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Impact of Managed-Lane Pricing Strategies on Vehicle-Sourced NO_x and HC Emissions

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Abstract: Ground-level ozone is a secondary air pollutant that is formed by chemical reactions between precursors, including nitrogen oxides (NO_x) and hydrocarbon (HC). Highway traffic, which can be controlled by traffic operational strategies, is one of the main sources of atmospheric NO_x and HC. Managed-lane pricing is one of the popularly used freeway traffic management approaches, while its impacts on ground-level ozone-related vehicle emissions is, however, still unclear. This motivated the purpose of this research. A case study in Houston, USA indicates that, vehicles on managed lanes had fewer hard accelerations/decelerations and higher average speed, which resulted in higher per-vehicle emissions in grams/hour, while the total emissions of a vehicle were roughly comparable to what they would be on a general-purpose lane. Total daily NO_x and HC emissions per managed lane were 31.9%–42.6% of those per general-purpose lane. The weight ratios between HC and NO_x show that, the ground-level ozone formation of this area is hydrocarbon-limited.

Keywords: ground-level ozone precursors; air pollution; managed lane; HOT lane; general purpose lane; vehicle emission

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1. Motivation and Related Works

One of the most critical environmental issues that human beings have encountered is air pollution. Ground-level ozone or tropospheric ozone is an air pollutant that is capable of inducing various deleterious consequences, including shortness of breath, lung damage, and asthma [1]. Unlike most air pollutants, the major amount of ground-level ozone pollution was formed in the atmosphere by several chemicals, including nitrogen oxide (NOx) and volatile organic compounds (VOC), mainly hydrocarbon (HC) [2] in the presence of sunlight rather than directly emitted from sources [3]. These chemicals are also called ozone precursors [4]. Due to numerous hazards that are triggered by ground-level ozone [5–8], strategies to decrease its concentration are demanded. While only a small amount of ground-level ozone is naturally sourced, fossil fuel combustion such as vehicle exhausts, power plant emitters, and oil refineries are the primary sources of ground-level ozone precursor chemicals [9]. On-road vehicle mobile emissions are responsible for a large number of various air pollutions that include ozone precursor chemicals. Among all the ground transportations options, highway traffic plays an important role in generating a significant amount of vehicle emissions [10]. As of 2016, $\frac{1}{4}$ of all vehicles' on-road miles in the US are driven on the highway systems [11]. Various highway-traffic control strategies can effectively reduce vehicle emissions, such as road pavement upgrading, ramp metering strategy, and weaving areas [12,13]. Managed-lane-related strategies such as the High Occupancy Vehicle (HOV) lane, High Occupancy Toll (HOT) lane, and Bus Rapid Transit (BRT) lane are widely used as highway-traffic control strategies to reduce congestions and mobile source emissions [14–16].

Air pollution sourced from human activities is also called anthropogenic air pollution, which is considered the most critical environmental issue nowadays [17–20]. Mobile-source air pollution, especially the on-road vehicle emission that is based on fossil fuel combustion, causes more than 50% of total air pollution in the USA [21] and accounts for 50–90% of total urban air pollution [22]. HC and NO_x are the predominant emissions from gasoline-fueled vehicles based on previous research [23]. In early research, the California Air Resources Board (CARB) concluded that 25% of its statewide emission of total organic gas emissions and 60% of its NO_x emissions were from on-road vehicles [23]. HC and NO_x are not only harmful to the environment by themselves, but they are also precursors of ground-level ozone, which is notorious for its significant adverse effects that impact on climate, the human respiratory system, and the ecosystem due to its solar radiation absorption [24], strong oxidation [25], and toxic nature [5]. Unlike most other air pollutants, ground-level ozone is not emitted from its sources directly. It is formed by a series of reactions between its precursors in the presence of sunlight that is called photochemical ozone creation (POC) [26]. Thus, to control ground-level ozone pollution, it is useful to limit the NO_x and HC emissions from all sources, especially mobile sources in urban areas.

Due to the important role of on-road transportation on air pollution, the systematic control of on-road traffic becomes one of the most effective ways to reduce ground-level ozone precursors and other forms of pollution [27,28]. Various strategies were introduced to control the traffic, aiming to keep vehicle speed more consistent and reduce travel time. The priced managed lane collecting tolls based on the level of on-road congestion or time of day to maintain the in-lane level of service was first introduced during the 1990s along with the wide reorganization of the congestion-management effects of pricing [13,29]. Compared to general-purpose lanes, the managed-lane strategy may significantly improve congestion and travel delay [30,31]. Currently, the HOV and HOT lanes are the most prevalent form of the managed lane in the USA [32]. Different from the HOV lane that restricts the lane usage by only the occupancy, the HOT lane combines the occupancy, price, and access restrictions to control the number of vehicles traveling on it [29]. Usually, HOT and HOV work together to lower the toll price for vehicles that meet the occupancy requirements. Drivers may use the pricing message signs to decide whether or not to drive on the HOT lane [33]. When compared to general-purpose lanes, price-managed lanes may reduce vehicles' greenhouse gases by limited stop-and-go traffic [32]. Previous researches show that the managed-lane strategy may affect some kinds of air pollutants. For example, Sinprasertkool [34] revealed that higher toll rates might reduce overall CO emission, while research based on a CORSIM simulation conducted by Lee et al., 2010, concluded that the NO_x, CO, and HC emissions are lower in the managed lane [35]. In addition, research conducted by Alexander et al., 2013, revealed that the emission effects of managed-lane strategies vary by pollutants and lane-management strategies [36]. On the contrary, research conducted by Stuart et al., 2010, in Florida, USA, claimed that the managed-lane strategy has small impacts on air quality [37]. Furthermore, Xu et al., 2017, discovered that the HOT lane strategy might increase the mass emissions on the corridor while the CO_2 emission might be reduced by a minimal level when comparing to the HOV lane strategy [38].

The impact of managed-lane strategies, especially the HOT lane, on air pollution is critical but is nevertheless insufficiently studied. Discovering the effects of the HOT managed-lane strategy on ground-level ozone precursors that include NO_x and HC is currently in urgent need. In this paper, the characteristics of the on-road emission of HOT lanes are analyzed and summarized. Based on the findings of this research, the environmental effects of the pricing-controlled managed-lane strategies can be identified by the stakeholders, and the toll rates of HOT lanes can be determined by decision-makers considering to optimize both in-lane level-of-service and vehicles' emissions.

