Role of Heavy-Duty Freight Vehicles in Reducing Emissions on Congested Freeways with Elastic Travel Demand Functions

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This paper investigates the effect of heavy-duty (HD) vehicles (primarily road freight) on the traffic congestion–emissions relationship. Unlike previous studies, this research explicitly considers the effects of travel demand elasticity by vehicle class on total emissions. Modeling results show that, even as a small share of the traffic volume, HD vehicles can contribute a large share of total pollution emissions, especially for particulate matter and nitrogen oxides. HD vehicle emission rates are more sensitive to congestion than are light-duty (LD) vehicle emission rates, and thus greater emissions benefits may result from mitigating congestion for these vehicles. Potentially lower travel demand elasticity with respect to speed for HD vehicles further indicates vehicle class–specific benefits from congestion mitigation. Differences between LD and HD vehicles suggest greater air quality benefits from vehicle class–targeted congestion mitigation or lane and capacity management strategies. HD vehicle travel demand elasticity is a key parameter for predicting the net emissions effects of congestion. It is strongly recommended that analysis of emissions effects from congestion mitigation strategies include class-specific volume forecasts. However, the estimation of HD vehicle travel demand elasticity values has received scant attention in the literature.

Pollution emissions from motorized vehicles degrade urban air quality and increase atmospheric greenhouse gases (GHGs). At the same time, the increase in vehicle usage in urban areas throughout the world is intensifying roadway congestion, with varying economic, social, and environmental costs. The full effects of traffic congestion on motor vehicle emissions and the potential air quality benefits of traffic congestion mitigation are the subjects of ongoing research.

Freight transportation accounts for 20% of the energy consumed by the transportation sector; for ground transportation [heavy-duty (HD) trucks only], approximately 40 billion gal of diesel fuel are consumed each year, with emissions of 400 million metric tons of carbon dioxide (CO_2) (*1*). Hence, accounting for emissions from freight vehicles is crucial in addressing concerns for air quality and public health in transportation studies. Most of the literature related to traffic congestion and vehicle emissions has focused on the impacts of the more numerous light-duty (LD) vehicles; LD vehicles in the United States are mostly gasoline-fueled passenger cars. This research also investigates the impacts of HD vehicles on total emissions by pollutant type; HD vehicles in the United States are mostly diesel-fueled commercial trucks.

This paper examines the characteristics of LD and HD vehicle emissions and their sensitivity to average travel speed. The potential contribution of HD vehicles in reducing emissions through congestion management is also assessed, with consideration of variable emissions rates and travel demand volumes.

LITERATURE REVIEW

GHG emissions inventories in the United States show that CO_2 emissions are the dominant GHG from the transportation sector, with medium-duty and HD trucks emitting 22% of domestic transportation-related CO_2 (*2*). CO_2 emissions are directly linked to fossil fuel consumption, which depends heavily on vehicle characteristics, travel speed, and road characteristics. Other transportation-related GHGs, such as nitrous oxide, are emitted in much smaller quantities but are still relevant because of stronger atmospheric effects.

In addition, concern over the health risks posed by emissions of mobile source air toxics (MSAT) is growing. MSAT are compounds emitted from mobile sources that present known or suspected health risks for humans (e.g., cancers, immune system damage, or respiratory disease). The Clean Air Act Amendments enacted in 1990 required the U.S. Environmental Protection Agency (EPA) to regulate 188 MSAT. EPA has compiled a list of several hundred compounds emitted from mobile sources (*3*). FHWA, in reviewing work by EPA, agreed on seven compounds with the greatest cancer risk from mobile sources: acrolein; benzene; 1,3-butadiene; diesel particulate matter (PM) plus diesel exhaust organic gases; formaldehyde; naphthalene; and polycyclic organic matter (*4*).

Various studies have shown that heavy congestion decreases vehicle efficiency and increases emission rates per mile of travel for conventional internal combustion engine vehicles, both LD and HD (*5–7*). HD vehicles have higher emissions rates than LD vehicles under the same conditions, largely because of higher gross vehicle weights (*8*). HD vehicles are also predominantly diesel-fueled, and diesel fuel has emissions characteristics different from those of gasoline (*9*), which powers most of the U.S. LD fleet (*10*). Previous emissions estimation using real-world traffic data showed that nitrogen oxides (NO_x) and PM emissions, especially on congested freeways,

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can be generated predominantly by commercial vehicles (*11*). In addition to congestion, vehicle weight and road grade strongly affect freight vehicle emissions (*8, 9, 12*).

Although congestion increases emissions rates, it suppresses travel demand (*13*)—and the balance of these two effects on total emissions is not well quantified. Most estimates of congestion costs and impacts consider efficiency and rate changes but neglect variable demand effects. The general consensus of published studies focusing on the congestion–emissions relationship is that the total emissions effects of congestion are either still not well understood or are highly variable (*14–16*).

Vehicle travel demand volume elasticity with respect to travel time is expected to be between −0.2 and −1.0 (*17–19*). The unique behavior response of road freight to travel time changes is less certain because few data are available and because of the complexity associated with estimating the economic impacts of freight delays. Time costs for road freight vehicles must be viewed in the context of supply chain, labor, and market costs (*20, 21*). Graham and Glaister (*18*) point out that freight travel demand in general is understudied and that while freight travel demand has traditionally been assumed to be inelastic, that is likely not the case. For intercity or regional travel, road–truck freight elasticities with respect to travel time from 0.0 to −1.0 have been reported (*22–24*). Demand elasticity with respect to generalized cost for road freight has been empirically estimated as a full order of magnitude greater than the demand elasticity with respect to travel time alone (*23*). Empirical data (*25*) and analytical models (*26*) have shown that increased congestion can lead to shorter, less efficient routes; fewer customers per route; and more commercial vehicle trips in urban areas. Hence, for certain trucking sectors such as less-than-truckload delivery or service routes, commercial vehicle travel demand elasticity with respect to travel time could be positive.

In summary, previous studies have investigated the impacts of freight vehicle characteristics and roadway characteristics on emission rates. There is still much uncertainty about the full impacts of congestion on emissions when separate vehicle classes and travel demand elasticity are also taken into account. The unique emissions and travel demand characteristics of LD and HD vehicle classes suggest a need for dissection of the congestion–emissions relationship by vehicle class. That need is the purview of this research.

