Case Study

Developing a 24-Hour Large-Scale Microscopic Traffic Simulation Model for the Before-and-After Study of a New Tolled Freeway in the Washington, DC–Baltimore Region

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Abstract: For determining highly disaggregate details about traffic dynamics, microscopic traffic simulation has long proven to be a valuable tool for the evaluation of development plans and operation/control strategies. With recent advances in computing capabilities, research interest in large-scale microscopic simulation has never been greater. This case study develops a 24-h large-scale microscopic traffic simulation model for the Washington, DC, metropolitan area. The model consists of over 7,000 links, 3,500 nodes, 400 signalized intersections, and over 40,000 origin-destination pairs. Various field measurements, such as time-dependent traffic counts and corridor travel times, have been used for model calibration/validation. The EPA's *Motor Vehicle Emission Simulator* is linked with the microscopic simulation model for the estimation of environmental impacts. The calibrated model system has been used to comprehensively evaluate a newly built toll road in Maryland, the Intercounty Connector. Various network-level and corridor-level performance measures are quantified. The case study demonstrates the feasibility and capability of large-scale microscopic simulation in transportation applications. It establishes an example for modelers and practitioners who are interested in constructing a large-scale model system. The developed 24-h simulation model system of traffic and emissions has the potential to serve as a test bed for integration with other analysis tools, such as behavioral and optimization models. **DOI: 10.1061/(ASCE)TE.1943-5436.0000767.**

Introduction

With growing vehicle populations and travel demands, excessive congestion, especially during peak hours, is a crucial problem for most cities and metropolitan areas. An historically hot research topic has been whether new infrastructure, planning policies, or management strategies would effectively nudge travel behavior, remit traffic congestion, and mitigate environmental impacts for the transportation system. Within the Washington, DC–Baltimore region, a brand-new toll road named the Intercounty Connector (ICC) has been constructed and operational since 2011. ICC runs 28.97 km (18 mi) between two interstate freeways: I-270 and I-95. Currently it is being expanded toward northeastern DC, connecting the dense and mixed development urban areas in Montgomery County, Prince George's County, and the Baltimore and Baltimore/Washington International (BWI) airport areas. All ICC toll revenues are collected electronically via EZ-Pass transponders. Vehicles without transponders are charged via mail. Predefined time-of-day toll levels are employed. ICC is publicly expected to serve as a time-saving alternative route for the already high travel demand in these areas. The ways ICC can improve traffic conditions and mitigate air pollutions are attracting growing research attention. Because it is an 29-km (18-mi), controlled access, tolled highway with approximately $0.17 per km ($0.27 per mile) peak-hour toll rate for two-axle vehicles, ICC's performance evaluation can serve as an interesting reference for researchers and practitioners in U.S. Motivated by these research needs, this case study focuses on developing a modeling tool that can quantitatively evaluate the network-wide and corridor-level impacts of ICC on travel conditions and the quality of the environment.

For decades, the infrastructure/policy changes have been qualitatively/quantitatively measured by before-and-after comparisons of a series of measures of effectiveness (MOEs) acquired from a variety of methodologies (e.g., transportation demand models, activity or agent based models, and traffic simulation models). Among these methods, microscopic traffic simulation models have drawn increasing attention. Coupled with simulation-based dynamic traffic assignment (DTA), they exhibit strong advantages in modeling traffic dynamics in highly disaggregate and spatial/temporal details.

Microscopic traffic simulation has gradually proved a powerful tool in transportation research. This trend has moved slowly toward large-scale applications as technological advancements have eased the computational burden of microscopic simulation. From the

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1990s, most applications focused on corridor analysis problems evaluating queue spillback, weaving, incidents, and signal control strategies (Algers et al. 1998). Toledo et al. (2005) presented a case study of a medium-sized simulation model (298 nodes and 618 links) in Irvine, California. The model was calibrated by comparing observed and simulated sensor counts for every time interval of 15 min. Similar studies were conducted, but few addressed large-scale networks that spatially cover multiple corridors and temporally cover multiple time periods (Oketch and Carrick 2005; Khalili and Khaksar 2003). Rakha et al. (1998) constructed and calibrated a 24-h large-scale microsimulation model (3,365 nodes and 7,926 links) for the Salt Lake City, Utah, metropolitan region. To make the large-scale model applicable, their study relied on simplifications; e.g., an all-or-nothing (AON) traffic assignment algorithm was chosen for model calibration, partly for its superior execution time. Compared to AON, simulation-based DTA is more realistic because it fully takes the advantages of microsimulation by considering the dynamics of traffic conditions, and thus, assigns trips dynamically. In return, it requires higher computational costs for large-scale systems. Several applications are used in practice, but are limited to their scales. Jha et al. (2004) applied a route choice and simulation based DTA for morning (AM; 7:15 to 8:30 a.m.) and evening (PM; 4:15 to 5:30 p.m.) for the city of Des Moines, Iowa. Balakrishna et al. (2007) adopted DTA and conducted the simultaneous calibration of a microsimulation model with 1,700 links for Lower Westchester County, New York. The study by Smith et al. (2008) represents the most recent attempts in large-scale microscopic simulation with DTA.

On the contrary to the scarce real-world application case studies, there is an imperative need to combine large scale and microscopic simulation. On one hand, microscopic simulation is needed for its capability of producing microscopic levels of detail, which is a crucial input for various performance measures. Especially for the emission modeling conducted in this case study, microscopic traffic simulation emits detailed information about instantaneous vehicle trajectories, vehicle speeds, and link volumes. The model can take advantage of these details for a more accurate estimation. On the other hand, the research goal is to evaluate the impact of an intelligent transportation system application on a particular corridor. This impact (caused by time-varying pricing, ramp metering control, dynamic lane control, and variable message signs) can easily be spilled over to other neighboring corridors. A corridor-level study can measure the direct impact but cannot account for the spillovers. Therefore, a study at research scale that is sufficiently large is necessary for researchers and practitioners to fully evaluate the impact. In terms of temporal scale, a 24-h model is needed because the impacts can also potentially spill over to off-peak hours. Traveler departure time shifts may occur, resulting in peak spreading that introduces various stimuli into the model, such as special events, excessive peak-hour congestion, and flexible work schedules. A 24-h model can better represent travel demand by time of day, and thus, provide a suitable test bed to incorporate these time-of-day behavioral changes performed by each simulated agent (Zhang et al. 2013). Motivated by the preceding discussion, this research aims at developing a 24-h large-scale microscopic traffic simulation model to meet all research needs in the case study.

