Study of Emissions Benefits of Commercial Vehicle Lane Management Strategies

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Traffic congestion mitigation has been proposed as a strategy to help attain air quality goals. A better understanding of the full effects 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 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 managed lane scenarios shows that vehicle class–segregated facilities tend to outperform general purpose lane strategies in 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 effects from vehicle class–targeted congestion management.

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

A better understanding of the full effects 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 in which total vehicle emissions increase with congestion mitigation (*1*). However, the specific effects 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, research went on to investigate the potential for emissions reductions through vehicle class–targeted congestion mitigation by using four 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.

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LITERATURE REVIEW

Although much work has been done in the field of motor vehicle emissions estimation, our understanding of the full effects 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 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 showed that the effects of congestion on truck emissions per route can be significant and complex, depending on depot and customer relative locations, routing constraints, and congestion levels (*10*).

Travel responses to changing congestion levels are typically assessed by 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 and 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, although this has yet to be established (*12, 15*). In fact, Figliozzi showed that more congestion can increase commercial vehicle trips because of shorter and less efficient routes (*10, 17*). Therefore, for certain trucking sectors such as less than truckload (LTL) 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 have spurred interest in vehicle class–targeted emissions reduction strategies. Truck-only lanes (TOLs) are roadway facilities that provide exclusive right-of-way and prioritized mobility for HD (commercial) vehicles. The effects of TOLs on traffic flow and travel demand vary with operation strategy, lane configuration, and tolling strategy, if any (*18–20*). Typically, TOLs are pursued for economic, safety, and operational efficiency reasons, with air quality as a potential co-benefit (*21–23*). Air quality benefits from TOLs come with the caveat that TOLs may increase truck travel demand by increasing travel speeds, which can lead to increased total emissions (*24*).

In their analysis of the emissions effects of tolled TOLs in Atlanta, Georgia, Chu and Meyer estimate net emissions reductions of 3% to 6% for hydrocarbons and 61% to 62% for carbon dioxide (depending on implementation) (*25*). They estimate net emissions increases of 2% to 5% for carbon monoxide (CO) and 1% to 18% for nitrogen oxides (NO_x), 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 effects 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 between 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 $f_j = q_j/q$ 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 as $\varepsilon_{e_j}^{v_j} = v_j/e_j \cdot \partial e_j/\partial v_j$. The long-term elasticity of travel demand volume q_j to v_j is expressed as $\eta_{q_j}^{v_j} = v_j/q_j \cdot \partial q_j/\partial v_j$. The value of $\eta_{q_j}^{v_j}$ represents the percentage change in class-j vehicle miles traveled (VMT) with a 1% 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 emissions 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 $\partial v_j/\partial\bar{v} = v_j/\bar{v}\ \forall j \in J$, is

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

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 in which each vehicle class's total emissions elasticity to speed is zero, $\varepsilon_{E_j}^{v_j} = 0\ \forall j \in J$.

For an 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 a 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 the 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 is calculated as $q' = q \cdot \sum_{j\in J}(\mathrm{PCE}_j \cdot f_j)$, where PCE_j is the passenger-car equivalence of each vehicle in class j. Assuming $\mathrm{PCE}_l = 1$, the effective volume of vehicle travel in PCE with $J = \{l, h\}$ is

$$q' = q\left(1 + f_h\left(\mathrm{PCE}_h - 1\right)\right) \quad (3)$$

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

$$E = E_l + E_h = q\left[(1 - f_h)e_l + f_h e_h\right] \quad (4)$$

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

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

With the ratio $E_{f_h=f_h}/E_{f_h=0}$, Equation 5 demonstrates the effect of the presence of HD vehicles on total emissions; 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, the functional form for emissions rates e_j as a function of speed v_j is an exponentiated polynomial

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

where $a_{i,j}$ are fitted parameters (*2, 27*). Differentiating Equation 6, the elasticity of e_j to v_j is