EMISSIONS FUNCTIONS

In this paper, estimates of vehicle emission rates are generated with EPA's MOVES (Motor Vehicle Emission Simulator) model (*27*). The modeled pollutants are GHG in CO_2 equivalent units (CO_2e), carbon monoxide (CO), NO_x, PM smaller than 2.5 microns ($PM_{2.5}$), and hydrocarbons (HC)—encompassing most of the primary-concern MSAT. The average speed emissions modeling approach of MOVES estimates average emissions rates by using facility-specific and vehicle class–specific driving patterns (speed profiles). The driving patterns are composed of archetypal combinations of acceleration, deceleration, cruise, and idle behavior at various congestion levels on specific facility types and are based on data collected on-road in U.S. cities. Driving patterns effectively represent typical congested traffic conditions for emissions modeling, as long as they are representative of real-world driving (*28, 29*).

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. The fleet composition, segmented into LD and HD vehicles, is shown in Table 1. The LD vehicle fleet includes MOVES source type IDs below 40: motorcycles, passenger cars, passenger trucks, and single-unit two-axle LD commercial trucks under 19,500 lb gross vehicle weight rating (GVWR). The HD vehicle fleet includes MOVES source type IDs above 40: buses, combination trucks, and other HD trucks exceeding 19,500 lb GVWR. With this partition, 8.9% of the full fleet is made up of HD vehicles, similar to the U.S. average of 8% of vehicle miles traveled by trucks on urban freeways (*1*). For the sake of generality and because fleet compositions can differ across facilities and by location, later results vary the proportion of HD vehicles from 0% to 50%.

TABLE 1 Modeled Distribution of Vehicle Types

MOVES Source Type	Vehicle Type	Fuel	% of Fleet
Light-Duty Vehicles			
11	Motorcycle	Gasoline	0.43
21	Passenger car	Gasoline	52.83
21	Passenger car	Diesel	0.21
31	Passenger truck	Gasoline	27.92
31	Passenger truck	Diesel	0.28
32	Light commercial truck	Gasoline	8.86
32	Light commercial truck	Diesel	0.57
Heavy-Duty Vehicles			
41	Intercity bus	Diesel	0.04
42	Transit bus	Diesel	0.03
43	School bus	Diesel	0.29
51	Refuse truck	Diesel	0.07
52	Single-unit short-haul truck	Gasoline	1.00
52	Single-unit short-haul truck	Diesel	2.34
53	Single-unit long-haul truck	Gasoline	0.06
53	Single-unit long-haul truck	Diesel	0.14
61	Combination short-haul truck	Diesel	2.84
62	Combination long-haul truck	Diesel	2.11

The MOVES model generates emissions rate estimates in 16 average speed bins for each emissions source type (combination of vehicle type and fuel type) on urban freeway (restricted) facilities. The average speed bins are in 5-mph increments, up to 75 mph. The modeled emissions are running exhaust and evaporative emissions. National average and county-specific (for Multnomah County, Oregon) values are used for other model inputs (meteorology, vehicle inspection and maintenance program, fuel formulation, vehicle age distributions, etc.).

On the basis of previous emissions research (*5, 30*), the functional form for vehicle class average spatial emissions rates, e_j, as a function of vehicle class average speed, v_j, for each vehicle class *j* is

$$e_j(v_j) = \exp\left(\sum_{i=0}^{4} a_{i,j} \cdot v_j^i\right) \qquad (1)$$

where $a_{i,j}$ are fitted parameters, e_j is in grams per vehicle mile, and v_j is in miles per hour. Note that v_j does not represent constant-speed driving but is instead an average speed representing facility-specific archetypal driving speed profiles.

From the MOVES-generated emissions rate–average speed (e_j, v_j) data points, the parameters $a_{i,j}$ in Equation 1 are estimated by using a least squares fit for all five pollutants and each vehicle class, and

TABLE 2 Fitted Parameters for Emissions–Speed Curve on Freeways

Parameter	CO_2e	CO	$PM_{2.5}$	NO_x	HC
Light-Duty 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
$a_{3,l}$	-9.550×10^{-5}	-1.077×10^{-4}	-1.157×10^{-4}	-6.270×10^{-5}	-9.570×10^{-5}
$a_{4,l}$	5.210×10^{-7}	6.460×10^{-7}	6.560×10^{-7}	3.440×10^{-7}	5.510×10^{-7}
Heavy-Duty 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
$a_{3,h}$	-1.007×10^{-4}	-1.097×10^{-4}	-1.141×10^{-4}	-1.003×10^{-4}	-1.018×10^{-4}
$a_{4,h}$	5.740×10^{-7}	6.201×10^{-7}	6.870×10^{-7}	5.599×10^{-7}	5.380×10^{-7}

$R^2 > .96$ is obtained 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 2 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 (because start, refueling, and hot and cold soak emissions were not modeled, results are relatively insensitive to weather). Meteorology will play a key role in pollutant dispersion and secondary pollutant formation (e.g., ozone), but those phenomena are outside the scope of this study.

EMISSIONS RATE COMPARISONS

This section compares the differing emissions rates of LD and HD vehicle classes: the set of vehicle classes is $J = \{l, h\}$, where l and h denote LD ($j = l$) and HD ($j = h$) vehicles, respectively. The two vehicle classes have average emissions rates e_l and e_h and average travel speeds v_l and v_h. On the basis of the parameters given in Table 2, Figure 1 shows the emissions rate relationships between LD and HD vehicle classes and average speed. Figure 1 plots the ratio of HD to LD emissions rates, e_h/e_l, for all five pollutants versus average speed $\bar{v}$. It is assumed that the average speed is the same across vehicle types (i.e., $v_l = v_h = \bar{v}$).