This case study applies the microscopic traffic simulation model to obtain MOEs for evaluating the ICC project. Various performance measures at different levels of detail can be developed to quantify the impacts of different scenarios. Vehicle kilometers traveled (VKT) is an important MOE that indicates both vehicle usage and congestion level. Similarly, measures such as average trip time, average trip length, vehicle hours traveled (VHT), and gravity-based accessibility, which can be obtained from travel demand model (Xie and Levinson 2011; Levinson et al. 2012), can also reflect regional-level performance. Although these MOEs are capable of evaluating the system, more detailed measures are necessary for a better understanding of impacts on specific and magnified link-level scopes, and can thus highlight the capability of a microscopic simulation model. Level of service (LOS) has proven to be a vital tool for agencies to consider a wider range of mitigation measures for congestion and growth (Dowling et al. 2002). With graded evaluation, LOS can reflect full-scale information for freeway/arterial corridor evaluation, such as vehicle mobility and driver psychological comfort. Additionally, unlike macroscopic models with a single average daily traffic value at a particular location, a time series of traffic conditions is analyzed and time-space diagrams are formed for this case study.

Moreover, little research has been conducted to quantify the effects of a new toll road on microscopic level vehicle emissions and energy consumption. Estimation of microlevel emissions takes advantage of the detailed traffic data produced by the microscopic traffic model, such as detailed traffic flow characteristics, instantaneous vehicle speeds, and acceleration/deceleration. This level of detail is crucial. For instance, accelerating vehicles can produce emissions with a much higher rate than cruising vehicles (Joumard et al. 1999). Similarly, an open-access high occupancy vehicle/high occupancy toll (HOV/HOT) lane can yield significantly different emission rates than limited-access toll lanes because the former can result in increased weaving intensity (Boriboonsomsin and Barth 2008). Although microscopic modeling can capture the desired level of details and is thus suitable for accurate emission estimation, the significant data demand hinders its wide application in the field because the models are always not well-calibrated or validated; it is challenging to obtain detailed vehicle information and fuel data. Among the limited number of studies, Chen and Yu (2007) applied the microscopic traffic model built in *VisSim* to provide input for an emission model (CMEM) for the evaluation of traffic control strategies. More recently, the EPA's *Motor Vehicle Emission Simulator (MOVES)* model gains its increasing popularity. Abou-Senna et al. (2013) employed *MOVES* to simulate air pollution emissions for a limited-access highway corridor. Similarly, Xie et al. (2012) combined a *Paramics* model and *MOVES* to analyze a multimodal corridor to understand the effects of alternative fueled vehicles. These corridor-level analyses emphasize the growing need for simulating the environmental effects of different schemes using microscopic traffic and emission models. This study attempts to further justify its applicability in a 24-h large-scale case study. This extension is particularly necessary in this case study because the environmental impacts from new infrastructures can spill over to other parts of the network and vary on different times of day.

To achieve the aforementioned research objectives, this study examines the ICC toll road case study by developing a 24-h large-scale microscopic traffic simulation model and using EPA's *MOVES* for microscopic emission modeling. The remainder of the paper is organized as follows. In the following section, the traffic simulation model is described, including a brief description of the methodology for origin-destination (OD) estimation and model calibration/validation. A detailed description of the microscopic emission modeling is also included. In the next section, the model calibration process is presented in a 24-h time frame, including calibration/validation data sets, methodology, and results. In the penultimate section, the case study of the new toll facility in Maryland is presented, and various MOEs and comparisons obtained from the calibrated simulation model are offered. Changes in four different types of emissions are also estimated, including greenhouse gas (GHG) emissions, poisonous pollutants, particulate matter, and fuel consumption. The conclusions and future work are offered at the end of the paper.

Simulation and Emissions Models

In this study, the effects of a new toll road, the ICC, built in Washington, DC, and a Maryland neighborhood, are examined by employing a combination of a microscopic traffic simulation model and the EPA's *MOVES* model. A regional traffic assignment model is employed to allocate trips on the metropolitan road network. Then, OD matrices for all trips in the study area are input into a microscopic traffic simulation model coupled with simulation-based DTA. These trips include those (1) generated outside the ICC area [from an external traffic analysis zone (TAZ)] and destined to the ICC area (external-internal trips); (2) generated in the ICC area and destined to an external TAZ (internal-external trips); (3) traveling within the ICC area (internal-internal trips); (4) traveling through the area (external-external trips). Next, a variety of performance measures are obtained from simulating the baseline no-build and ICC scenarios. Under each scenario, instantaneous travel speed data for each link are extracted and used for emissions modeling using *MOVES*.

Traffic Simulation Model

First, this case study employs a regional travel demand model developed for the Metropolitan Washington Council of Government (MWCOG) to assign daily trips for the region. The MWCOG planning model includes 27,743 links, 10,505 nodes, and 2,119 TAZs, whereas the case study subnetwork contains 162 internal TAZ centroids and 39 external centroids through which the subnetwork is connected with the rest of the MWCOG model. The gradient projection (GP) path-based traffic assignment is primarily chosen for the subnetwork analysis for its superior efficiency in addressing large-scale networks (Chen et al. 2002). With the application of the GP algorithm, the regional traffic assignment output is used to derive hourly OD matrices for all internal-external, external-internal, internal-internal, and external-external trips for the 24-h period. Important steps in estimating the OD matrices are listed as follows:

1. Assign HOV by using the GP algorithm;
2. Assign trucks by excluding HOV lanes and maintaining the path flow of HOV;
3. With the path flow of HOV and trucks, assign single-occupancy vehicle (SOV);
4. Compare the shortest and longest OD travel times; if any exceed the predetermined threshold, go back to Step 1; and
5. Compare paths with positive flow to the external stations and centroids. If any part of the path is located in the ICC area, assign path flow to the corresponding OD pair and vehicle class for the area. Repeat this for all OD pairs and for each vehicle class.