2. Methodology

2.1. Data Collection

2.1.1. Test Route Information

Houston, Texas, USA is one of the most polluted urban areas in terms of ground-level ozone in the United States [39]. Houston is currently operating a total of 120 miles

(193 km) of managed lanes in its highway system [40], including the Katy Freeway Managed Lane as part of the Interstate Highway 10 (I-10). In this study, on-road driving tests were conducted on a segment of the Katy Freeway in Houston, which contains two managed lanes and five general-purpose lanes. Both Eastbound- and Westbound-managed lanes are HOV/HOT shared with EZ TAG to pay tolls. Vehicles with two or more passengers can use the managed lane for free during specific periods of a weekday. Figure 1 shows the detailed information of the test location.

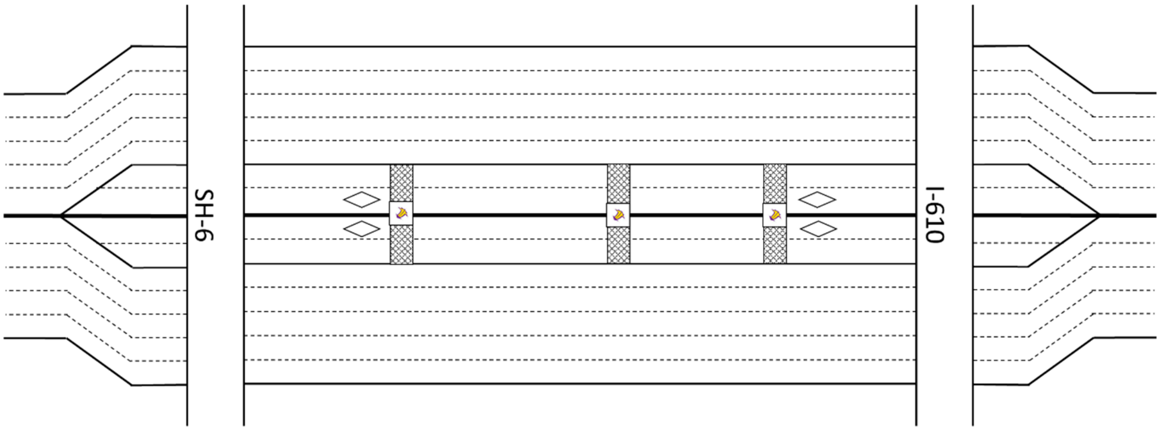

Figure 1. Sketch of Katy Freeway along I-10.

Table 1. Detailed tolling rates on I-10 HOT lane in Houston, TX.

Eldridge Tolling Plaza	Eastbound	6:00 a.m. Mon–Fri	2.1 USD	Other periods: 0.4 USD
		7:00 a.m. Mon–Fri	3.2 USD	
		8:00 a.m. Mon–Fri	2.6 USD	
		9:00 a.m. Mon–Fri	1.5 USD	
	Westbound	3:00 p.m. Mon–Fri	2.1 USD	
		4:00 p.m. Mon–Fri	3.2 USD	
		5:00 p.m. Mon–Fri	3.2 USD	
		6:00 p.m. Mon–Fri	2.1 USD	
Wilcrest and Wirt Tolling Plazas	Eastbound	6:00 a.m. Mon–Fri	1.2 USD	Other periods: 0.3 USD
		7:00 a.m. Mon–Fri	1.9 USD	
		8:00 a.m. Mon–Fri	1.9 USD	
		9:00 a.m. Mon–Fri	1.0 USD	
	Westbound	3:00 p.m. Mon–Fri	1.2	
		4:00 p.m. Mon–Fri	1.9	
		5:00 p.m. Mon–Fri	1.9	
		6:00 p.m. Mon–Fri	1.2	

As Figure 1 shows, the test route was a segment of Katy Freeway (also called Interstate Highway I-10) between Interstate Highway I-610 and Texas State Highway 6. The total length of the testing segment is 12.2 miles (19.6 km) for each direction. There are three tolling plazas within this segment: (1) the Eldridge Tolling Plaza; (2) the Wilcrest Tolling Plaza; (3) the Wirt Tolling Plaza. The toll rates are currently following a dynamic-tolling strategy depending on the hours of a day. The toll rate for three-plus axle vehicles is set at 7.00 USD per tolling plaza all the time. The two-axle vehicle rates are subject to change based on traffic conditions. Table 1 shows detailed tolling rates.

In Table 1, the tolling rates for Eastbound lanes from 6:00 a.m. to 10:00 a.m. and Westbound lanes from 3:00 to 7:00 p.m. are higher than all other periods. Five types of rates are in use for the whole test segments.

- 3.5 USD for weekdays 9:00–10:00 a.m. Eastbound;
- 4.5 USD for weekdays 6:00–7:00 a.m. Eastbound and 3:00–4:00 p.m., 6:00–7:00 p.m. Westbound;

- 6.4 USD for weekdays 8:00–9:00 a.m. Eastbound;
- 7 USD for weekdays 7:00–8:00 a.m. Eastbound and 4:00–6:00 p.m. Westbound; and
- 0.7 USD for all other times.

2.1.2. Test Plan

The test scenarios are designed by the toll rates mentioned above. Two experienced drivers were recruited to perform the field test driving two light-duty vehicles (2014 TOYOTA 4 Runner and 2012 TOYOTA Camry). The testing equipment included a GPS receiver, a dashcam, a laptop, and a smartphone. The field tests were performed on sunny weekdays of June and July in 2019. The field test contained five scenarios, which are listed in Table 2.

Table 2. Designed scenarios for tests.

Scenario Number	Scene Class	Lane	Toll Rate
1	Test scene	HOV/HOT lane	0.7 USD
	Control scene	Parallel general-purpose lanes	Free
2	Test scene	HOV/HOT lane	3.5 USD
	Control scene	Parallel general-purpose lanes	Free
3	Test scene	HOV/HOT lane	4.5 USD
	Control scene	Parallel general-purpose lanes	Free
4	Test scene	HOV/HOT lane	6.4 USD
	Control scene	Parallel general-purpose lanes	Free
5	Test scene	HOV/HOT lane	7 USD
	Control scene	Parallel general-purpose lanes	Free

In Table 2, there were five scenarios designed in response to the five toll rates. Each scenario includes the test scene performed on the managed lane and the control scene performed on the general-purpose lane. For all scenarios, the two test vehicles performed the tests simultaneously. One drove on the managed lanes; another one drove on the general-purpose lanes. To eliminate unexpected, accidental traffic situations, the field tests were designed to drive for three rounds for each scenario, and the average geolocation-based speed data from these three rounds are used for further analyses.