From Figure 1 it is clear that the emissions rate ratio e_h/e_l is a function of both average travel speed and pollutant type. The largest emissions rate differences are found for $PM_{2.5}$ and NO_x; Figure 1 indicates that, on average, one HD vehicle can produce as much $PM_{2.5}$ and NO_x pollution per mile as 60 or 28 average LD vehicles, respectively. The generally negative slopes of the curves in Figure 1 show that low-speed inefficiency is proportionally greater for HD vehicles. In other words, HD vehicles' emissions rates increase proportionally more in congestion. HC emissions rates are four to eight times greater for HD vehicles than LD vehicles (per vehicle mile), and CO_2e emissions rates are about four times greater for HD vehicles. Only CO emissions rates are somewhat similar between the two vehicle classes (with a ratio of 1 to 2).

Some of the differences in Figure 1 relate to the greater fuel consumption required to move heavier vehicles, as evidenced by four times higher CO_2e emissions rates (which are closely tied to fuel consumption). Another main cause of the differences in $PM_{2.5}$ and

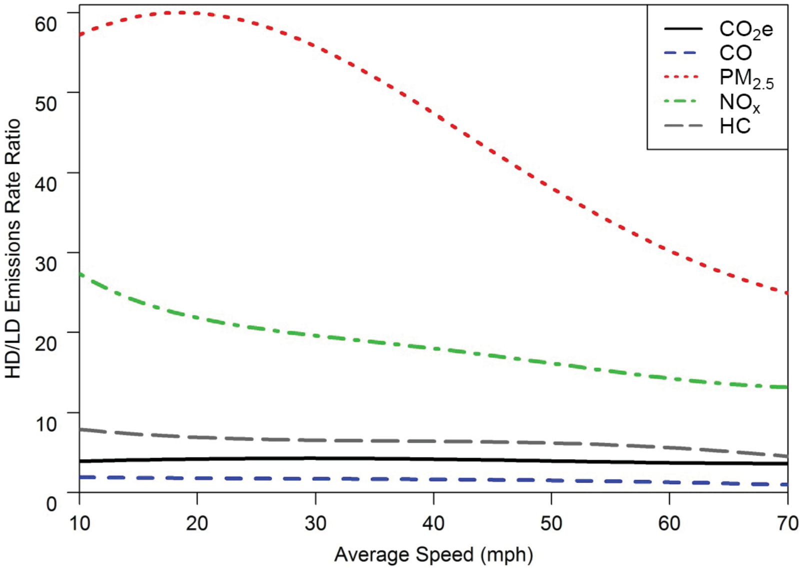
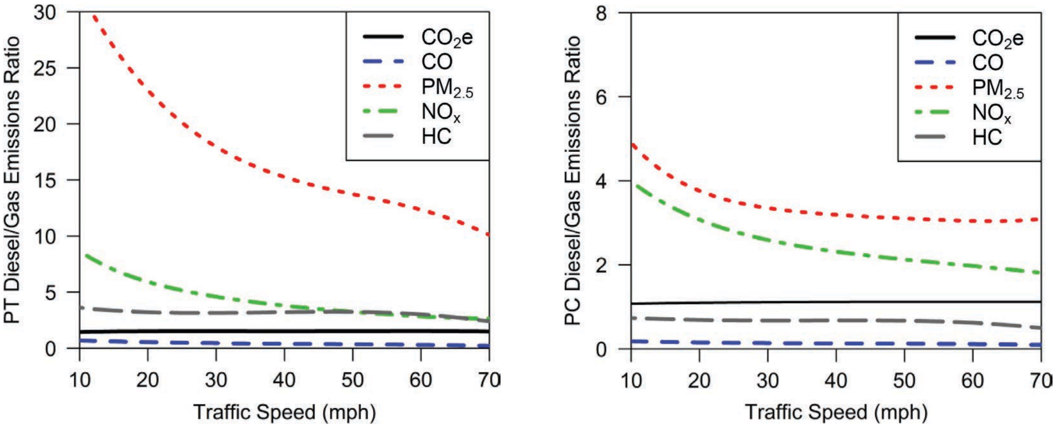


FIGURE 1 Ratio of HD to LD emissions rates versus average speed.



(a) (b)

FIGURE 2 Diesel-to-gasoline vehicle emissions rate ratios for (*a*) passenger trucks and (*b*) passenger cars.

NO$_x$ emissions rates is the dominance of diesel-fueled compression–ignition engines in the HD vehicle fleet and gasoline-fueled spark–ignition engines in the LD vehicle fleet. As an illustration of the impact of fuel and engine type, Figure 2 shows the emissions rate ratios for diesel-fueled versus gasoline-fueled passenger cars (PC) and passenger trucks (PT), both of which are in the LD vehicle class. The figure uses vehicle classes of gasoline PC (j = pcg), diesel PC (j = pcd), gasoline PT (j = ptg), and diesel PT (j = ptd). Figure 2*a* shows emissions rate ratios for diesel and gasoline PT, $e_{\text{ptd}}/e_{\text{ptg}}$, versus average speed $\bar{v}$; Figure 2*b* shows emissions rate ratios for diesel and gasoline PC, $e_{\text{pcd}}/e_{\text{pcg}}$, versus $\bar{v}$ (it is assumed that $\bar{v} = v_{\text{pcg}} = v_{\text{pcd}} = v_{\text{ptg}} = v_{\text{ptd}}$). The different vertical scales in Figure 2 reflect that the differences between diesel and gasoline are more pronounced for PT than for PC.

For both PC and PT, PM$_{2.5}$ and NO$_x$ have the highest emissions rate ratios for diesel versus gasoline, though the ratios are many times greater for PT than for PC. CO$_2$e emissions rates are similar for the two fuel types, while CO emissions rates are lower for diesel vehicles. As with the HD-to-LD emissions rate ratios in Figure 1, the differences in emissions rates are magnified at lower average speeds. Thus, diesel LD vehicle emissions are proportionally more affected by congestion than are gasoline LD vehicle emissions.

The contribution of HD vehicles to total emissions is shown in Figure 3 as the fraction of total per mile emissions that are from HD vehicles. Let f_j be the fractional per mile fleet composition of vehicle class j. For $J = \{l, h\}$, the fraction of total per mile emissions that are from vehicle class h is $f_h e_h/(f_l e_l + f_h e_h)$. This fraction is shown in Figure 3 versus average speed, under the assumption of 8.9% HD vehicles (i.e., $f_h = 0.089$). It is also assumed that $v_l = v_h = \bar{v}$.