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

TABLE 1 Emissions–Speed Curve Fit Parameters on Freeways

Parameter	CO_2e	CO	$PM_{2.5}$	NO_x	HC
LD Vehicles (e_l)					
$a_{0,l}$	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
$a_{3,l}$	–9.550 E–05	–1.077 E–04	–1.157 E–04	–6.270 E–05	–9.570 E–05
$a_{4,l}$	5.210 E–07	6.460 E–07	6.560 E–07	3.440 E–07	5.510 E–07
HD Vehicles (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
$a_{3,h}$	–1.007 E–04	–1.097 E–04	–1.141 E–04	–1.003 E–04	–1.018 E–04
$a_{4,h}$	5.740 E–07	6.201 E–07	6.870 E–07	5.599 E–07	5.380 E–07

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

To generate data for fitting $a_{i,j}$ in Equation 6, the Environmental Protection Agency's Motor Vehicle Emissions Simulator (MOVES) model is used for estimates of emissions rates e_j (*28*). The modeled pollutants are GHG in carbon dioxide equivalent units (CO_2e), CO, NO_x, particulate matter smaller than 2.5 microns ($PM_{2.5}$), and hydrocarbons (HC). The average-speed emissions-modeling approach used 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 by 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 seven MOVES Source Type IDs below 40: motorcycles, passenger cars, passenger trucks, and single-unit two-axle LD commercial trucks under a 19,500-lb gross vehicle weight rating (GVWR). The HD vehicle fleet includes 10 MOVES Source Type IDs above 40: buses, combination trucks, and other HD trucks over 19,500 lb 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 by using a least-squares fit for all five pollutants and each vehicle class, obtaining $R^2 > .96$ for all 10 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, one can see that emissions rate differences for LD and HD vehicles vary with pollutant type and average speed. The largest emissions rate ratio between the two vehicle classes, 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 four 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 (an e_h/e_l ratio of 1 to 2, depending on the speed). The emissions rate ratio 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 (about 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 e_h/e_l, the fraction of total per-mile emissions from HD vehicles, 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 ($E_{f_h=0.1}/E_{f_h=0}$) 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 seven times greater per-mile emissions of $PM_{2.5}$ and more than three times greater emissions of NO_x compared with an 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 effect of HD vehicles in Figure 1. In other words, for the same PCE-adjusted volume q', the effect of HD vehicles' consistently higher emissions rates ($e_h/e_l > 1$) 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

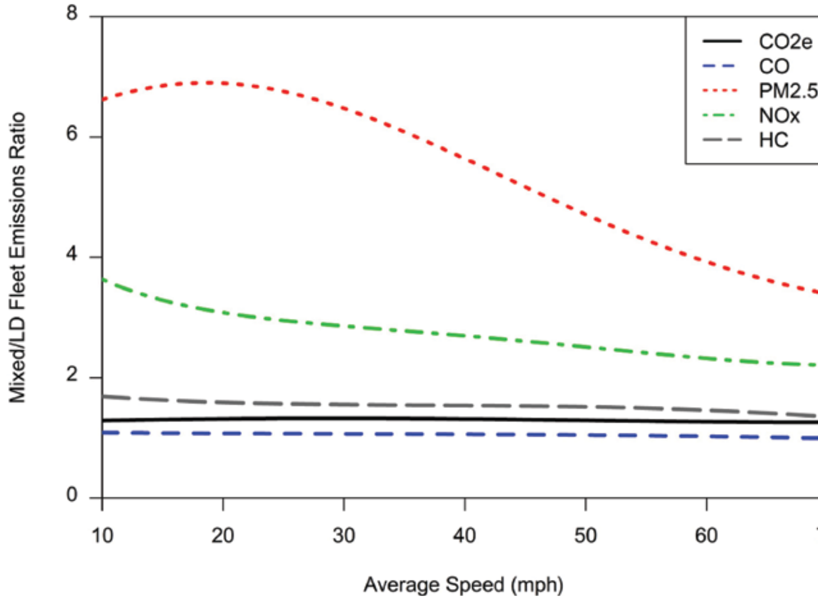

FIGURE 1 Comparison of emissions from mixed and LD-only fleets.

mitigation strategies. Vehicle class–segregated lane management strategies aim to improve safety and reduce congestion effects by separating vehicles with dissimilar operating characteristics. To explore the potential emissions effects of vehicle class–targeted congestion management, four different managed lane scenarios are assessed, including vehicle class segregation through TOLs. The four lane management scenarios are as follows:

I. Add capacity:
   a. Add a TOL.
   b. Add a general purpose (GP) lane.
II. Manage existing capacity:
   a. Convert one GP lane to a TOL.
   b. Remove a GP lane (i.e., decrease existing capacity).