2.2. Vehicle Emission Calculation

During the tests, the geolocation information was collected from GPS devices and converted into second-by-second speed data. Such temporal second-by-second speeds were further interpolated into meter-based spatial speeds data so that the three rounds of space speeds for each scenario can be easily aggregated and averaged. Then, statistical ANOVA tests could be conducted among the five scenarios with a confidence interval of 97%. Further, based on the speed and time information, the acceleration rates were calculated. The Vehicle Specific Power (VSP) was calculated using Equation (1) [41].

$$VSP = \left(A \times V_t + B \times {V_t}^2 + C \times {V_t}^3 + m \times V_t \times a_t\right)/m \tag{1}$$

where, VSP: vehicle-specific power in kW/tonne; V_t: the speed at time t in m/s; a_t: acceleration at time t in m/s^2; A: rolling resistance coefficient in kW-sec/m, 0.1565 kW-sec/m for a passenger car; B: rotational resistance coefficient in kW-sec2/m^2, 2.002×10^{-3} kW-sec^2/m^2 for a passenger car; C: aerodynamic drag coefficient in kW-sec3/m^3, 4.926×10^{-4} kW-sec3/m^3 for a passenger car; m: vehicle mass in tons.

With the speed and VSP data, vehicle emission rates can be calculated by 23 operating mode bins defined by the mobile emission model MOVES, which was developed by the United States Environmental Protection Agency (EPA). Each operating mode identification (OMID) bin is related to the emission rates for a set of emission indexes, including the ozone precursors NO_x and HC. The emission rates were calculated from the average emission rates collected by Frey et al. (2013) using a 5-year-old light-duty gasoline passenger vehicle [41], which are also utilized in MOVES. Table 3 shows the specification of the OMID bins and corresponding NO_x and HC emission rates in grams per hour.

Table 3. Average emission rates for gasoline passenger cars [41].

Operational Mode ID	Operation Mode Description (a_t in mi/h/s and v_t in mph)		Average Emission Rate (g/hr) NO_x	HC
0	Braking/ Deceleration	$a_t \leq -2.0$ OR ($a_t < -1.0$ AND $a_{t-1} < -1.0$ AND $a_{t-2} < -1.0$)	0.23	0.19
1	Idling	$-1.0 \leq v_t < 1.0$	0.10	0.05
11	VSP<0	$1 \leq v_t < 25$	0.34	0.13
12	$0 \leq$ VSP < 3		0.52	0.10
13	$3 \leq$ VSP < 6		1.22	0.19
14	$6 \leq$ VSP < 9		2.15	0.26
15	$9 \leq$ VSP < 12		3.81	0.36
16	$12 \leq$ VSP		7.94	0.58
21	VSP < 0	$25 \leq v_t < 50$	0.67	0.20
22	$0 \leq$ VSP < 3		1.09	0.18
23	$3 \leq$ VSP < 6		1.65	0.20
24	$6 \leq$ VSP < 9		2.79	0.38
25	$9 \leq$ VSP < 12		3.91	0.37
27	$12 \leq$ VSP < 18		6.16	0.59
28	$18 \leq$ VSP < 24		13.54	3.84
29	$24 \leq$ VSP < 30		23.78	6.81
30	$30 \leq$ VSP		31.29	11.25
33	VSP < 6	$50 \leq v_t$	1.44	0.19
35	$6 \leq$ VSP < 12		3.96	0.27
37	$12 \leq$ VSP < 18		5.54	0.34
38	$18 \leq$ VSP < 24		11.50	2.59
39	$24 \leq$ VSP < 30		17.12	3.76
40	$30 \leq$ VSP		21.56	4.92

From Table 3, the emission rates were closely related to acceleration, where 1 mph equals 1.6 km/h. For each speed bin, NOx is positively related to VSP, HC is higher at the lowest VSP and increases at a lower rate when VSP is increasing. The emission rate of NO_x reaches its lowest during decelerations and idle, while HC reaches its lowest during decelerations, but it is higher during idle. The test vehicle's trajectory and vehicle's emission factor along the test route were obtained by interpolating temporal driving speed and emission rate into spatial speed and emission factor for every 100 m. The on-road emission along a single lane was calculated to analyze the macroscopic NO_x and HC emission performance of toll rates by using Equations (2)–(4).

$$EPL = \frac{TE}{L} \tag{2}$$

$$TE = D \times RL \times EPV \tag{3}$$

$$D = \frac{FR}{V} \tag{4}$$

where, *EPL*: on-road emission per lane in grams; *TE*: total on-road emission in grams; *L*: number of lanes, two managed lanes and five general-purpose lanes in this research; *TE*: total on-road emission in grams; *D*: vehicle density in vehicle per mile (vpm); *RL*: route length, 12.2 miles in this research; *EPV*: total emissions per vehicle in grames, calculated by emission rates from Table 3; *FR*: flow rate, which is the traffic volume on a facility in vehicles per hour (vph); *V*: average travel speed, which is average traffic speed of a vehicle platoon passing through a facility in mph; this could be achieved from GPS data.

The flow rates along different time periods on Katy Freeway are shown in Table 4.

Table 4. Katy Freeway flow rate by the time period in vph [42].

	Rush Hour Periods								
	EB				WB				Non-Rush Hours
	6:00–7:00 a.m.	7:00–8:00 a.m.	8:00–9:00 a.m.	9:00–10:00 a.m.	3:00–4:00 p.m.	4:00–5:00 p.m.	5:00–6:00 p.m.	6:00–7:00 p.m.	
ML (vph)	1985	2105	1350	480	540	1750	1805	860	15
GPL (vph)	5950	5465	5860	6155	6140	6285	5530	5635	915

The traffic flow rates in Table 4 were derived from the 2013 data collected by TxDOT sensors, which was further updated to 2019 values by applying correction factors. In the table, 'EB' means Eastbound, and 'WB' means Westbound. The correction factors were calculated by the field sample observations in vph during rush hours in July 2019 divided by the corresponding 2013 TxDOT data. Table 4 indicates that traffic volumes are higher on general-purpose lanes than on managed lanes, ranging from 3 times higher during peak periods (6–8 a.m. EB, and 4–6 p.m. WB) to over 12 times higher (between 9 and 10 a.m. EB). During non-rush hours, traffic volumes are over 60 times higher on general-purpose lanes than managed lanes.

3. Case Study Data Analysis

In order to check if the managed-lane strategies are effective, the ANOVA statistical tests were conducted with the results shown in Table 5. The second row of Table 5 shows the results of significance tests on travel speed between each managed-lane scenario and their adjacent general-purpose lane scenario (control).

Table 5. One way ANOVA test on each set of scenario.

Scenarios	1		2		3		4		5	
Scene	Test Scene	Control Scene	Test Scene	Control Scene	Test Scene	Control Scene	Test Scene	Control Scene	Test Scene	Control Scene
Toll Rate	\$0.7	Free	\$3.5	Free	\$4.5	Free	\$6.4	Free	\$7	Free
ANOVA *p-value*	6.77×10^{-35}		8.857×10^{-48}		1.107×10^{-43}		2.55×10^{-33}		1.037×10^{-16}	

Based on Table 5, significant differences were obtained for all sets of scenarios. Thus, the differences in speeds on managed lanes and adjacent general-purpose lanes are statistically significant for all scenarios. The speed profiles are analyzed by each scenario that contains a control set.