Even at less than 10% of the fleet, HD vehicle emissions dominate total PM$_{2.5}$ and NO$_x$ emissions per mile (around 80% and 70%, respectively). LD vehicle emissions dominate total CO and CO$_2$e emissions. HC emissions are more balanced than are emissions of other pollutants and are about evenly split between LD and HD vehicles when $f_h = 0.12$. Almost all pollutants trend downward; because HD vehicle emissions rates increase proportionally more in congestion (Figure 1), there is a higher HD share of total emissions in congestion.

Figure 4 shows how the full-fleet emissions–speed curves (ESCs) change with the fraction of HD vehicles, f_h. In addition to the emissions

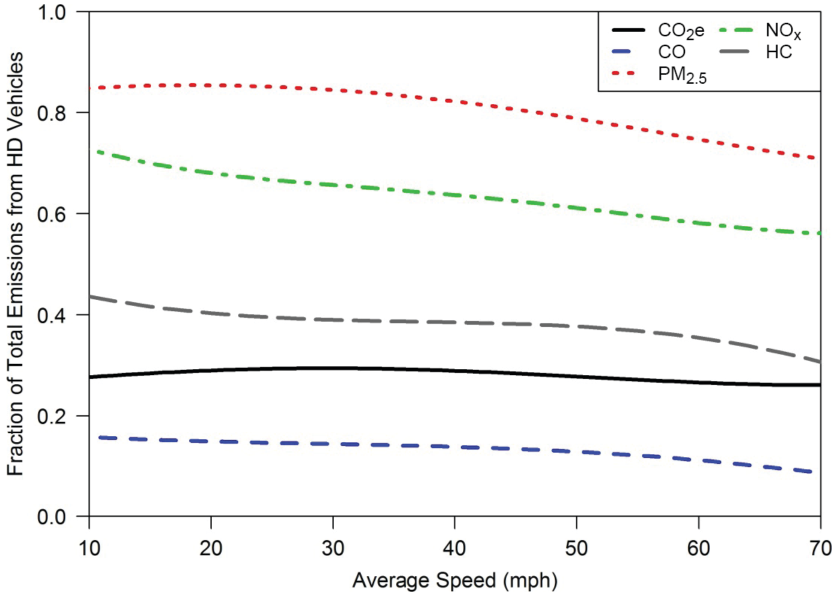
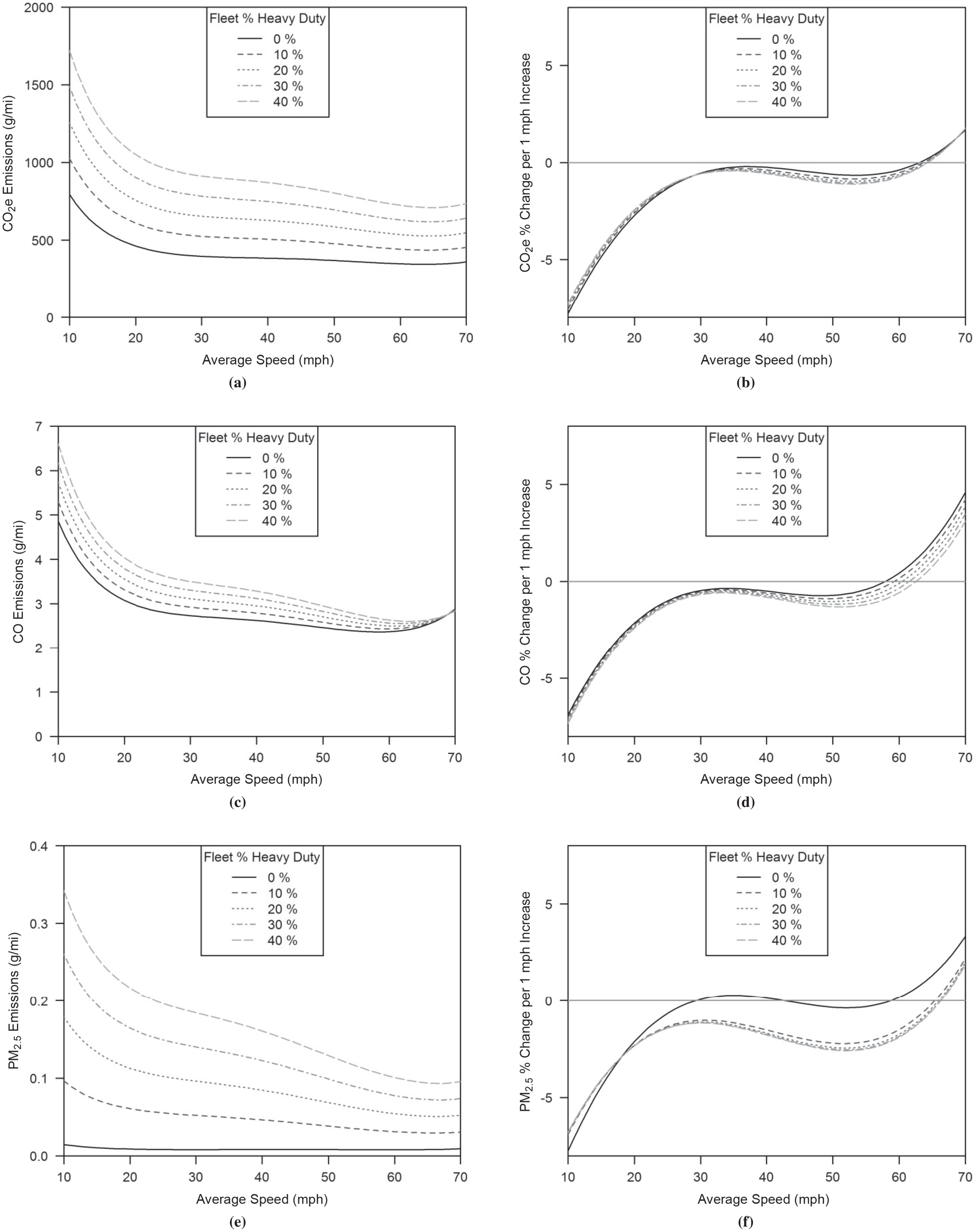


FIGURE 3 Fraction of total emissions from HD vehicles versus average speed.