Supported by Maryland State Highway Administration (SHA), a large-scale microscopic traffic simulation model is developed, which includes all freeways (I-270, I-495, I-95, and I-370), major arterials (MD-355, MD-97, MD-650, and MD-28), most minor arterials, and some important local streets in the central and eastern Montgomery County and northwestern Prince George's County of the State of Maryland (Fig. 1). To achieve this objective, a database of all links and intersections in the study area is constructed. Real-world signal timing plans and turning restrictions for all intersections are used as input. The model also includes all stop signs, traffic signals, speed limits, and school zones.

Various microscopic traffic simulators are available. Although there is no consensus regarding the supremacy of any simulator, *TransModeler* is selected (Wojtowicz et al. 2011) for its well-developed interface with geographic information systems (GISs), which is important when working with various data sources of a large-scale network. The simulated network is constructed by using high-resolution satellite images provided by Google Earth; therefore, it accurately conforms to the true geometry of links and intersections. This simulation model consists of a total number of 7,121 links, 3,521 nodes, and 466 signalized intersections. With such a large-scale network, the simulation model can capture the impact of several new developments within this area; e.g., the new toll road currently under construction, the ICC, the Great Seneca Science Corridor (GSSC) in West Gaithersburg, and the military base in Fort Meade (Zhang et al. 2013).

Emission Estimation Model

This case study combines the EPA's *MOVES* as a postprocessing module to process simulation outputs and estimate emissions. *MOVES* model is a reliable tool in emission estimation (Koupal et al. 2002). Compared with other models, *MOVES* has several advantages. One example is that *MOVES* is integrated with an information-rich county-level database for the whole United States, which makes emission estimation for any simulated local areas more convenient (Koupal et al. 2002).

MOVES employs information about link length, traffic volume, traffic composition, and vehicle speeds to estimate emissions. These information profiles for each link can be extracted from the microscopic traffic model. Second-by-second travel speed data are the most important input for *MOVES*, because they capture vehicle movements, including acceleration, deceleration, cruising, and idling. Other required inputs for emission estimation include the following items:

1. Total VKT, directly available from simulated results;
2. Ratio of different vehicle types, obtained from the regional planning model (i.e., the MWCOG model, version 2.2) to reflect local conditions;
3. Ratios of different road types, obtained from the link data of the simulation model;
4. Vehicle age distribution and population. This was obtained from the 2007–2008 Transportation Planning Board and Baltimore Metropolitan Council (TPB/BMC) Household Travel Survey, in which daily number of trips, trip production per household and number of vehicles per household are used to estimate population; and
5. Meteorology data (temperature and humidity), posted at The Weather Channel website. Meteorology data input is selected in correspondence with the period for traffic counts.

All traffic related data can be prepared from the output of the traffic simulation model. Thus, a linkage is built between *MOVES* and the large-scale microsimulation model. After processing the data, *MOVES* estimates hourly emissions such as GHG emissions, particulate matter (PM), and energy consumption for the entire network.

Model Calibration and Validation

Calibration of Dynamic OD Matrices

As mentioned in the literature review, model calibration is the most time-consuming and critical step in model development. Before moving to the calibration, complete 24-h signal timing information for all signalized intersections in the study area needs to be accurate. The study area shown in Fig. 1 includes a total number of 466 signalized intersections. Signal timing plans for these intersections are obtained from the state and county Departments of Transportation, then implemented in the simulation model. Signal timing plans are in standard Synchro data format, including information about phase timing (minimum initial/split, total split, yellow time, and all-red time), phase sequence, and detector locations for different times of day. In this study, 24-h field count data are used for model calibration. The data come from 24 freeway and 38 local arterial sensors (represented as dots in Fig. 1), and are collected for multiple days. Using the hourly OD, the calibration algorithm [details are provided by Zhang et al. (2013)] evaluates demand adjustment factor, $\alpha_{ij,r,t}$, associated with each path, r, between an OD pair, i, j, and for a given time period, t, by using the following equation:

$$\alpha_{ij,r,t} = \frac{\sum_{a \in S(ij,r,t)} \zeta_{ij,r,a,t}[(F_{a,t} + \Delta t_{ij,r,a,t})/(f_{a,t} + \Delta t_{ij,r,a,t})]}{\sum_{a \in S(ij,r,t)} \zeta_{ij,r,a,t}} \tag{1}$$

where ij = OD pair from origin i to destination j; $r \in R(ij,t)$ where R = complete set of all paths used for OD pair ij at time t; $S(ij,r,t)$ = link set of path r at time t; $F_{a,t}$ = actual link flow on link a at time t; $f_{a,t}$ = simulated link flow on link a at time t; $\Delta t_{ij,r,a,t}$ = travel time from origin i to link a starting at time t; $\zeta_{ij,r,a,t}$ = indicator that equals 1 if $a \in S(ij,t)$ and 0 otherwise.

When attempting to conduct the calibration on 24-h period at a time, the DTA run time of the model tends to be extremely long because during the first few iterations, the assignment gridlocks the network and considerably slows the simulation. Thus, the authors address this by dividing the all-day study period into six subperiods: early morning (12–6 a.m.), morning peak (6–9 a.m.), midday 1 (9 a.m. to 1 p.m.), midday 2 (1–4 p.m.), evening peak (4–7 p.m.), and night (7 p.m. to 12 a.m.) and calibrating them separately. The simulation state of the traffic condition by the end of each subperiod is saved as an initial state loaded to the simulation of the following subperiod to ensure continuous and consistent simulation.

Various performance measures have been applied to evaluate the accuracy of the match between field data and simulated counts.