3.1. Speed Profile Analysis

Figure 2 shows the speed profile of all five scenarios along with each control test.

In Figure 2, the black lines are the speeds on managed lanes, while the gray lines are the speeds on adjacent general-purpose lanes in the same direction. The vertical lines between the black and gray curves illustrate the difference in average speed between managed and general-purpose lanes. Darker gray vertical lines mean that managed-lane speeds are higher than general-purpose lane speeds, while lighter gray vertical lines mean that managed-lane speeds are lower than general-purpose lane speeds. The x-axis shows the travel distance of each scenario, and the y-axis shows the average travel speed for every 100 m in m/s. Based on Figure 2, scenario 4 with a toll rate of 6.4 USD shows the lowest speed difference between managed lanes and general-purpose lanes.

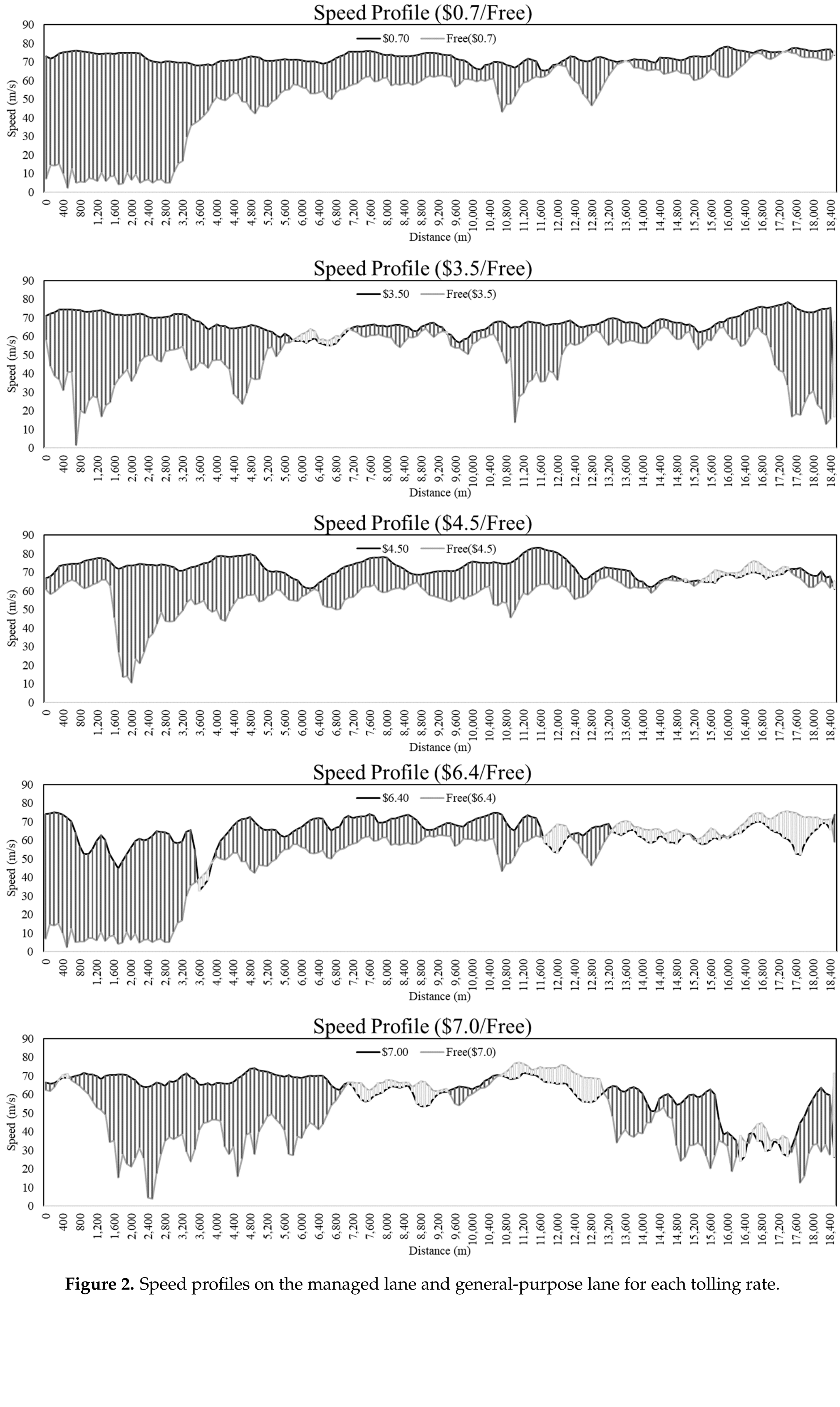

Figure 2. Speed profiles on the managed lane and general-purpose lane for each tolling rate.

Managed-lane speeds are always higher than the adjacent general-purpose lanes for scenario 1, with a toll rate of 0.7 USD. For scenarios 2–4, with toll rates being 3.5, 4.5, 6.4, and 7 USD, managed-lane speeds are higher than general-purpose lane speeds along with most travel distances. However, at several locations (5800–7,000 m for scenario 2 with a toll rate of 3.5 USD; 14,800–17,500 m for scenario 2 with a toll rate of 4.5 USD; 800–2000 m and 16,900–18,000 m for scenario 4 with a toll rate of 6.4 USD; 7000–9200m, 10,600–13,100m, 16,200–17,500m for scenario 5 with a toll rate of 7 USD), general-purpose lane travel speeds are higher than managed-lane travel speeds. Thus, it can be concluded that driving on managed lanes is not always faster than on general-purpose lanes. During rush hours, the driving speed on general-purpose lanes may be faster than that on the managed lanes.

Based on the speed profile, one advantage of tolling strategies is that the speeds on managed lanes are more constant than the parallel general-purpose lanes. Speeds on managed lanes are mostly higher than 25 m/s (55.9 mph) and vary smoother than speeds on general-purpose lanes due to lighter traffic conditions, especially for scenarios 1–4 with toll rates of 0.7, 3.5, 4.5, and 6.4 USD. One notable scenario is scenario 5, with a toll rate of 7 USD, where a larger portion of speeds on managed lanes are lower than speeds on the general-purpose lane, and the managed-lane speeds fluctuate heavily. This may be attributed to the extremely heavy traffic volume, even on managed lanes, during peak hours. In order to better illustrate the fluctuation feature of speeds, the acceleration profile is further analyzed.