(a) (b)

(c) (d)

(e) (f)

FIGURE 4 Total fleet emissions rate sensitivity to fraction of HD vehicles: (*a*) CO$_2$e emissions–speed curve, (*b*) CO$_2$e emissions–speed gradient, (*c*) CO emissions–speed curve, (*d*) CO emissions–speed gradient, (*e*) PM$_{2.5}$ emissions–speed curve, and (*f*) PM$_{2.5}$ emissions–speed gradient.

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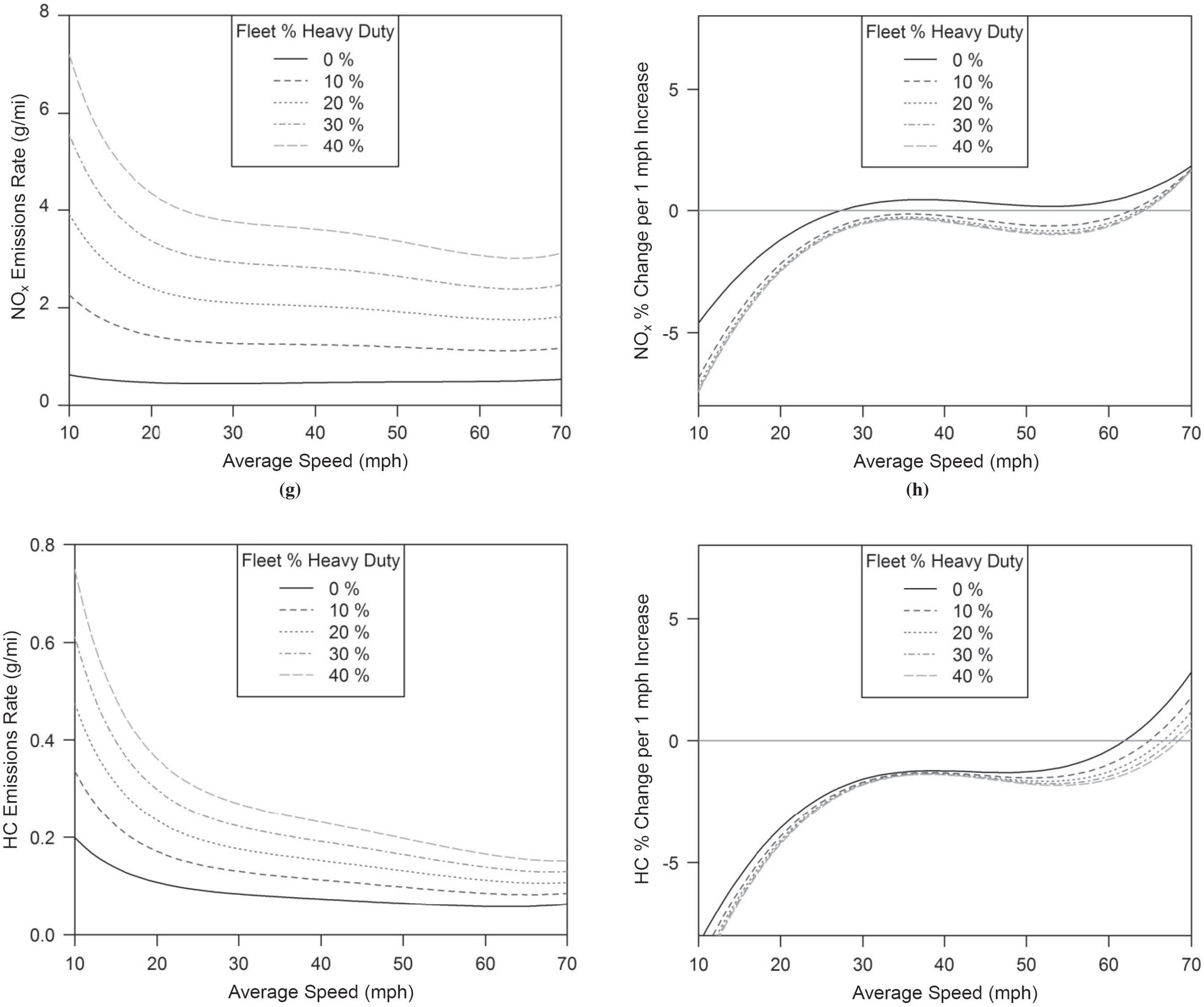


(g) (h)

(i) (j)

FIGURE 4 *(continued)* **Total fleet emissions rate sensitivity to fraction of HD vehicles: (*g*) NO_x emissions–speed curve, (*h*) NO_x emissions–speed gradient, (*i*) HC emissions–speed curve, and (*j*) HC emissions–speed gradient.**

rate curves, Figure 4 shows ESC gradients versus speed—expressed as the percentage change in average emissions rate with each 1-mph speed increase. As expected, a higher fraction of HD vehicles f_h increases full-fleet emissions rates. The emissions rate increases with f_h are proportionally larger for pollutants with higher HD-to-LD emissions rate ratios, e_h/e_l, in Figure 1 ($PM_{2.5}$ and NO_x).

Total fleet emissions rate sensitivity to speed also increases with HD vehicle fraction f_h. This is evidenced by the larger absolute values of the gradients in Figure 4. That effect is also expected because HD vehicles are more sensitive to average speed (Figure 1). For $PM_{2.5}$ and NO_x (which are dominated by HD vehicle emissions), the gradient changes most dramatically with the initial introduction of HD vehicles; compare the ESC gradients at $f_h = 0$ and $f_h = 0.1$ for these pollutants. The emissions-optimal speed also increases with f_h—shown by the gradients crossing the horizontal (speed) axis at higher values with higher percentage HD. The curves in Figure 4 are for a highly aggregate vehicle fleet, however, and optimal travel speeds will depend on the road grade and on more detailed vehicle characteristics such as trailer loads (*9*).

The greatest potential for emissions rate reductions from speed increases (congestion mitigation) is observed below a speed of 30 mph. This observation is consistent across the five pollutants, as is indicated by the most negative values for ESC gradients in Figure 4. Emissions rates are less sensitive to speed at moderate speeds above 30 mph, and they increase with speed above 65 mph—again indicated by the ESC gradients.

