics and assumptions: initial volume (q), initial fraction HD vehicles (f_h), and demand elasticity to speed ($\eta_{q_j}^{v_j}$). FIGURE 5 shows the percent change in total CO_2e emissions (E) for varying initial volumes (q) in vehicles per hour (veh/hr). The base condition is 5,400 veh/hr. GP lane removal without TOL (IIb) loses benefits quickly at higher initial volumes, leading to increased E at 6,000 veh/hr or above. Adding a GP lane (Ib) increases emissions at the lowest initial q (5,700 veh/hr). TOL conversion (IIa) maintains emissions benefits up to almost 6,500 veh/hr, above which adding a TOL (Ia) becomes the preferred strategy. FIGURE 5 shows that the TOL strategy emissions benefits are the most robust to initial congestion level.

Varying initial fractions of HD vehicles in the fleet (f_h) has only a small effect on the percent change in total CO_2e emissions with each strategy. For CO_2e, total emissions effects of GP lane addition (Ib) are nearly insensitive to f_h, while GP lane removal (IIb) is slightly less effective at higher f_h because HD vehicles are proportionally more inefficient at low speeds. The TOL strategies (Ia and Ib) are less effective at reducing emissions with too high initial f_h (over 15%) because the TOL are saturated and not operating at more efficient speeds. Conversely, at very low f_h, additional TOL are minimally utilized and have little effect beyond the change in GP capacity (if any).

FIGURE 6 shows the strong effect on total CO_2e emissions (E) of varying demand elasticity to speed $\eta_{q_j}^{v_j}$ for both vehicle classes. Total emissions after lane additions (Ia and Ib) are higher with increasing $\eta_{q_j}^{v_j}$ because of greater induced travel demand (higher q_j) and smaller emissions rate benefits (higher e_j because the new equilibrium occurs at a lower v_j). Increasing $\eta_{q_j}^{v_j}$ has the opposite effect on capacity reductions, as q_j falls more and e_j increases less. At low demand elasticity, lane reductions are ineffective at reducing emissions because they decrease efficiency without suppressing demand. FIGURE 6 shows that the assumed demand elasticity of 0.3 is within a narrow range that leads to E reductions for all four strategies. Importantly, the emissions benefits of TOL conversion (IIa) are the most robust to uncertainty in travel demand elasticity.

Varying only HD vehicle demand elasticity to speed ($\eta_{q_h}^{v_h}$) and not LD vehicle demand elasticity ($\eta_{q_l}^{v_l}$), the results are smaller in scale but similar in shape to FIGURE 6, with the exception of TOL conversion (IIa) at low $\eta_{q_h}^{v_h}$. Only varying $\eta_{q_h}^{v_h}$, TOL conversion is increasingly effective in reducing emissions at lower $\eta_{q_h}^{v_h}$ because it continues to suppress q_l while not inducing higher q_h, unlike in FIGURE 6. Although GP lane removal (IIb) outperforms TOL conversion (IIa) for emissions reductions in some situations (particularly at high $\eta_{q_h}^{v_h}$), TOL conversion is more likely to be a politically feasible GP capacity-restricting option for implementation (particularly if it garners the support of the trucking industry and is complimented by transit improvements).

A corridor with many opportunities for traffic diversion (uncongested parallel routes) would have lower net demand elasticity to speed, if total VMT changes are considered. For strategies where low demand elasticity would have a detrimental effect on total emissions (IIa and IIb), provision of travel alternatives (i.e. an accompanying increase in public transportation quality and frequency) can increase vehicle travel demand sensitivity to speed. Alternatively, where high demand elasticity would lead to increases in total emissions (Ia and Ib), tolling or road pricing can be implemented to mitigate induced demand. Better travel options and road pricing can be reflected in this analysis framework by higher or lower estimates of $\eta_{q_j}^{v_j}$, respectively. Similarly, lower estimates of $\eta_{q_j}^{v_j}$ would reflect situations where changes in v_j on the corridor are easily met with a diversion of traffic to parallel facilities, with little net change in total VMT. More congested (or non-existent) parallel facilities reduce opportunities for diversion, which would be reflected here by higher $\eta_{q_j}^{v_j}$.