3.2. Acceleration Profile Analysis

The emission rates are also directly influenced by the acceleration of the vehicle. Higher NO_x and HC emissions are closely associated with harder acceleration. Figure 3 shows the acceleration distribution of each scenario and its corresponding control scene.

In Figure 3, solid black bars are the acceleration distributions on managed lanes, while the gray bars are the acceleration distribution on the parallel general-purpose lanes. The x-axis is the distribution intervals of acceleration in m/s^2, and the y-axis is the percentage of the acceleration counts in each interval. In Figure 3, negative acceleration values mean braking, and positive acceleration values mean accelerating. The distribution bars closer to 0 on the x-axis mean milder acceleration or braking, while those bars that are away from 0 on the x-axis mean harder acceleration or braking.

Figure 3 shows that the acceleration distributions are closely related to the toll rate. For scenario 1 with a toll rate of 0.7 USD, the largest portion of accelerations and breakings are in the range of $(-0.2, 0.2)$, especially within the range of $(-0.1, 0)$, which means mild acceleration and braking are dominating states for a very lower toll rate (0.7 USD). As the toll rate increases, acceleration distributions shift more to the range of harder accelerations and harder breakings. For scenario 5, with a toll rate of 7 USD, the acceleration rates are almost evenly distributed along with all ranges of acceleration bins. Therefore, the acceleration distribution profile suggests that, as the toll rate rises during rush hours when traffic volumes are also high, the vehicle tends to accelerate and decelerate even harder.

Based on Figure 3, for scenarios 1, 2, 3 with toll rates of 0.7, 3.5, and 4.5 USD, the portion of accelerations on the managed lane in range $(-0.2, 0.2)$ is significantly higher than that for the general-purpose lane. This means the accelerations on managed lanes are overall milder than that on parallel general-purpose lanes, which is a result of less stop-and-go driving behavior that creates harder accelerations and is induced by the heavy traffic during these tolling hours. However, for scenarios 4 and 5 with toll rates of 6.4 and 7 USD, the acceleration advantages of the managed lanes are not that significant when compared to the general-purpose lanes. Especially for scenario 4, the general-purpose lane accelerations are milder than managed-lane accelerations. It is noteworthy that the portion of accelerations on general-purpose lanes remains similar for scenario 4, 5, and others, while the portion of milder accelerations on managed lanes are lower. One possible reason is that the morning traffic peak hours in Houston are 7 a.m.–9 a.m. with toll rates of 6.4 and

7 USD, during when the traffic volumes are high even on managed lanes, which induces more stop-and-go driving behavior and associated harder accelerations.

3.3. Emission Analysis

The per-hour emission rates for individual vehicle runs were estimated by multiplying the speed profile of each run by the measured emission rates in Table 3. Figure 4 shows the distribution of ozone precursors (NO_x and HC) under the five test scenarios.