1. Root-mean-square error(RMSE)

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\{f[\mathbf{x}^{(i)}] - \hat{f}[\mathbf{x}^{(i)}]\}^2} \tag{2}$$

2. Normalized root-mean-squared error (NRMSE)

$$\text{NRMSE} = \sqrt{\frac{\sum_{i=1}^{N}\{f[\mathbf{x}^{(i)}] - \hat{f}[\mathbf{x}^{(i)}]\}^2}{\sum_{i=1}^{N}\{f[\mathbf{x}^{(i)}]\}^2}} \tag{3}$$

3. Pearson correlation coefficient (PCC)

$$\text{PCC} = \left(\frac{N\sum_{i=1}^{N}\hat{f}[\mathbf{x}^{(i)}]^2 - \sum_{i=1}^{N} f(\mathbf{x}^{(i)})\sum_{i=1}^{N}\hat{f}[\mathbf{x}^{(i)}]}{\sqrt{\{N\sum_{i=1}^{N} f[\mathbf{x}^{(i)}]^2 - [\sum_{i=1}^{N} f(\mathbf{x}^{(i)})]^2\}\{N\sum_{i=1}^{N}\hat{f}[\mathbf{x}^{(i)}]^2 - [\sum_{i=1}^{N}\hat{f}(\mathbf{x}^{(i)})]\}^2}}\right)^2 \tag{4}$$

where N = number of independent set data to be compared; $f[\mathbf{x}^{(i)}]$ and $\hat{f}[\mathbf{x}^{(i)}]$ = observed and simulated counts at sensor i. RMSE represents the sample standard deviation of the difference between simulated and observed counts; NRMSE indicates the relative deviation, in which observed counts are weighted by volume; PCC is a measurement indicating the correlation between field counts and simulated counts. If $r^2 = 1$, the model is exactly predicting the test data, whereas $r^2 = 0$ indicates that there is no correlation between the model results and the field measurements.

The performance measures of the calibration are reported in Table 1. RMSE indicates that the average difference in counts was 595.2 for freeway stations and 493.4 for all stations (the average counts for freeway stations and all stations are 4,349 and 2,247, respectively). NRMSE shows that the convergence of normalized relative errors for both freeway and all sensor stations are 12.95 and 16.77%, respectively. The PCC results also imply that simulated counts conform to the observed counts with high accuracy. Fig. 2 plots the final comparison of field and simulated traffic count data at all counting stations. Results show reasonable agreement between simulated and observed data.

Model Validation

The calibration results have demonstrated the consistency of the simulation model with the field measurements on most freeways and arterials. To further validate travel times and speeds generated from the simulation, multiple probe vehicle trajectory data, collected on 12 major arterial corridors within the ICC area, are used as the validation data set. The corridors are as labeled in Fig. 1. Table 2 reports the validation results. The overall differences between simulated and observed travel times are 12.6 and 11.2% for AM peak and PM peak, respectively. Validation results indicate that the model calibrated by field count data performs well for corridor-level travel times. Future research will validate speed once the observations on link-level instantaneous speed become readily available.

Case Study of Intercounty Connector, Maryland

The previous section reported the work on modeling travel demand in the ICC study area, estimating multimodal OD matrices, and model calibration/validation. This case study aims at