CONCLUSIONS

This paper assesses the unique emissions characteristics of LD and HD vehicle classes and their impacts on the congestion-emissions relationship, including variable vehicle efficiency, travel demand elasticity, and class-specific lane management. Because of higher emissions rates, HD vehicles contribute a large share of on-road emissions, even as a minority of vehicles. HD vehicles also have greater potential for emissions reductions through congestion mitigation because of emissions rates that are more sensitive to speed.

To investigate the emissions effects of vehicle class-targeted congestion management, four different managed lane scenarios are analyzed. Results show that TOL strategies consistently out-perform GP lane strategies in terms of total emissions reductions. Converting a GP lane to TOL reduces emissions more than adding a new TOL for all pollutants except HC (and is more realistically implemented than removing a lane from overall capacity). When adding a lane, adding a TOL produces lower total emissions than adding a GP lane for all pollutants. HC emissions are the most sensitive to speed and benefit most from capacity expansions; NO_x emissions are least sensitive to speed and benefit most from capacity restriction or capacity-neutral lane management. $PM_{2.5}$ emissions are primarily from HD vehicles and so benefit most from the TOL strategies.

The estimated emissions effects are sensitive to the assumed travel demand elasticity and initial congestion level, though the benefits of TOL conversion are robust to uncertainty in travel demand elasticity. Predicting the emissions effects of TOL requires estimation of demand elasticity for HD vehicles, and as described in Section 0, tools for quantification of this value are scant. Further research investigating the real-world freight travel demand response to changes in roadway network performance is essential to understanding the full effects of traffic management.

Network effects or traffic diversions are not explicitly considered, though the potential influence of traffic diversion is estimated by varying travel demand elasticity. It is recommended for emissions reductions that lane management strategies that decrease LD vehicle travel speeds are accompanied by a significant increase in public or alternative transportation mode level of service and quality. Conversely, lane management strategies with likely emissions increases from induced demand can implement tolling to offset elastic demand effects and capture the efficiency benefits of less congestion.

This analysis of managed lane scenarios does not cover the breadth of possible configurations and initial conditions. But it is informative in showing the emissions trade-offs inherent in congestion management between emissions rates and travel volumes by vehicle class. The results also demonstrate the potential emissions benefits of vehicle class-targeted congestion management over general-purpose strategies. Actual emissions rates will vary with a number of factors (terrain, temperature, vehicle fleet, etc.), but this main conclusion is expected to hold across a wide range of conditions. The same methodological framework can be readily applied in other contexts for sketch-level analysis of emissions impacts from vehicle class-targeted congestion management.

ACKNOWLEDGMENTS

The authors would like to thank the Oregon Transportation Research and Education Consortium and the U.S. Department of Transportation (through the Eisenhower Graduate Fellowship program).

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TABLE 1 Emissions-Speed Curve Fit Parameters on Freeways.

LD Vehicles ($\boldsymbol{e_l}$)	CO_2e	CO	$PM_{2.5}$	NO_x	HC
$a_{0,l}$	7.987	2.788	-2.856	0.3239	-0.2644
$a_{1,l}$	-0.1856	-0.1760	-0.2000	-0.1152	-0.1878
$a_{2,l}$	0.006352	0.006535	0.007365	0.004155	0.006173
$a_{3,l}$	-9.550E-05	-1.077E-04	-1.157E-04	-6.270E-05	-9.570E-05
$a_{4,l}$	5.210E-07	6.460E-07	6.560E-07	3.440E-07	5.510E-07
HD Vehicles ($\boldsymbol{e_h}$)					
$a_{0,h}$	9.254	3.541	1.005	4.124	2.059
$a_{1,h}$	-0.1748	-0.1900	-0.1740	-0.1839	-0.2206
$a_{2,h}$	0.006307	0.006843	0.006599	0.006461	0.006967
$a_{3,h}$	-1.007E-04	-1.097E-04	-1.141E-04	-1.003E-04	-1.018E-04
$a_{4,h}$	5.740E-07	6.201E-07	6.870E-07	5.599E-07	5.380E-07

TABLE 2 Volume, Speed, and CO_2e Emissions Changes with Lane Scenarios.