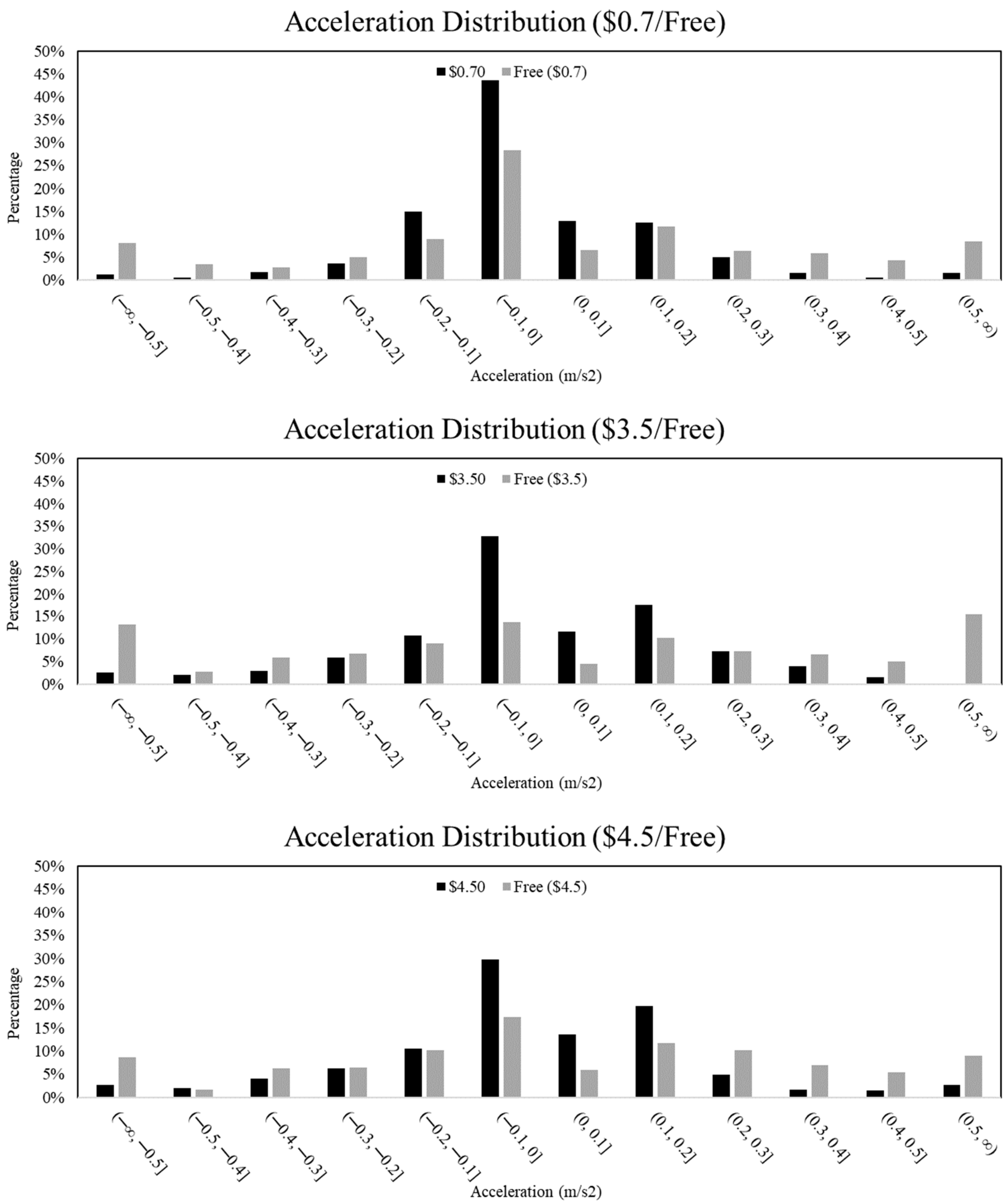

Figure 3. *Cont.*

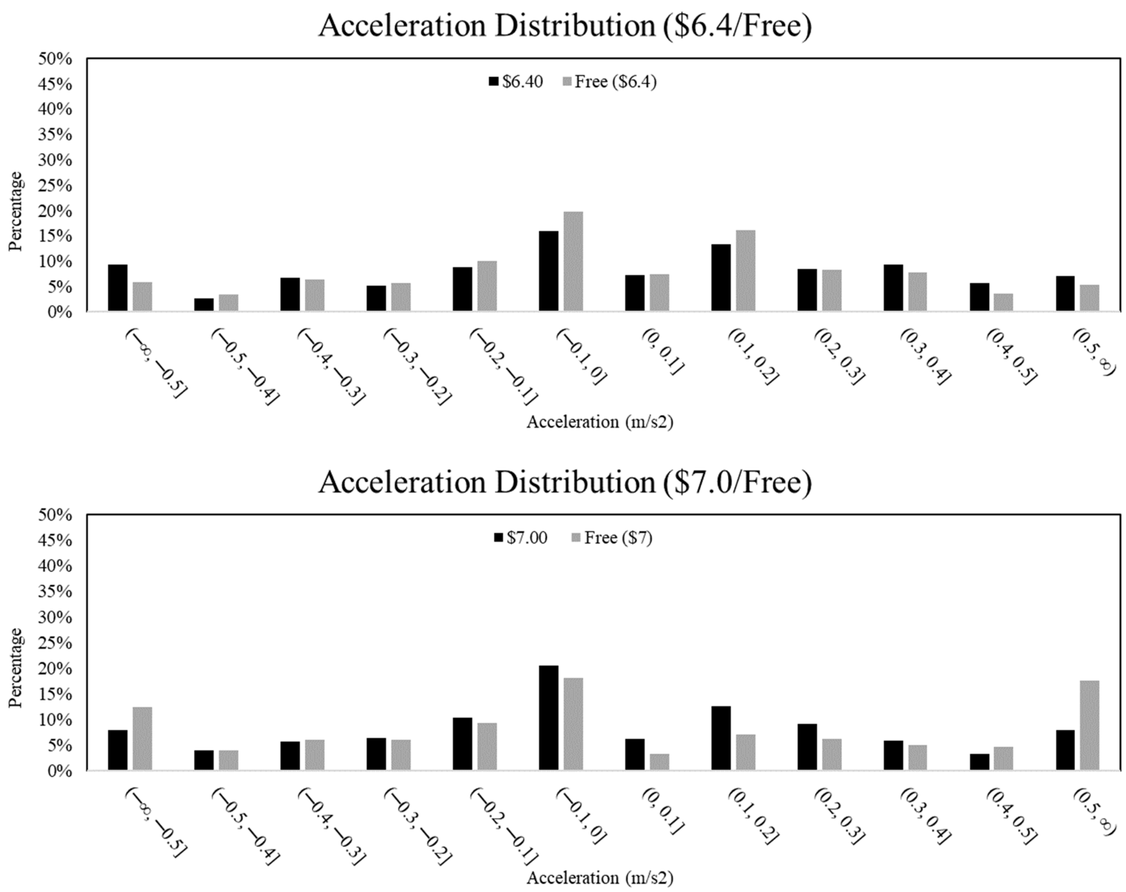

Figure 3. Acceleration distributions on the managed lane and general-purpose lane for each tolling rate.

Figure 4 demonstrates the box-whisker plots of NO_x and HC emission distributions under five scenarios. The x-axis shows the information of the scenarios, and the y-axis shows the emission rates in grams per hour. The cross signs in Figure 4 show the mean value, and bars within boxes show the median values. From Figure 4, the toll lane traffic has higher average and median emission rates than the general-purpose lanes for all scenarios. The NO_x emission rates on managed lanes in scenarios 1, 3, 4, and 5 with toll rates of 0.7, 4.5, 6.4, and 7 USD show higher variability than on general-purpose lanes. Only for scenario 2, with a toll rate of 3.5 USD, the general-purpose lane NO_x emission rates exhibit higher variability than on managed lane. The same trends could be found for HC emission rates. The managed-lane HC emission rates are higher than general-purpose lane emission rates for all scenarios, especially for scenarios 1, 3, and 5 with toll rates of 0.7, 4.5, and 7 USD. This implies that the increase in emissions from higher speeds on managed lanes overwhelms the decrease in emissions from milder accelerations/decelerations; as a result, vehicles travel on managed lanes tend to have higher NO_x and HC emission rates (measured in g/hr) than those on general-purpose lanes.

From Table 3, it is seen that emission rates are heavily impacted by speed. Through the analyses of speed profiles, driving speeds on managed lanes are normally higher than that on general-purpose lanes; the emission rates on managed lanes are also be higher than on general-purpose lanes. Therefore, the findings in Figure 4 are reasonable. To combine the effects of emission rates with speed (and therefore travel time), the total NO_x and HC emissions are further analyzed. Figure 5 is the total NO_x and HC emission generated from the test vehicle under all five scenarios.