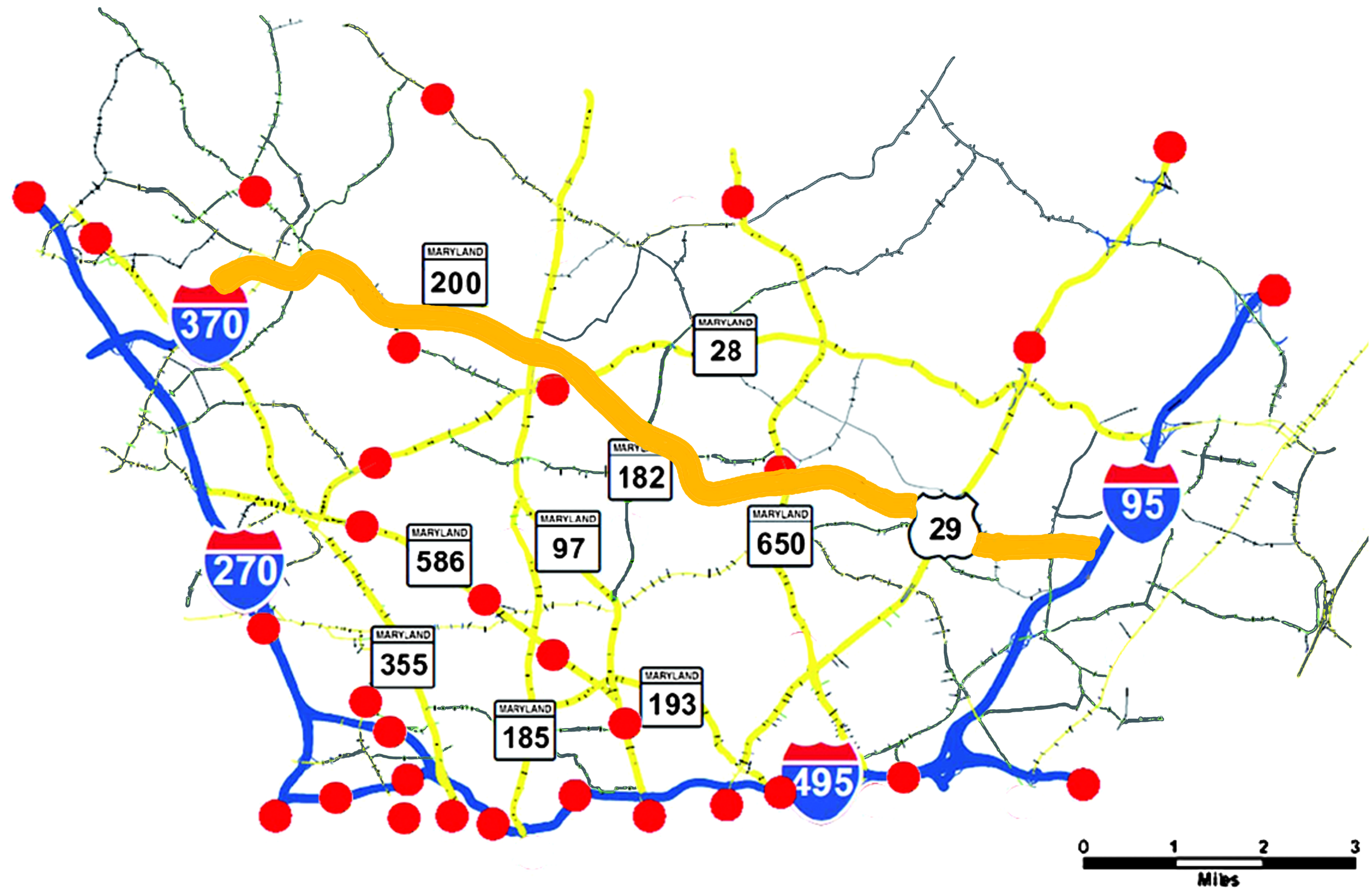

Fig. 1. Microscopic traffic simulation modeling study area

Table 1. Twenty-Four Hour Calibration Results

	RMSE		NRMSE (%)		PCC	
Time period	Freeway	All	Freeway	All	Freeway	All
Average	595.2	493.4	12.95	16.77	0.927	0.974
0:00 to 1:00	72.3	101.2	6.59	14.52	0.978	0.980
1:00 to 2:00	106.7	86.5	15.58	20.02	0.923	0.974
2:00 to 3:00	99.0	74.4	17.61	21.06	0.886	0.966
3:00 to 4:00	94.9	77.8	15.14	19.79	0.914	0.976
4:00 to 5:00	195.9	155.3	14.40	18.16	0.946	0.982
5:00 to 6:00	390.9	366.2	9.36	13.90	0.973	0.984
6:00 to 7:00	899.5	650.5	14.05	15.80	0.918	0.976
7:00 to 8:00	1,108.7	871.6	16.28	19.54	0.877	0.964
8:00 to 9:00	1,030.8	844.8	15.33	19.14	0.881	0.962
9:00 to 10:00	1,134.1	847.1	17.85	20.56	0.866	0.957
10:00 to 11:00	805.8	585.1	13.99	15.81	0.921	0.977
11:00 to 12:00	613.6	507.1	11.08	14.21	0.924	0.980
12:00 to 13:00	513.2	498.8	8.99	13.52	0.946	0.983
13:00 to 14:00	562.5	507.5	9.59	13.41	0.954	0.984
14:00 to 15:00	986.0	758.3	14.57	17.42	0.910	0.977
15:00 to 16:00	1,128.2	901.4	16.18	19.95	0.877	0.964
16:00 to 17:00	861.7	750.6	13.13	17.40	0.930	0.967
17:00 to 18:00	794.2	782.6	12.46	18.44	0.943	0.967
18:00 to 19:00	756.8	705.5	11.93	16.90	0.958	0.975
19:00 to 20:00	560.4	486.5	10.05	13.45	0.956	0.980
20:00 to 21:00	563.2	445.2	12.92	15.76	0.927	0.974
21:00 to 22:00	460.0	384.9	11.95	15.46	0.949	0.977
22:00 to 23:00	329.3	273.4	10.83	14.05	0.939	0.980
23:00 to 0:00	216.9	179.7	10.93	14.19	0.947	0.981

comprehensively investigating the impacts of a new toll road, named MD-200 or ICC (as shown in Fig. 1), on the overall traffic conditions and the environment in Maryland. To evaluate its effects, two categories of measurement are proposed: network-wide measures (total vehicle kilometers/hours traveled within the network and average delay per kilometer) and corridor-level measures (corridor level of service and time-dependent speed).

ICC was built in 2011 and is currently being expanded toward northeastern DC, connecting a dense and mixed development urban area in Montgomery County, Prince George's County, and the Baltimore metropolitan and BWI airport areas. ICC is publicly expected to serve as a time-saving alternative route for the already high travel demand in these areas. It is a research interest to determine how ICC can improve traffic and mitigate emissions pollution. To analyze various before-and-after MOEs, both traffic performances with and without ICC are compared by microscopic traffic simulation. Taking advantage of the 24-h large-scale microscopic traffic simulation model, MOEs on different levels of details are evaluated. The regional level evaluation, and corridor and freeway level analyses are presented. Comprehensive MOEs for multiple time scales not only reveal the impacts of ICC, but also demonstrate the capability of the microscopic traffic simulation model for simulating and analyzing regional traffic.

Network-Wide Evaluation

Table 3 presents the network-wide MOEs, including VKT, VHT, delay per kilometer, stop time per kilometer, and average speed