	Base Conditions	Ia. TOL Added		Ib. GP Lane Added		IIa. TOL Conversion		IIb. GP Lane Removed	
q_l (veh/hr)	4860	5056	4%	5176	6%	4428	-9%	4130	-15%
q_h (veh/hr)	540	591	9%	575	6%	591	9%	459	-15%
v_l (mph)	44	50	14%	54	23%	32	-27%	25	-43%
v_h (mph)	44	60	35%	54	23%	60	35%	25	-43%
E_l (kg CO2e /hr/road-mile)	1844	1862	1%	1858	1%	1733	-6%	1708	-7%
E_h (kg CO2e /hr/road-mile)	837	764	-9%	792	-5%	764	-9%	807	-4%
E (kg CO2e /hr/road-mile)	2681	2626	-2%	2651	-1%	2497	-7%	2514	-6%

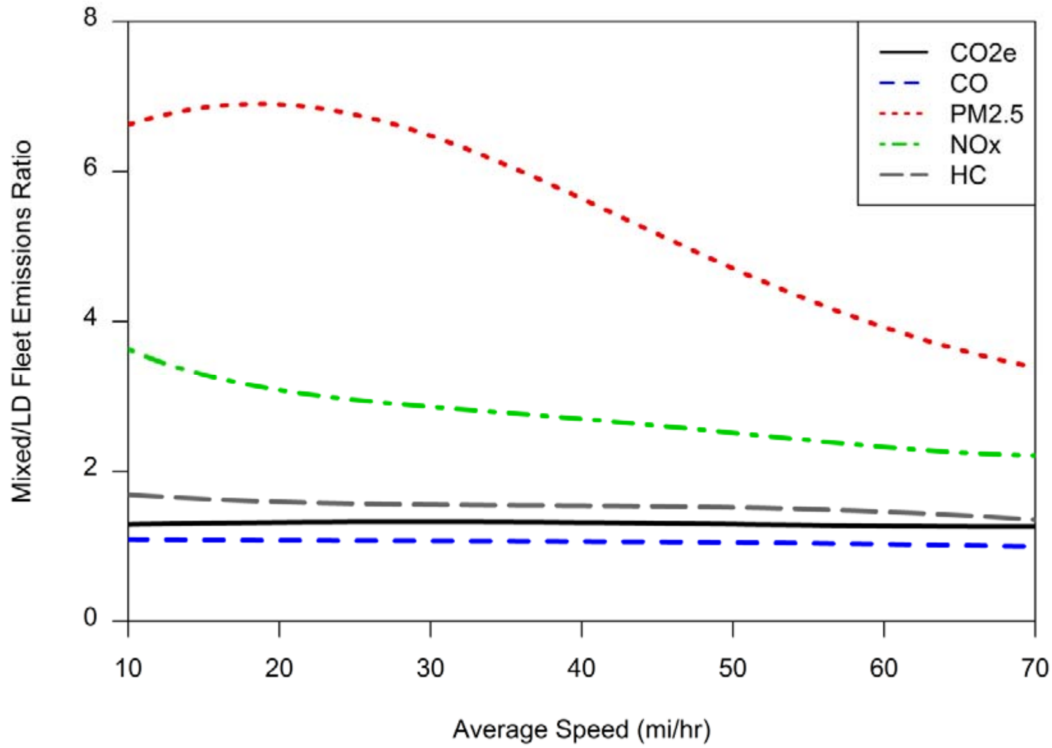

FIGURE 1 Comparison of Emissions from Mixed and LD-only Fleets.