Tolling is not explicitly considered, although 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

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

where

t_o = free-flow travel rate,
c = roadway capacity in pcphpl, and
α and β = dimensionless parameters.

The average travel speed, $\bar{v}$, is the inverse of average travel rate, $\bar{v} = 1/\bar{t}$. From Horowitz, the assumed BPR parameters are $\alpha = 0.83$ and $\beta = 5.5$ (*31*). 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 effect 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}, by using

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

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

The effect 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, $v_{j_2} = 1/t_o(1 + \alpha(q'_2/c)^{\beta})$. Rearranging Equation 9 and substituting for v_{j_2} obtains

$$\begin{aligned} &q_{j_2}\left[q_2'^{\beta}v_{j_1}t_o\alpha c^{-\beta}\left(1+\eta_{q_j}^{v_j}\right)+v_{j_1}t_o\left(1+\eta_{q_j}^{v_j}\right)+1-\eta_{q_j}^{v_j}\right] \\ &\quad + q_2'^{\beta}q_{j_1}v_{j_1}t_o\alpha c^{-\beta}\left(1-\eta_{q_j}^{v_j}\right) = q_{j_1}v_{j_1}t_o\left(1-\eta_{q_j}^{v_j}\right)+q_{j_1}\left(1+\eta_{q_j}^{v_j}\right) \end{aligned} \tag{10}$$

Combining vehicle classes, the total volume in PCE is

$$q'_2 = \sum_{j\in J} q_{j_2} \cdot \text{PCE}_j \tag{11}$$

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 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 lane management scenarios for a three-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 three-lane freeway corridor of arbitrary length—all GP lanes—with the following characteristics:

1. Ten percent 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 HD and LD vehicles ($\eta^{v_l}_{q_l} = \eta^{v_h}_{q_h} = 0.3$),
3. Roadway capacity of $c = 2,200$ pcphpl and free-flow speed of 60 mph, and
4. Initial volume of $q = 1,800$ vehicles per hour per lane (vphpl); 86% of capacity, considering PCE.

The assumed travel demand elasticity is based on values found in the literature (see section on the literature). 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. Travel demand volume is evenly distributed 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, although results were largely unchanged.
3. When TOLs exist, they are mandatory and exclusive for all HD vehicles—meaning there are no mixed LD-HD flow lanes when TOLs exist.

Figure 2 shows the total emissions results of this analysis for all five pollutants as the percentage of change in total emissions E from base conditions for each strategy. The largest percentage of 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 and congestion changes than the other pollutants, which 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 disproportionately emitted by HD vehicles, it is reduced more from the TOL conversion than HC, although 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 CO_2e, 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 in which 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. The percentage of changes in Table 2 are calculated with respect to base conditions (i.e., $x_2 - x_1/x_1$), while arc elasticities for $\eta^{v_j}_{q_j}$ are calculated with respect to midpoints (i.e., $x_2 - x_1/(x_2 + x_1)/2$). 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%