Figure 4 shows that traffic streams with more HD vehicles potentially have greater per mile emissions benefits from increasing average travel speeds through congestion mitigation. Because of their different emissions rate–speed relationships demonstrated in previous figures, LD and HD vehicles could also be targeted separately by using lane and capacity management for congestion mitigation with air quality objectives. However, to assess the effects of congestion on total emissions, variable travel demand volume must also be considered.

TOTAL EMISSIONS AND TRAVEL DEMAND

This section examines how varying both vehicle emissions rates and travel demand volume with average speed affects the total emissions–congestion relationship. Increasing average travel speeds are expected to decrease emissions rates per mile, but they also increase travel demand volume. The combined effect is assessed by using the concept of emissions "break-even" conditions. The emissions break-even travel demand elasticity with respect to speed is the condition for which total emissions are unaffected by average travel speed increases because induced travel demand volume exactly offsets decreased emissions rates. When true demand elasticity with respect to speed exceeds the break-even demand elasticity, total emissions will increase with travel speed because of the dominance of induced demand. When true demand elasticity with respect to speed is lower than the break-even demand elasticity, total emissions will decrease with a travel speed increase because of the dominance of increased efficiency (indicating potential emissions benefits from congestion mitigation). This section discusses the travel demand elasticity with respect to average travel speed, which is the negative of the travel demand elasticity with respect to travel time discussed in the literature review.

Figure 5 shows the vehicle class–specific freeway emissions break-even demand elasticity for CO_2e, calculated as $-(v_j/e_j)(\partial e_j/\partial v_j)$ (*31*). Inspection of Figure 5 reveals the average speed and demand elasticity value combinations for which capacity-based congestion mitigation is expected to increase or decrease total emissions for each vehicle class. Four areas can be distinguished in Figure 5: *a,* a speed increase will lead to net emissions reductions for both HD and LD vehicles; *b* and *c,* a speed increase will lead to net emissions reductions for only one vehicle class (HD or LD) and emissions increases in the other; and *d,* a speed increase will lead to net emissions increases for both HD and LD vehicles.

Break-even demand elasticity for the other pollutants is shown in Figure 6. The plots for CO, NO_x, and HC in Figure 6 contain only three of the areas in Figure 5: *a, c,* and *d.* Note the larger vertical scale in Figure 6 to accommodate the wider range of break-even elasticities. The vertical distance between the break-even demand elasticity curve and the true demand elasticity is the elasticity of total emissions with respect to average travel speed: the greater the distance, the greater the emissions impact, positive or negative (*31*).

Figures 5 and 6 show that in most cases the break-even demand elasticity for HD vehicles is higher than for LD vehicles. This is the result of HD vehicles being proportionally more inefficient at lower speeds (i.e., more sensitive to congestion). Because of this difference, there is a range of true demand elasticity values between the curves for which total LD vehicle emissions would be expected to increase but total HD vehicle emissions to decrease with increasing travel speeds—Area *c*. This gap is largest for $PM_{2.5}$ emissions. NO_x has the lowest break-even demand elasticity curves in Figure 6, while $PM_{2.5}$ and HC have the highest (for HD vehicles). For a reasonable range of demand elasticity with respect to speed for each vehicle class, total emissions are much more likely to decrease from congestion mitigation for HC than NO_x. $PM_{2.5}$ and NO_x have little opportunity for reduction from LD vehicles, but reasonably good opportunities for HD vehicles. Thus, although the HD vehicle emissions rates are much higher for some pollutants, the potential for total emissions reductions through congestion mitigation can be higher for HD vehicles, too—depending on the true demand elasticity of each vehicle class.

As discussed in the literature review section, freight demand elasticity estimates are highly uncertain. However, there is some empirical and theoretical evidence indicating that freight travel demand is less elastic than passenger travel demand with respect to travel speed changes and may even have a negative relationship with speed for some industries. A lower true demand elasticity with respect to speed for HD vehicles improves the potential for emissions reductions through congestion mitigation for HD vehicles.

Greater emissions rate sensitivity to speed and lower demand elasticity with respect to speed both indicate greater potential emissions benefits from speed increases for HD vehicles than for