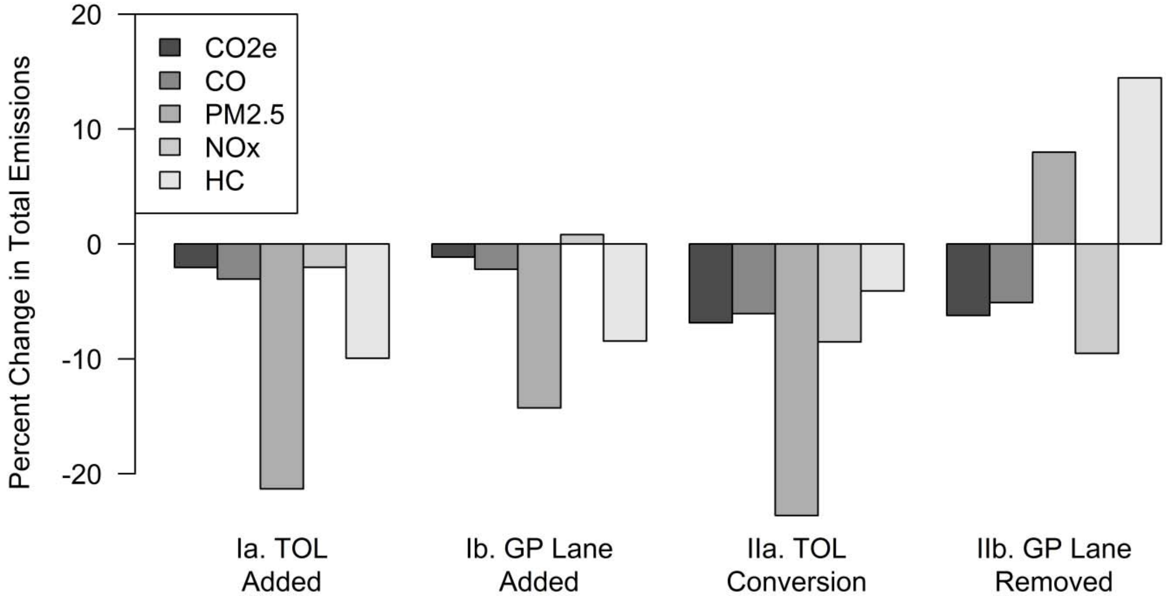

FIGURE 2 Percent Reductions in Total Emissions for Each Lane Scenario and Pollutant.