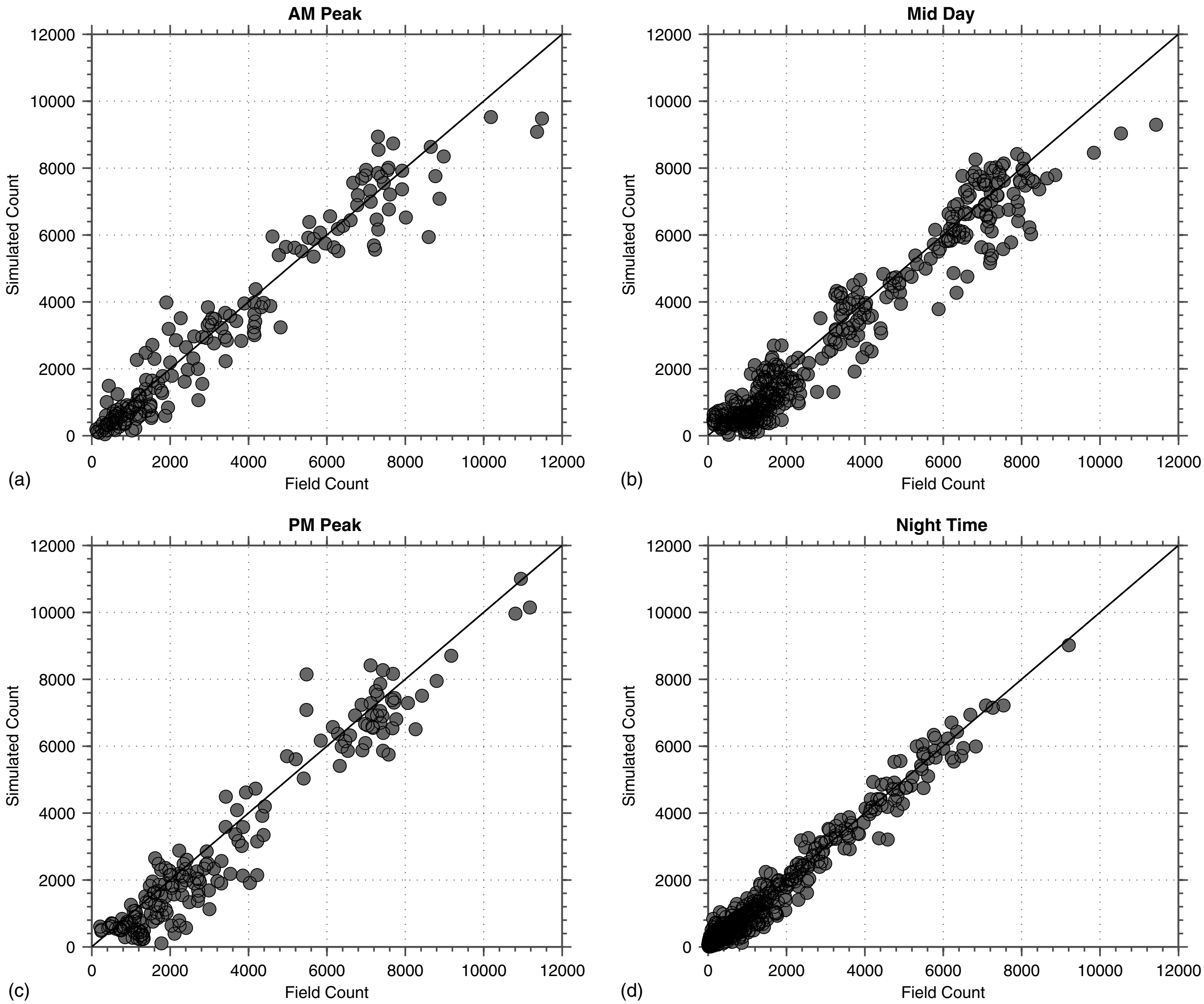

Fig. 2. Comparison of field and simulated counts after calibration: (a) AM peak, 6 a.m.–9 a.m.; (b) midday, 9 a.m.–4 p.m.; (c) PM peak, 4 p.m.–7 p.m.; (d) night, 7 p.m.–6 a.m.

Table 2. Validation Results for Morning and Evening Peaks

		AM peak			PM peak		
Corridors	Direction	Simulated time (minimum)	Observed time (minimum)	12.6% difference (%)	Simulated time (minimum)	Observed time (minimum)	11.2% difference (%)
MD182	NB	13.9	15.3	−9.3	17.4	14.0	24.0
	SB	18.5	17.5	5.7	11.5	12.8	−10.1
MD28	EB	20.4	16.9	20.7	21.9	22.3	−1.9
	WB	26.2	23.9	9.6	22.7	20.0	13.2
MD355	NB	18.0	23.0	−21.8	24.5	30.3	−19.2
	SB	23.1	27.0	−14.5	23.7	25.1	5.4
MD650	NB	18.1	17.1	5.8	20.1	19.3	4.0
	SB	16.8	19.5	13.9	17.4	16.9	3.0
MD97	NB	15.2	12.8	18.8	17.4	14.2	22.2
	SB	15.1	17.2	−12.1	14.7	14.0	5.2
US29	NB	14.1	13.8	2.2	18.9	20.7	−8.6
	SB	32.7	27.9	17.2	15.4	13.1	17.1

Table 3. Comparisons of the Two Scenarios Using the Regional Level MOEs

Measures	Scenarios	Early AM: 12–6 a.m.	AM peak: 6–9 a.m.	Midday: 9 a.m.–4 p.m.	PM peak: 4–7 p.m.	Night: 7 p.m.–12 a.m.
Total VKT [k km (k mi)]	Before ICC	1,707.47 (1,061.2)	3,645.03 (2,265.4)	7,385.15 (4,589.9)	4,298.12 (2,671.3)	4,081.23 (2,536.5)
	After ICC	1,692.67 (1,052.0)	3,687.35 (2,291.7)	7,396.25 (4,596.8)	4,381.15 (2,722.9)	4,047.28 (2,515.4)
	(% change)	−0.87	1.16	0.15	1.93	−0.83
Total VHT (k h)	Before ICC	25.6	75.0	143.1	115.8	76.4
	After ICC	25.4	74.9	139.2	112.2	74.2
	(% change)	−0.78	−0.13	−2.73	−3.11	−2.88
Average delay [s/km (s/mi)]	Before ICC	18.89 (30.4)	38.16 (61.4)	33.75 (54.3)	60.35 (97.1)	31.20 (50.2)
	After ICC	19.08 (30.7)	37.48 (60.3)	32.13 (51.7)	55.75 (89.7)	30.02 (48.3)
	(% change)	0.99	−1.79	−4.79	−7.62	−3.78
Average stop time [s/km (s/mi)]	Before ICC	9.70 (15.6)	17.90 (28.8)	15.85 (25.5)	23.93 (38.5)	14.36 (23.1)
	After ICC	9.57 (15.4)	16.41 (26.4)	15.48 (24.9)	22.13 (35.6)	13.24 (21.3)
	(% change)	−1.28	−8.33	−2.35	−7.53	−7.79
Average speed [km/h (mi/h)]	Before ICC	66.77 (41.5)	48.59 (30.2)	51.65 (32.1)	37.17 (23.1)	53.42 (33.2)
	After ICC	66.61 (41.4)	49.24 (30.6)	53.10 (33)	39.10 (24.3)	54.55 (33.9)
	(% change)	−0.24	1.32	2.80	5.19	2.11