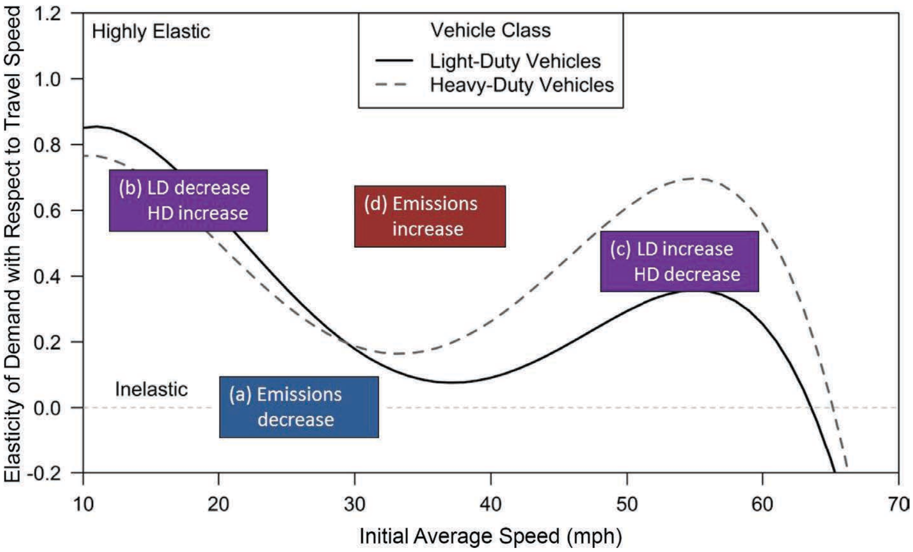
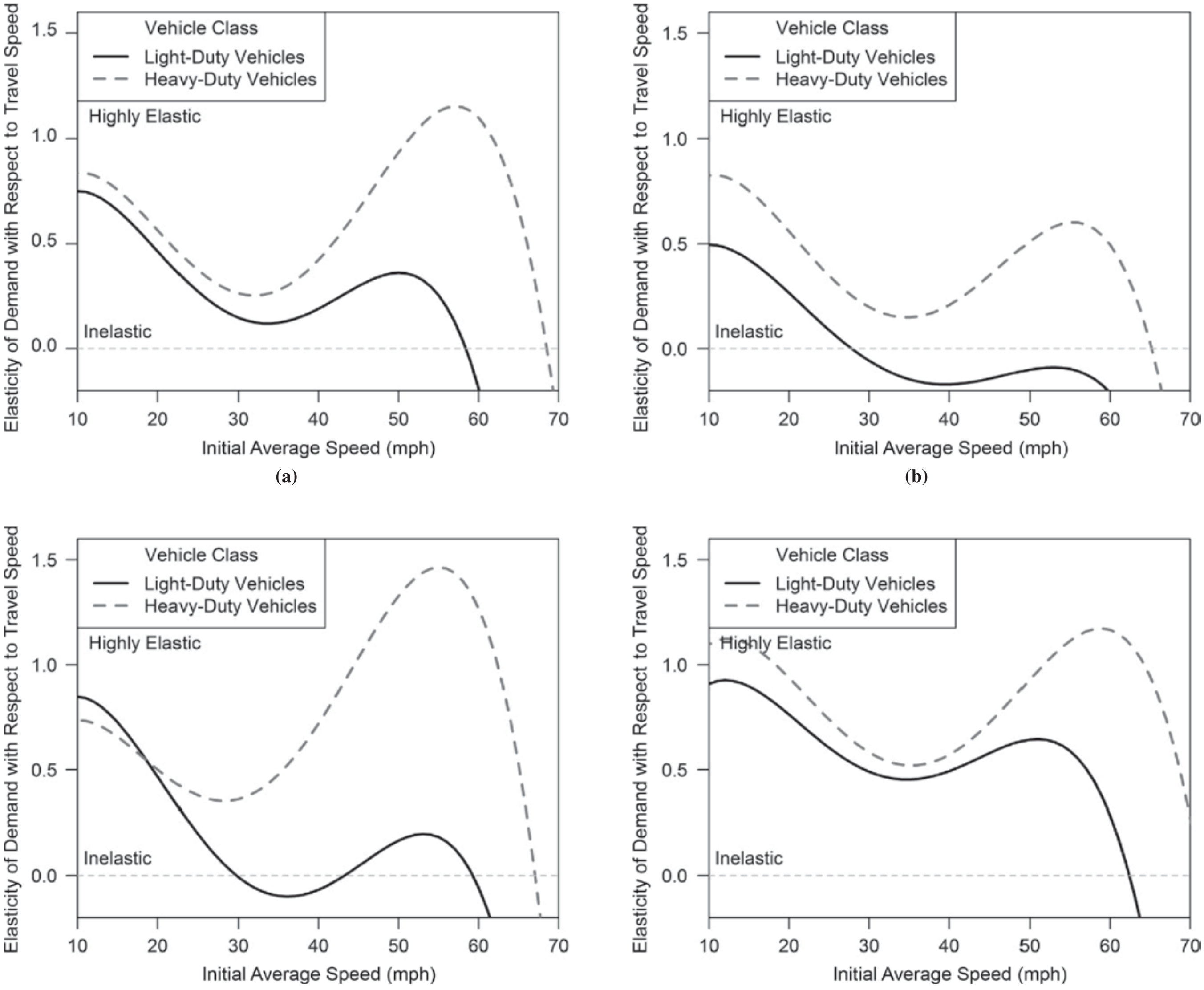


FIGURE 5 Vehicle class–specific emissions break-even demand elasticity for CO_2e.



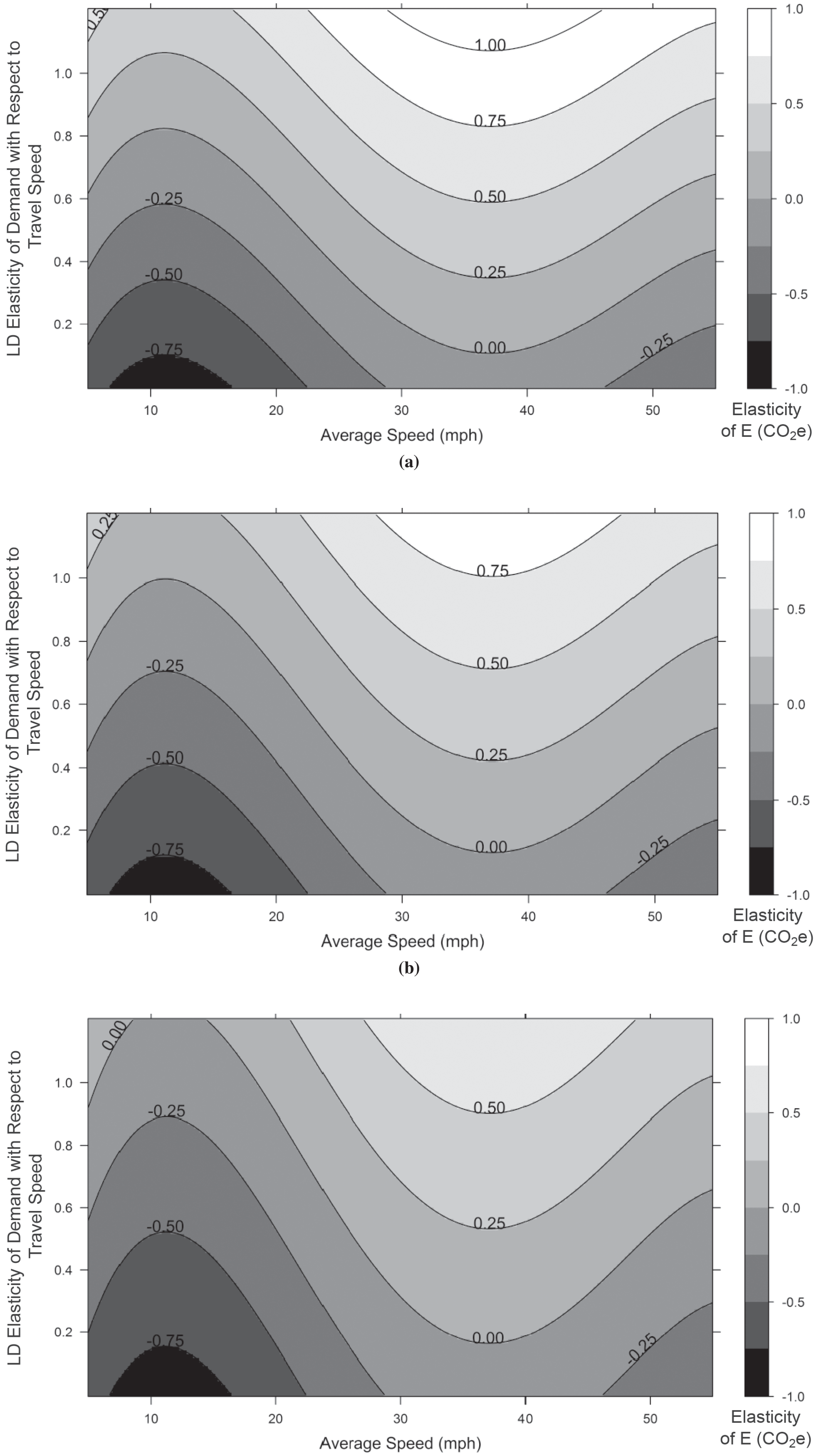
(a) (b) (c) (d)