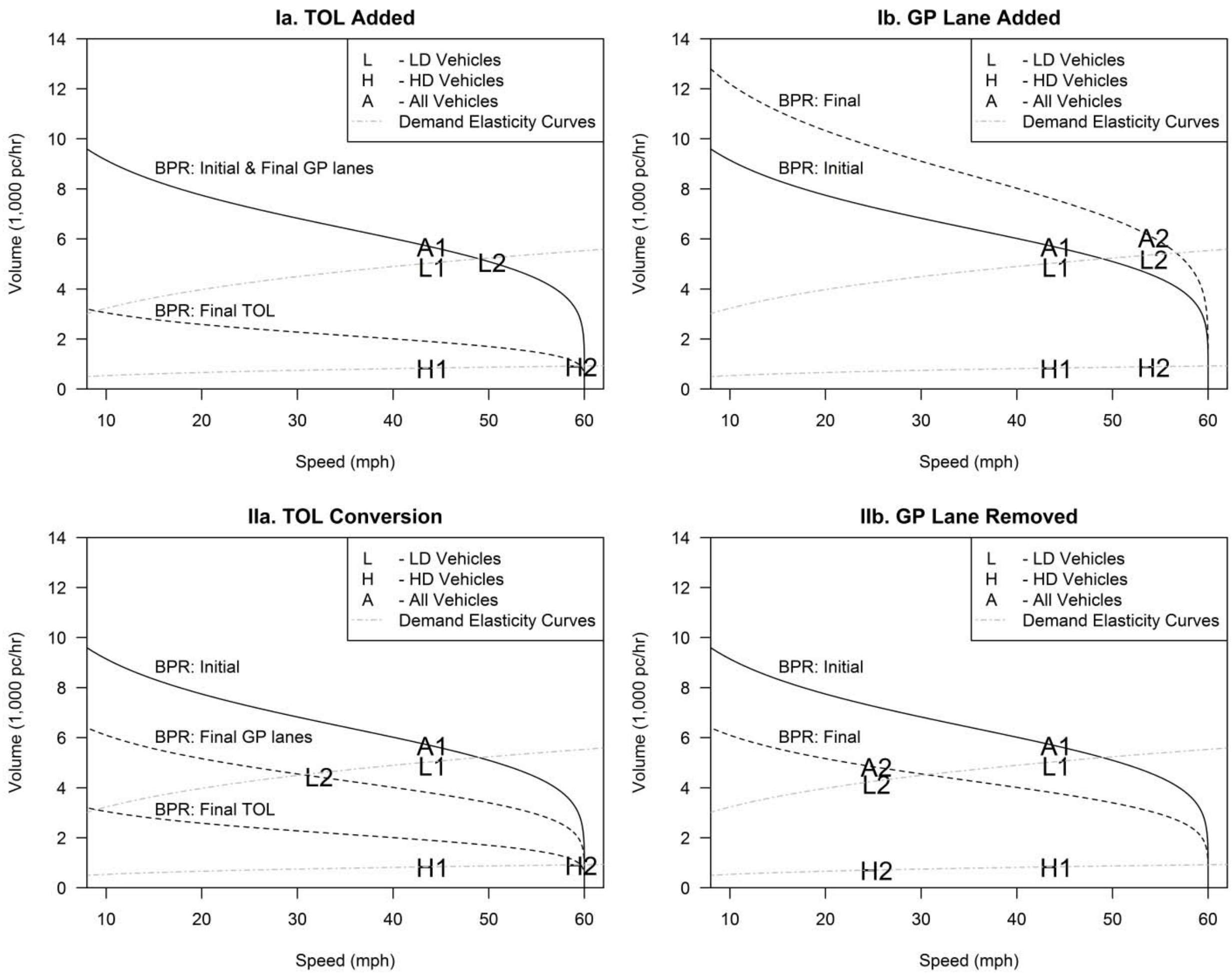

FIGURE 3 Volume and Speed Changes for Each Lane Management Scenario.

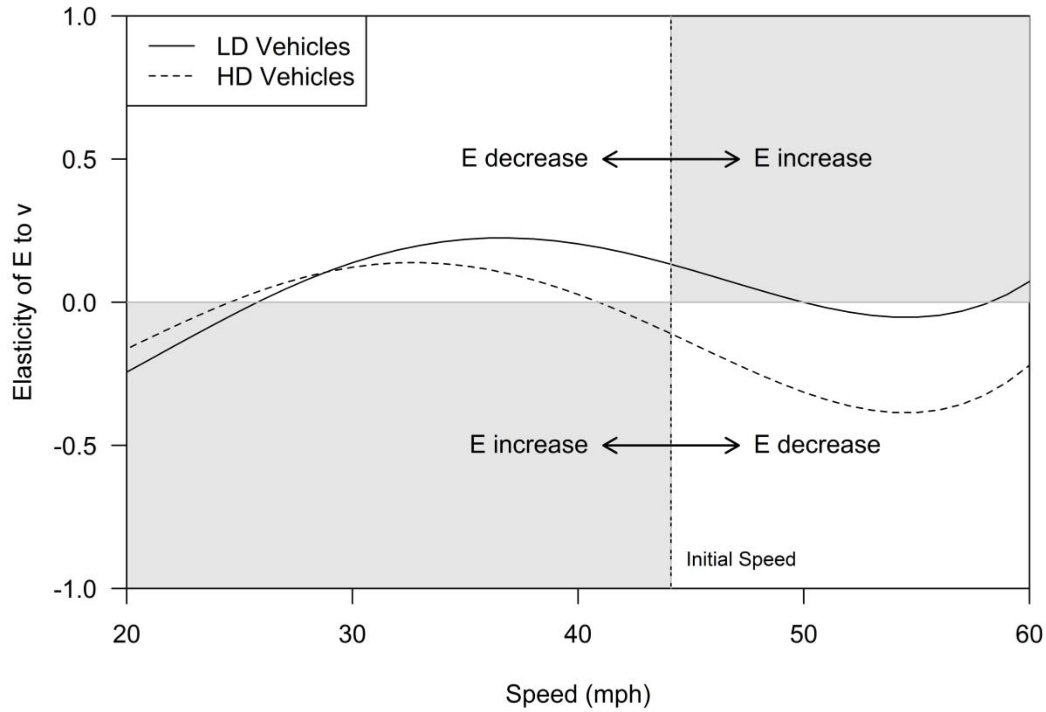

FIGURE 4 Elasticity of Total CO_2e Emissions to Speed.