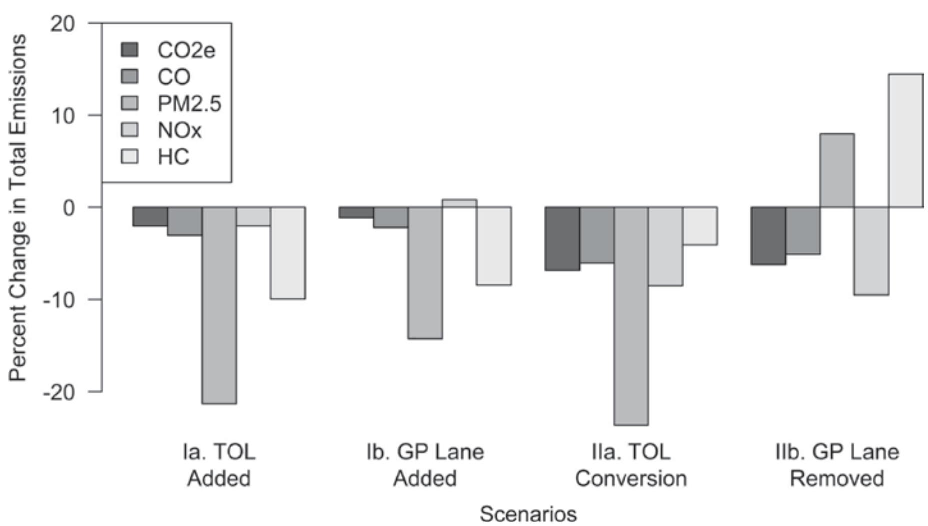

FIGURE 2 Percentage of reductions in total emissions for each lane scenario and pollutant.

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

Parameter	Base Conditions	Ia. TOL Added		Ib. GP Lane Added		IIa. TOL Conversion		IIb. GP Lane Removed	
		Absolute Value	Percentage Change	Absolute Value	Percentage Change	Absolute Value	Percentage Change	Absolute Value	Percentage Change
q_l (veh/h)	4,860	5,056	4	5,176	6	4,428	–9	4,130	–15
q_h (veh/h)	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 CO_2e/h/road-mile)	1,844	1,862	1	1,858	1	1,733	–6	1,708	–7
E_h (kg CO_2e/h/road-mile)	837	764	–9	792	–5	764	–9	807	–4
E (kg CO_2e/h/road-mile)	2,681	2,626	–2	2,651	–1	2,497	–7	2,514	–6

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 a lane is added 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 (see section on managed lane strategy framework). 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, higher total emissions could result, especially because arterials are more sensitive to emissions increases in congestion (*1*). A TOL conversion that is accompanied by bus rapid transit 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 effects 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 gray 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, although 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. By 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 with 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, four regions are shaded on Figure 4, two of which lead to total emissions increases (gray) 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 by 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 $\varepsilon_{e_j}^{v_j}$ according to 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).

Next, the sensitivity of these results to several key characteristics and assumptions are explored: initial volume (q), initial fraction of HD vehicles (f_h), and demand elasticity to speed ($\eta_{q_j}^{v_j}$). Figure 5 shows the percentage of change in total CO_2e emissions (E) for varying initial volumes (q) in vehicles per hour (veh/h). The base condition is 5,400 veh/h. GP lane removal without TOL (IIb) loses benefits quickly at higher initial volumes, leading to increased E at 6,000 veh/h or