FIGURE 6 Vehicle class–specific emissions break-even elasticities for other pollutants: (*a*) CO, (*b*) NO_x, (*c*) $PM_{2.5}$, and (*d*) HC.

LD vehicles. With non-class-specific congestion mitigation, a net emissions increase from one vehicle class (LD) can be offset by a net emissions decrease from the other (HD). In this case, cumulative emissions changes will depend on each vehicle class's share of total emissions (Figure 3). If HD vehicle emissions are being reduced while LD vehicle emissions are increasing, the greatest benefits will be for pollutants with a larger fraction of total emissions from HD vehicles (e.g., $PM_{2.5}$ and NO_x).

Figure 7 illustrates the impact of different demand elasticity by vehicle class on cumulative emissions changes. Figure 7 shows the elasticity of total CO_2e emissions (E) with respect to uniform travel speed changes, including changing emissions rates and travel demand volumes. The total emissions elasticity with respect to speed is shown as shaded contours for varying LD vehicle demand elasticity (vertical axis) and average travel speed (horizontal axis) under the assumptions of $f_h = 0.1$ (10% HD vehicles) and equivalent speeds, $v_l = v_h = \bar{v}$. Negative values of total emissions elasticity indicate a net emissions reduction with speed increases, while positive values indicate net emissions increases with speed. Figures 7*a, b,* and *c* present the results on the assumption of (*a*) equal demand elasticity by vehicle class, (*b*) HD vehicle demand elasticity at half of LD vehicle demand elasticity, and (*c*) inelastic HD vehicle demand, respectively.

Even at just 10% of the fleet, lower HD vehicle demand elasticity substantially increases the potential GHG emissions benefits of travel speed increases (i.e., lower total emissions elasticity with respect to speed). While Figure 7*a* has only a small area with likely emissions benefits from speed increases, Figure 7*c* has a much larger area with negative emissions elasticity with respect to speed—and where emissions elasticity is positive in Figure 7*c,* it is smaller than in Figure 7*a.* The results in Figure 7 are for CO_2e emissions, of which about 30% come from HD vehicles (Figure 3). The impact is even greater for $PM_{2.5}$ and NO_x because HD vehicles dominate those emissions.



(a)

(b)

(c)

FIGURE 7 CO_2e emissions elasticity with respect to speed with 10% HD vehicles and HD vehicle demand elasticity at (*a*) 100%, (*b*) 50%, and (*c*) 0% of LD vehicle demand elasticity.

CONCLUSIONS

This paper assesses the impacts of LD and HD vehicle classes on the congestion–emissions relationship, including variable emissions rates and travel demand. Compared with LD vehicle emissions rates, HD vehicle emissions rates range from roughly equal (for CO) to up to 60 times greater (for $PM_{2.5}$). This difference is partly due to the dominance of diesel fuel in the HD vehicle fleet. Even as a minority of vehicles in the fleet, HD vehicles contribute a large share of total per mile on-road emissions: around 80% for $PM_{2.5}$ and 70% for NO_x with 9% HD vehicles.

HD vehicle emissions rates are more sensitive to average speed than are LD vehicle emissions rates, leading to higher emissions break-even demand elasticities for HD vehicles and potentially greater emissions benefits from congestion mitigation. If HD vehicle travel demand elasticity with respect to speed is lower than that of LD vehicles, the potential emissions benefits of congestion mitigation for HD vehicles are even greater. These differences between LD and HD vehicles suggest air quality benefits from vehicle class–targeted congestion mitigation or lane–capacity management strategies such as truck-only lanes or traffic signal prioritization for heavy vehicles.

Similarly, the combined vehicle fleet is more sensitive to speed (and has more potential emissions benefits from congestion mitigation) with greater fractions of HD vehicles. Whether capacity-based congestion mitigation increases or decreases total emissions depends on the travel demand elasticity with respect to speed. Where congestion management leads to reduced HD vehicle emissions and increased LD vehicle emissions, the net effect on emissions is more likely to be beneficial for the HD vehicle–dominated pollutants ($PM_{2.5}$ and NO_x). This also means that total emissions of these pollutants are most likely to increase in heavier congestion. The sensitivity of these results to HD vehicle demand elasticity shows that a complete analysis of emissions mitigation strategies must include class-specific volume forecasts. Unfortunately, HD vehicle travel demand elasticity is a key parameter that has received scant attention in the literature.

The analysis in this paper uses modeled emissions rates from an example 2010 on-road vehicle fleet. Actual emissions rates will vary with a number of factors, including local fuels, vehicles, road grades, and weather. Nevertheless, the main causes of emissions differences between LD and HD vehicles (greater fuel consumption and diesel-related pollutants for HD vehicles) will hold across a range of conditions, so the primary results and conclusions of this paper are expected to apply broadly.

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