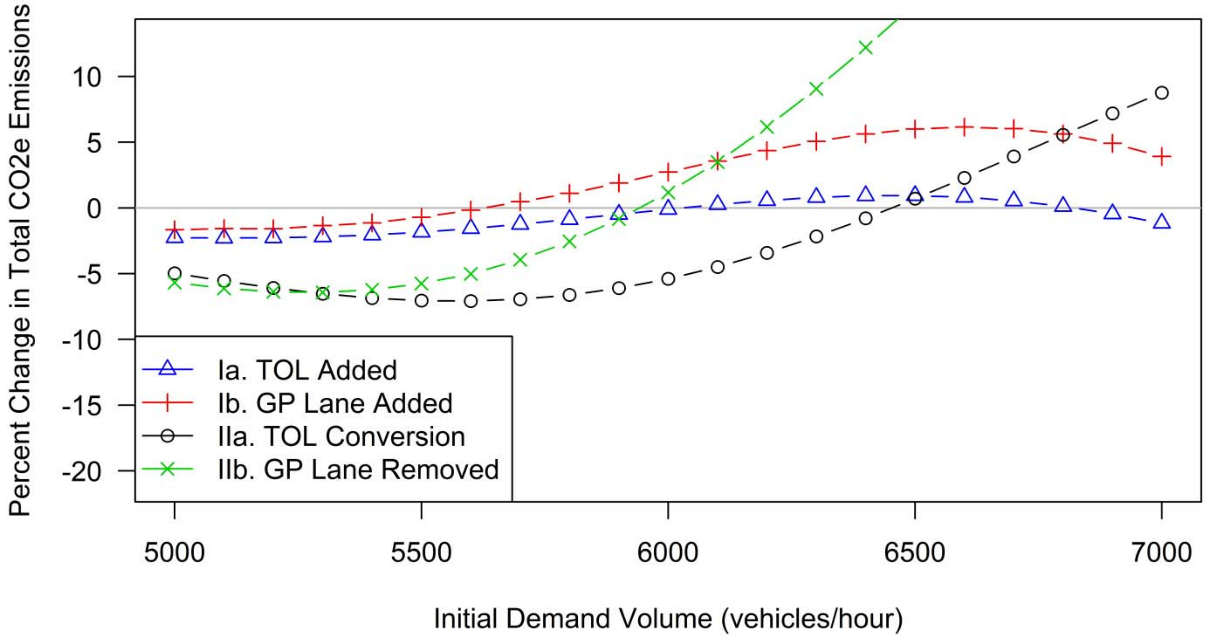

FIGURE 5 Total CO_2e Emissions Sensitivity to Initial *q*.

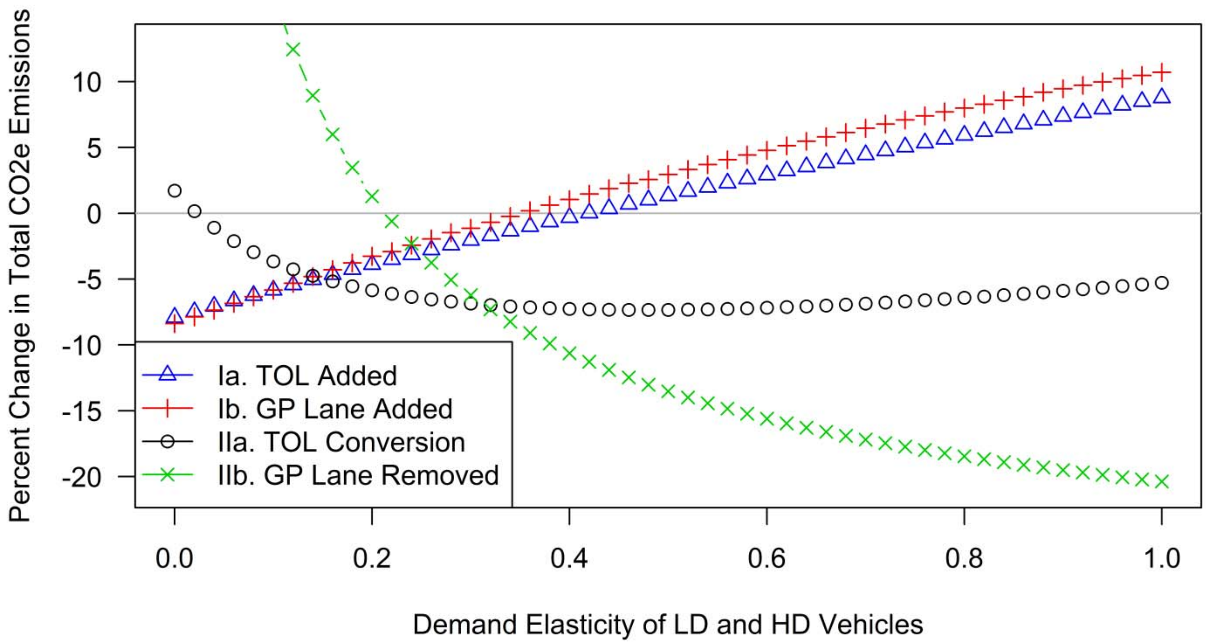

FIGURE 6 Total CO_2e Emissions Sensitivity to Demand Elasticity (Both $\eta_{q_l}^{v_l}$ and $\eta_{q_h}^{v_h}$).