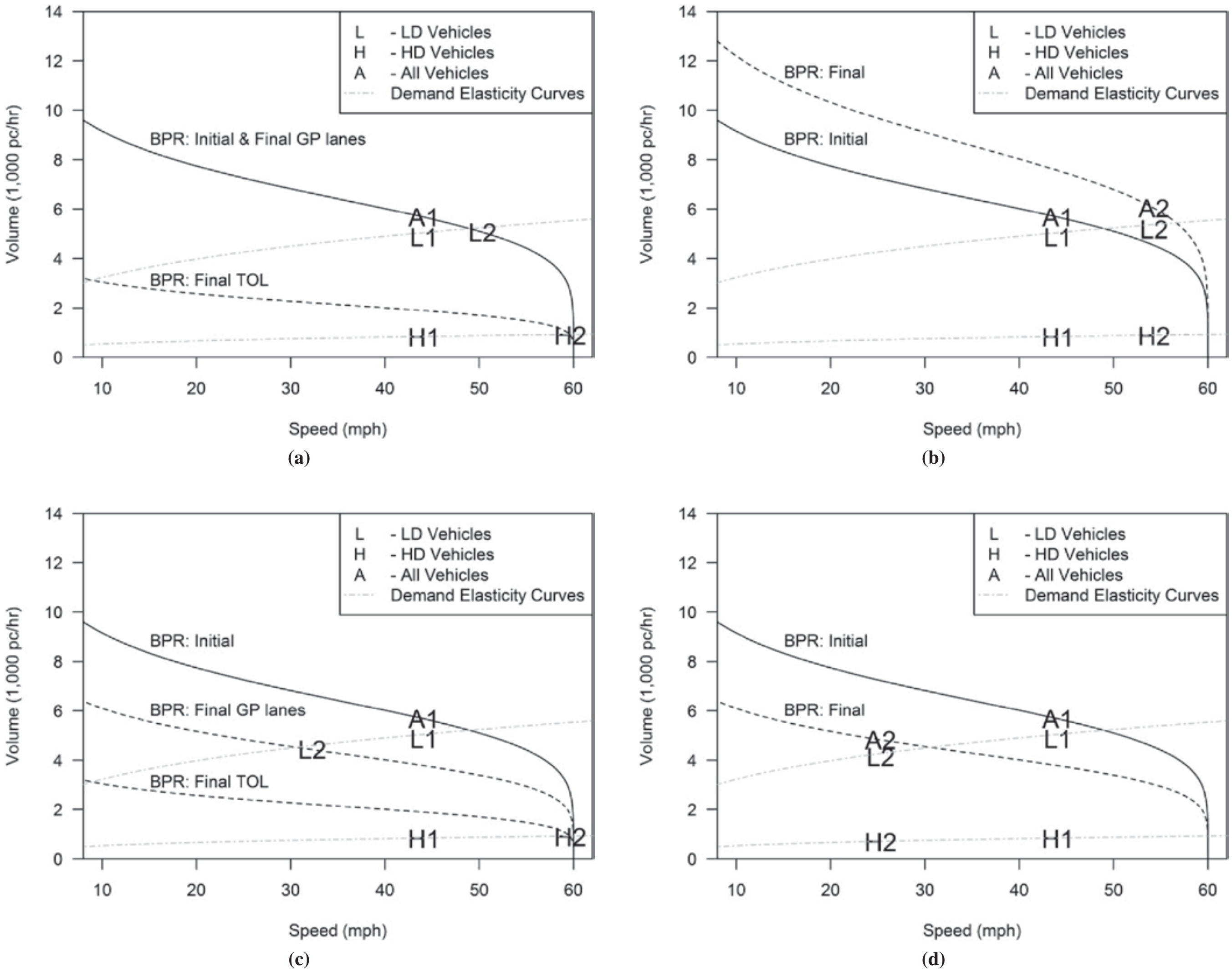

FIGURE 3 Volume and speed changes for each lane management scenario: (*a*) Ia, TOL added; (*b*) Ib, GP lane added; (*c*) IIa, TOL conversion; and (*d*) IIb, GP lane removed (PC = passenger car).

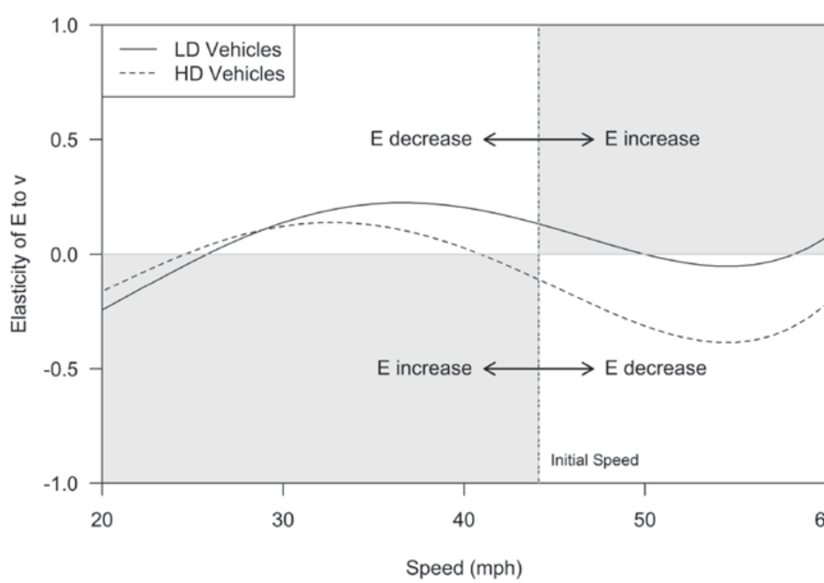

FIGURE 4 Elasticity of total CO_2e emissions to speed.