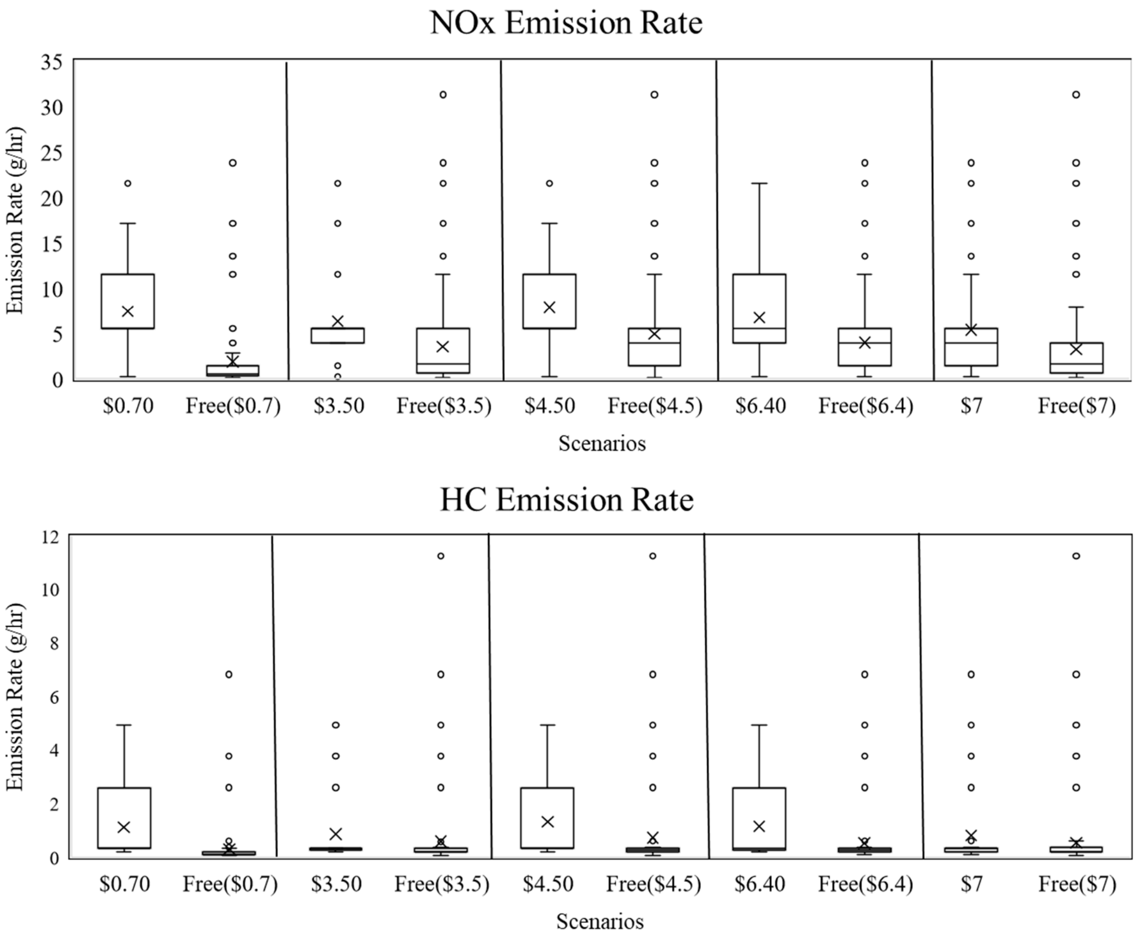

Figure 4. Emission rate distribution of ozone precursors NO_x and HC.

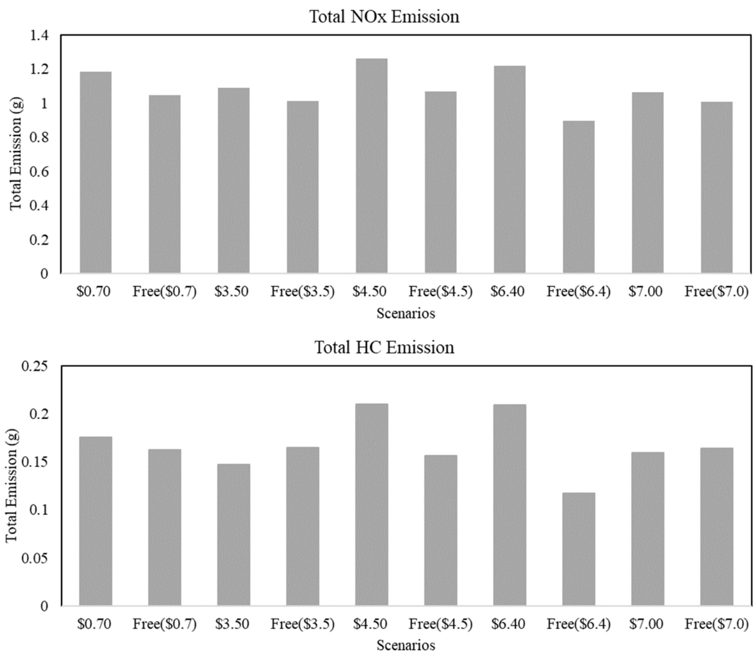

Figure 5. The total emission of one single vehicle under all scenarios.

Total emissions that are shown in Figure 5 are calculated by unit emission rate times their corresponding travel time along the whole test segment. The differences in per-vehicle emission rates (in Figure 5) between managed and general-purpose lanes are smaller than the differences in per-hour emission rates (Figure 4) because Figure 5 accounts for the higher speed and shorter travel times on managed lanes than on general-purpose lanes.

The total HC emission generated from the vehicle on general-purpose lanes is more than that on managed lanes, except for scenarios 2 and 5, with toll rates of 3.5 and 7.0 USD. Even for scenarios 2 ad 5 with toll rates of 3.5 and 7.0 USD, the differences in HC emissions between managed lanes and general-purpose lanes are rather limited. In the meantime, the total NO_x emission per vehicle driving on the managed lane is always higher than that on the general-purpose lane. From the per vehicle emission analysis, the weight ratios between the on-road HC and NO_x emission are all smaller than 4: 1 for all scenarios; thus, this area's ground-level ozone formation for a single vehicle is hydrocarbon-limited.

The above analyses are all based on the emissions generated by one vehicle. Considering the total number of vehicles on this freeway segment, the total emission generated by all vehicles along managed lanes and adjacent general-purpose lanes are presented in Table 6 and Figure 6 with the unit of grams (g).

Table 6. Total vehicle emission based on the total number of vehicles.

NO_x Emission										
Scenarios	**1** 0.7 USD	**Free (0.7 USD)**	**2** 3.5 USD	**Free (3.5 USD)**	**3** 4.5 USD	**Free (4.5 USD)**	**4** 6.4 USD	**Free (6.4 USD)**	**5** 7 USD	**Free (7.0 USD)**
Total Emission (g)	2.35	586.9	935	1859	245	1405	309	1243	409.1	1985
Emission Per Lane (g)	1.18	117.4	46.62	371.9	122.5	280.9	154.5	248.7	204.6	397.1
HC Emission										
Scenarios	**1** 0.7 USD	**Free (0.7 USD)**	**2** 3.5 USD	**Free (3.5 USD)**	**3** 4.5 USD	0.7 USD	**4** Free (0.7 USD)	3.5 USD	**5** Free (3.5 USD)	4.5 USD
Total Emission (g)	0.34	91.7	12.72	311.9	40.97	209.6	53.33	163.9	61.55	345.3
Emission Per Lane (g)	0.17	18.34	6.36	62.39	20.48	41.92	26.67	32.78	30.77	69.06

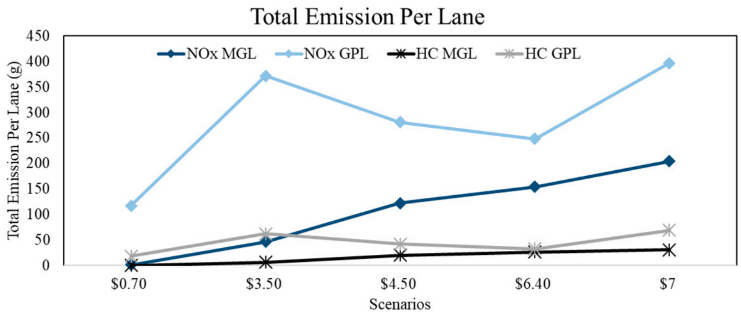

Figure 6. Total NO_x and HC emission per lane based on the total number of vehicles from density.