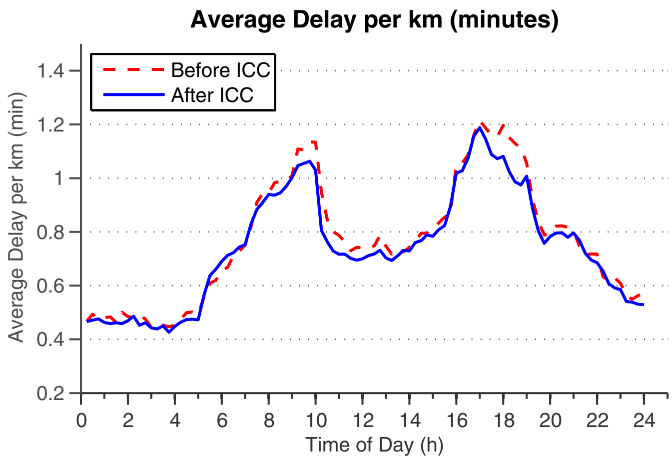

Fig. 3. Average delay per kilometer by time of day

for both scenarios. These MOEs provide a general vision of network-level travel mobility and traffic congestion changes. As expected, because the new toll road serves as a relatively faster alternative travel path and particularly attracts travelers during peak hours, this new infrastructure decreases the delay time in the area compared to the base case. For the early AM and night periods, there is no obvious difference between the two scenarios (early AM only takes up 8% of the entire day's demand). Significant congestion mitigation effects are captured during daytime, especially during the AM and PM peak hours. Fig. 3 illustrates the average delay per network kilometer by time of day to better visualize the time-varying impact of ICC. In terms of average delay per vehicle kilometer, the introduction of ICC causes a 7.62% delay reduction during PM peak hours.

By integrating EPA's *MOVES* model with the microscopic simulation model, the study is capable of estimating the environmental impacts of ICC. The emissions and fuel consumption before and after the construction of ICC are compared in Table 4. Four different types of measures are simulated, including GHG emissions, poisonous emissions, PM contamination, and energy consumptions. In general, the ICC scenario indicates a smaller GHG emission rate and a higher energy utilization ratio, which conforms to the enhanced network-wide traffic conditions obtained from the traffic simulation. Estimated hour-by-hour emission changes for the four major pollutant types and two types of energy consumption are shown in Figs. 4(a–f). A negative value in the figure indicates a reduction in emissions/energy consumption. The scenario with ICC produces slightly higher emissions during the evening and early morning when compared to the baseline scenario. These excessive emissions are generated at the new-build junctions of ICC and its crossing arterials. During the day, the scenario with ICC

Table 4. Comparison of the Two Scenarios Using Emissions and Fuel Consumption

Emission per vehicle kilometer	Early AM:12–6 a.m.		AM peak: 6–9 a.m.		Midday: 9 a.m.–4 p.m.		PM peak: 4–7 p.m.		Night: 7 p.m.–12 a.m.	
	Before ICC	After ICC	Before ICC	After ICC	Before ICC	After ICC	Before ICC	After ICC	Before ICC	After ICC
GHG emissions										
CO_2 (g)	229.63	229.82	240.24	238.91	229.07	228.83	241.05	237.04	222.83	223.64
NO_x (mg)	342.64	342.78	329.29	328.26	382.26	380.15	373.38	368.96	339.16	339.29
CH_4 (mg)	9.90	9.94	21.60	21.44	21.09	20.87	21.21	20.70	16.40	16.52
Poisonous emissions										
NH_3 (mg)	19.15	19.12	18.64	18.51	19.08	18.69	18.83	18.73	18.71	18.59
CO (g)	3.79	3.80	6.32	6.28	6.60	6.54	6.66	6.52	5.47	5.49
SO_2 (mg)	4.52	4.52	4.67	4.65	4.46	4.45	4.69	4.61	4.32	4.34
PM contamination										
Total PM_{10} (mg)	15.76	15.80	17.20	17.14	17.38	17.30	17.39	17.15	15.62	15.76
Total $PM_{2.5}$ (mg)	14.61	14.66	15.87	15.81	16.02	15.95	16.03	15.81	14.41	14.53
Energy consumption										
Petrol energy (KJ)	3,039.53	3,042.01	3,176.88	3,159.29	3,029.09	3,025.79	3,187.26	3,134.31	2,946.55	2,957.24
Fossil energy (KJ)	3,192.60	3,195.15	3,341.95	3,323.43	3,186.76	3,183.34	3,353.51	3,297.82	3,100.06	3,111.31