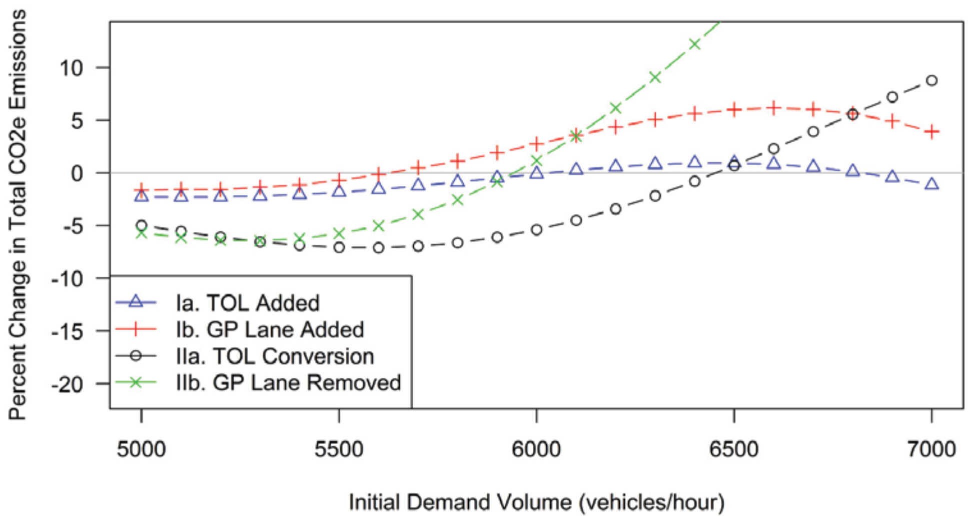

FIGURE 5 Total CO_2e emissions sensitivity to initial *q*.

above. Adding a GP lane (Ib) increases emissions at the lowest initial *q* (5,700 veh/h). TOL conversion (IIa) maintains emissions benefits up to almost 6,500 veh/h, above which adding a TOL (Ia) becomes the preferred strategy. Figure 5 shows that the TOL strategy emissions benefits are the most robust to the initial congestion level.

Varying initial fractions of HD vehicles in the fleet (f_h) has only a small effect on the percentage of 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 an initial f_h (more than 15%) because the TOLs are saturated and not operating at more efficient speeds. Conversely, at very low f_h, additional TOLs 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. 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 reduc-

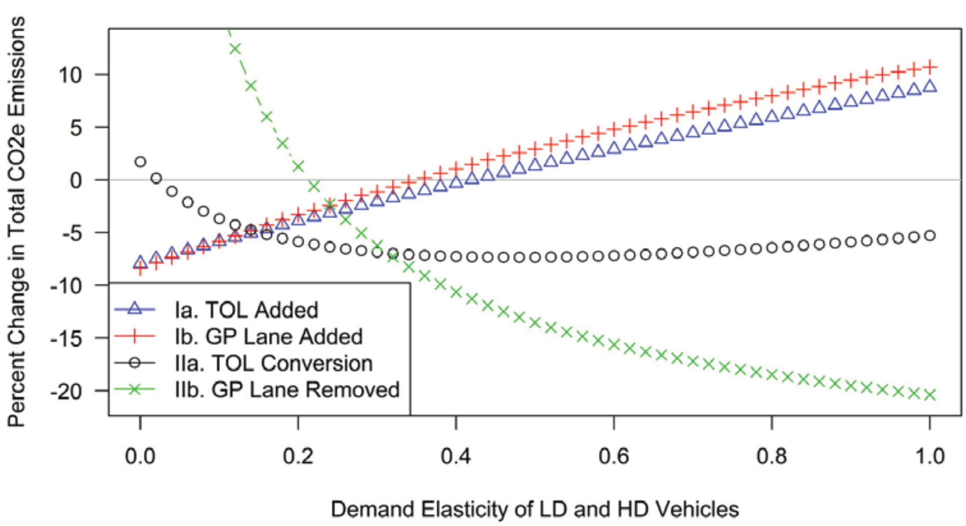

FIGURE 6 Total CO_2e emissions sensitivity to demand elasticity (both $\eta_{q_l}^{v_l}$ and $\eta_{q_h}^{v_h}$).