The total on-road vehicle emission in Table 6 is estimated based on the total number of vehicles N and the emissions from a single vehicle. N is calculated by using Equation (5).

$$N = K \cdot L = \frac{Q}{U} \cdot L = \frac{Q}{L/T} \cdot L = Q \cdot T \tag{5}$$

where, K is the density along a target lane, L is the total length of the lane, Q is the volume on the lane, and T is the average travel time driving over the test segment. Traffic volume Q is provided in Table 4, and the average travel time was calculated based on the test vehicle, which followed the traffic flow.

From Table 6, it is clear that, because of the larger traffic volume on general-purpose lanes, the total NO_x and HC emissions on a general-purpose lane are higher than that on a managed lane for all tolling price scenarios. This is partly because the density on a managed lane is from 3 to 13 times lower than the density along a general-purpose lane. As there are five general-purpose lanes and only two managed lanes in each direction; the emissions per lane are plotted in Figure 6. In Figure 6, the total NO_x and HC emissions on each single managed lane are still lower than the relevant emissions on each general-purpose lane for all scenarios. The trends for emissions based on time of day can be found in the figure that the emissions on the managed lanes are positively related to the toll price. However, for the general-purpose lanes, the peak emission appears during toll prices of 3.5 and 7 USD, which occurs during 9:00–10:00 a.m. Eastbound, 7:00–8:00 a.m. Eastbound, and 4:00–6:00 p.m. Westbound. During these hours, the vehicle densities are relatively high (9:00–10:00 a.m.: 6155 vph, 7:00–8:00 a.m.: 5465 vph, 4:00–6:00 p.m.: 6285, 5530 vph), which shows a significant effect on the on-road emissions.

Per vehicle emissions of ground-level ozone precursors are higher on managed than on general-purpose lanes because of higher travel speeds; however, total per lane emissions are lower on managed lanes because of much lower traffic volume. Based on Table 6, the highest on-road total NO_x and HC emission is on the general-purpose lane at scenario 5 with a toll rate of 7 USD when traffic volumes are high, even though average speeds are relatively low. Table 6 also indicates that the emission per managed lane increases mostly because traffic volume on the managed lane increases in response to congestion on the general-purpose lane.

While the toll rate of the managed lane is scheduled to change by time of the day, the total one-lane emission for each hour and a day are listed in Table 7.

Table 7. Total hourly and daily emissions per lane.

Lane Specification	Rush Hour Periods										
	6:00–7:00 a.m. EB	**7:00–8:00 a.m. EB**	**8:00–9:00 a.m. EB**	**9:00–10:00 a.m. EB**	**3:00–4:00 p.m. WB**	**4:00–5:00 p.m. WB**	**5:00–6:00 p.m. WB**	**6:00–7:00 p.m. WB**	**Non-Rush Hours**	**Daily Total EB**	**Daily Total WB**
ML Total NO_x (grams/Lane)	1287	1110	817.9	260.2	350.0	922.6	951.6	557.4	8.820	3651 (42% of GPL)	2958 (32.7% of GPL)
GPL Total NO_x (grams/Lane)	1254	1164	1058	1244	1294	1339	1178	1188	202.3	8765	9044
ML Total HC (grams/Lane)	215.1	166.9	141.2	35.50	58.53	138.8	143.2	93.21	1.270	584.2 (42.6% of GPL)	459.1 (31.9% of GPL)
GPL Total HC (grams/Lane)	187.1	202.5	139.4	208.7	193.1	232.9	204.9	177.2	31.60	1370	1440

Table 7 shows the hourly and total daily emissions for each managed lane and each general-purpose lane. Due to the pricing strategies of the toll lanes varying by the bounds of the road, the total daily emission is then analyzed by Eastbound and Westbound separately. Table 7 is generated using the traffic volume in Table 4 and then the single-vehicle emissions for each managed lane and each general-managed lane under all scenarios is estimated.

In Table 7, from 6:00 a.m. to 8:00 a.m., both NO_x and HC emissions on a managed lane are close to those on a general-purpose lane. However, for the other periods of the day, NOx and HC emissions on a general-purpose lane are higher than those on a managed lane. The daily emissions on a managed lane are only 31.9%–42.6% of the daily emissions on a general-purpose lane. It means, on a daily scale, managed-lane strategies could significantly reduce the emission of the precursors (NO_x and HC) for ground-level ozone. From the daily emission analysis, the weight ratio between the on-road HC and NO_x emission is smaller than 4: 1; thus, this area's ground-level ozone formation is hydrocarbon-limited.

4. Conclusions

In this paper, on-road NO_x and HC emissions, as precursors of ground-level ozone, are analyzed based on field tests along the HOV/HOT lanes and general-purpose lanes on Interstate Freeway I-10 in Houston. Results show that toll lane managed-lane strategies could increase vehicles' travel speed significantly and smooth acceleration and deceleration rates. In terms of the two ozone precursors, NO_x and HC, a single vehicle on managed lanes tends to produce more NO_x and HC in a unit of time. However, due to the decreased travel time along managed lanes, each vehicle's total NO_x and HC emissions in some cases are lower than those along general-purpose lanes. However, the greater number of vehicles on general lanes results in higher per-lane emissions on general-purpose than managed lanes, especially when traffic volumes are highest. The exceptions are that, when the toll rate is 3.5 or 7 USD, the single vehicle's total HC emissions on managed lanes outperforms that on general-purpose lanes. When considering the emissions per lane for the total number of vehicles, the managed-lane strategies could reduce the NO_x and HC emissions significantly for all toll-rate scenarios. On a daily scale, total emissions on a managed lane are only 31.9%–42.6% of the total emissions on a general-purpose lane. Hence, the managed-lane strategies are beneficial for emission reductions of the precursors for ground-level ozone. Based on the results that are achieved from this research, future decision-makers and traffic planning engineers could design managed-lane and pricing strategies based on not only traffic situation improvement purposes but also to achieve eco-transportation goals. There are some limitations to this research. First, different vehicle emission models might be developed using different research approaches; however, not all emission models were considered in this research. Second, different weight ratios between NO_x and HC will affect the ground-level ozone formation, and the reduction in NO_x may result in increases in ground-level ozone concentrations. Third, the per-vehicle emission rates are calculated based on selected test vehicles, rather than various types of vehicles driving on roads with diverse emission rates. In future research, the relationship between the on-road vehicle emitted precursors and the ground-level ozone concentration levels will be analyzed, and the impact of the managed-lane strategies on ground-level ozone formation will be discovered. It is also recommended that different types of vehicles should be considered to obtain more realistic emission rates.

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