tions 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 complemented 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 were considered. For strategies in which 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, in cases in which 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 in which 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 nonexistent) 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 effects 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 managed lane scenarios are analyzed. Results show that TOL strategies consistently outperform GP lane strategies in regard to 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 a lane is added, 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 although 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 previously, 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, although 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 be 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 effects from vehicle class–targeted congestion management.

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REFERENCES

1. Bigazzi, A. Y., and M. A. Figliozzi. Congestion and Emissions Mitigation: A Comparison of Capacity, Demand, and Vehicle Based Strategies. *Transportation Research Part D: Transport and Environment,* Vol. 17, No. 7, Oct. 2012, pp. 538–547.
2. Barth, M. J., and K. Boriboonsomsin. Real-World Carbon Dioxide Impacts of Traffic Congestion. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2058,* Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 163–171.
3. Barth, M. J., G. Scora, and T. Younglove. Estimating Emissions and Fuel Consumption for Different Levels of Freeway Congestion. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1664,* TRB, National Research Council, Washington, D.C., 1999, pp. 47–57.
4. Hymel, K. M., K. A. Small, and K. V. Dender. Induced Demand and Rebound Effects in Road Transport. *Transportation Research Part B: Methodological,* Vol. 44, No. 10, Dec. 2010, pp. 1220–1241.
5. HDR. *Assessing the Full Costs of Congestion on Surface Transportation Systems and Reducing Them through Pricing.* U.S. Department of Transportation, Feb. 2009.
6. Dowling, R. G. *NCHRP Report 535: Predicting Air Quality Effects of Traffic-Flow Improvements: Final Report and User's Guide.* Transportation Research Board of the National Academies, Washington, D.C., 2005.
7. Noland, R. B., and M. A. Quddus. Flow Improvements and Vehicle Emissions: Effects of Trip Generation and Emission Control Technology. *Transportation Research Part D: Transport and Environment,* Vol. 11, No. 1, 2006, pp. 1–14.
8. Scora, G., K. Boriboonsomsin, and M. J. Barth. Effects of Operational Variability on Heavy-Duty Truck Greenhouse Gas Emissions. Presented at 89th Annual Meeting of the Transportation Research Board, Washington, D.C., 2010.
9. Weisbrod, G., D. Vary, and G. Treyz. *NCHRP Report 463: Economic Implications of Congestion.* TRB, National Research Council, Washington, D.C., 2001.
10. Figliozzi, M. A. The Impacts of Congestion on Time-Definitive Urban Freight Distribution Networks CO_2 Emission Levels: Results from a Case Study in Portland, Oregon. *Transportation Research Part C: Emerging Technologies,* Vol. 19, No. 5, Aug. 2011, pp. 766–778.
11. Goodwin, P., J. Dargay, and M. Hanly. Elasticities of Road Traffic and Fuel Consumption with Respect to Price and Income: A Review. *Transport Reviews,* Vol. 24, No. 3, 2004, pp. 275–292.
12. Graham, D. J., and S. Glaister. Road Traffic Demand Elasticity Estimates: A Review. *Transport Reviews,* Vol. 24, No. 3, 2004, pp. 261–274.

13. Oum, T. H., W. G. Waters II, and J.-S. Yong. Concepts of Price Elasticities of Transport Demand and Recent Empirical Estimates: An Interpretative Survey. *Journal of Transport Economics and Policy,* Vol. 26, No. 2, May 1992, pp. 139–154.
14. Abdelwahab, W. M. Elasticities of Mode Choice Probabilities and Market Elasticities of Demand: Evidence from a Simultaneous Mode Choice/Shipment-Size Freight Transport Model. *Transportation Research Part E: Logistics and Transportation Review,* Vol. 34, No. 4, Dec. 1998, pp. 257–266.
15. HLB Decision Economics, Inc. *Freight Benefit/Cost Study: Phase III—Analysis of Regional Benefits of Highway-Freight Improvements.* Publication FHWA-HOP-08-019. FHWA, Feb. 2008.
16. Oum, T. H. Alternative Demand Models and Their Elasticity Estimates. *Journal of Transport Economics and Policy,* Vol. 23, No. 2, 1989, pp. 163–187.
17. Figliozzi, M. A. The Impacts of Congestion on Commercial Vehicle Tour Characteristics and Costs. *Transportation Research Part E: Logistics and Transportation Review,* Vol. 46, No. 4, July 2010, pp. 496–506.
18. Middleton, D. *Strategies for Separating Trucks from Passenger Vehicles: Truck Facility Guidebook.* Texas Transportation Institute, Texas A&M University System, College Station, 2006.
19. *NCHRP Report 649: Separation of Vehicles—CMV-Only Lanes.* Transportation Research Board of the National Academies, Washington, D.C., July 2010.
20. Chu, H.-C., and M. D. Meyer. Screening Process for Identifying Potential Truck-Only Toll Lanes in a Metropolitan Area: The Atlanta, Georgia, Case. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2066,* Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 79–89.
21. Vidunas, J. E., and L. A. Hoel. Exclusive Lanes for Trucks and Cars on Interstate Highways. In *Transportation Research Record 1576,* TRB, National Research Council, Washington, D.C., 1997, pp. 114–122.
22. Holguín-Veras, J., D. Sackey, S. Hussain, and V. Ochieng. Economic and Financial Feasibility of Truck Toll Lanes. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1833,* Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 66–72.
23. De Palma, A., M. Kilani, and R. Lindsey. The Merits of Separating Cars and Trucks. *Journal of Urban Economics,* Vol. 64, No. 2, 2008, pp. 340–361.
24. Roorda, M. J., M. Hain, G. Amirjamshidi, R. Cavalcante, B. Abdulhai, and C. Woudsma. Exclusive Truck Facilities in Toronto, Ontario, Canada: Analysis of Truck and Automobile Demand. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2168,* Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 114–128.
25. Chu, H.-C., and M. D. Meyer. Methodology for Assessing Emission Reduction of Truck-Only Toll Lanes. *Energy Policy,* Vol. 37, No. 8, Aug. 2009, pp. 3287–3294.
26. *Highway Capacity Manual.* TRB, National Research Council, Washington, D.C., 2000.
27. Sugawara, S., and D. A. Niemeier. How Much Can Vehicle Emissions Be Reduced? Exploratory Analysis of an Upper Boundary Using an Emissions-Optimized Trip Assignment. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1815,* Transportation Research Board of the National Academies, Washington, D.C., 2002, pp. 29–37.
28. *Motor Vehicle Emission Simulator (MOVES) 2010 User's Guide.* Publication EPA-420-B-09-041. U.S. Environmental Protection Agency, Dec. 2009, p. 150.
29. Barlow, T., and P. Boulter. *Emissions Factors 2009: Report 2—A Review of the Average-Speed Approach for Estimating Hot Exhaust Emissions.* Publication PPR355. UK Department for Transport, London, 2009.
30. Smit, R., A. L. Brown, and Y. C. Chan. Do Air Pollution Emissions and Fuel Consumption Models for Roadways Include the Effects of Congestion in the Roadway Traffic Flow? *Environmental Modelling and Software,* Vol. 23, No. 10–11, 2008, pp. 1262–1270.
31. Horowitz, A. J. *Delay/Volume Relations for Travel Forecasting Based upon the 1985 Highway Capacity Manual.* FHWA, 1991.
32. Bai, S., Y. Nie, and D. Niemeier. The Impact of Speed Post-Processing Methods on Regional Mobile Emissions Estimation. *Transportation Research Part D: Transport and Environment,* Vol. 12, No. 5, 2007, pp. 307–324.

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