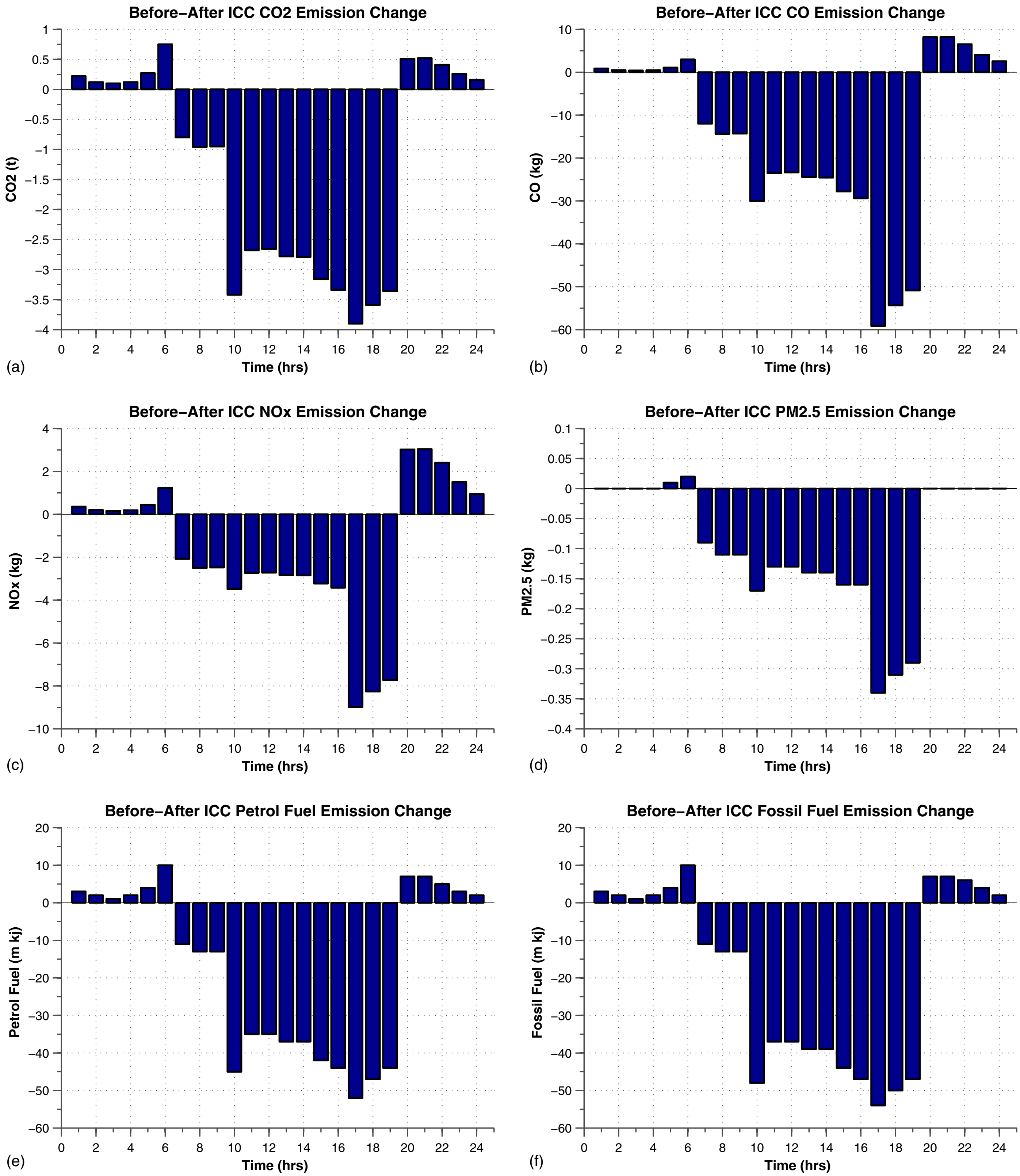

Fig. 4. Emission changes by different emission types: (a) change in CO_2 emission; (b) change in CO emission; (c) change in NO_x emission; (d) change in $PM_{2.5}$ emission; (e) change in petrol fuel consumption; (f) change in fossil fuel consumption

significantly reduces emissions and energy consumption. The most significant energy savings and GHG mitigation happens during the PM peak period. The total savings on fuel energy consumption per kilometer can reach 3.90%, whereas the total reduction of carbon dioxide per kilometer reaches 1.67%. For PM and other gaseous pollutants, the most significant improvement occurs during peak hours. For instance, PM_{10} can be reduced by 1.39% during the PM peak period.

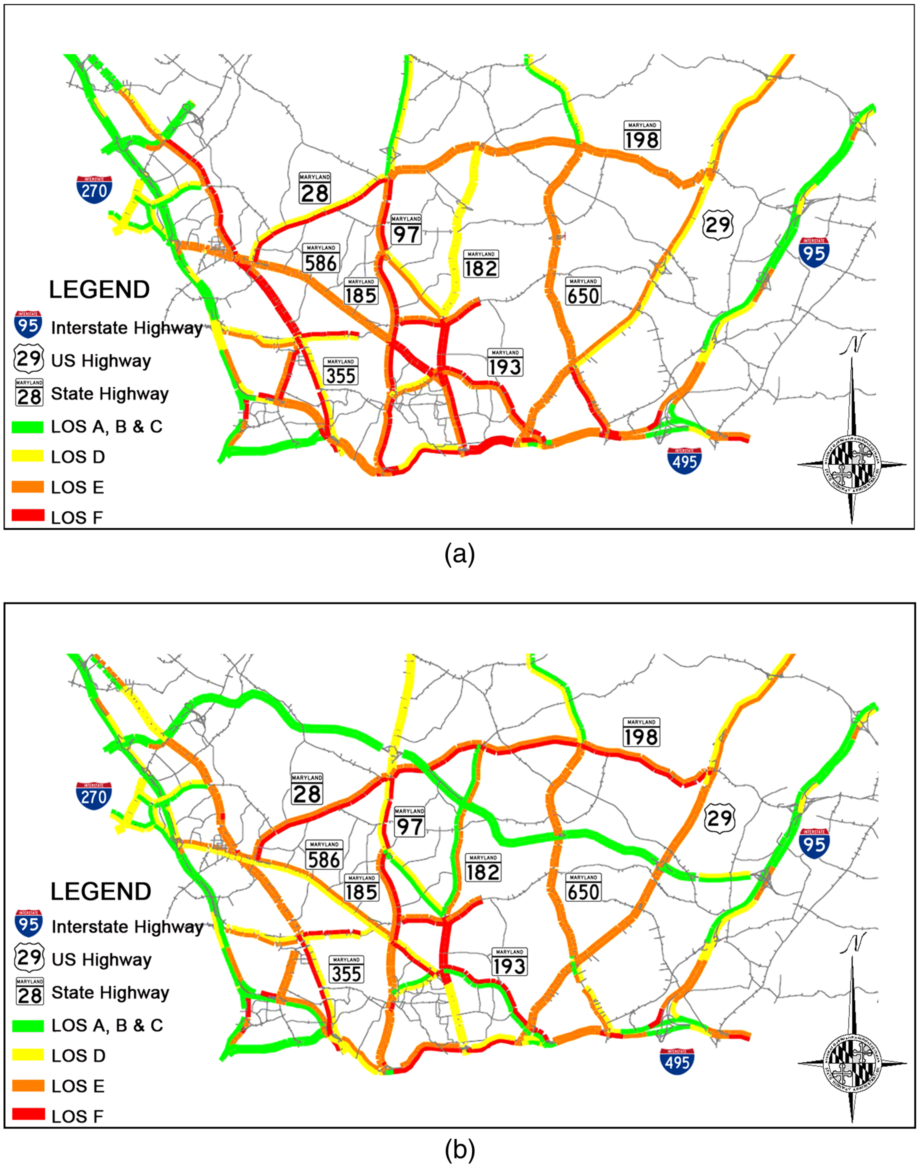

Fig. 5. Freeway and arterial LOS map before and after ICC: (a) freeway and arterial LOS for the no-build scenario; (b) freeway and arterial LOS for the ICC scenario

Corridor Level Impacts

ICC leads to positive impacts on overall traffic condition and emissions control. The model can be used to further evaluate performances of different corridors. Corridor LOS maps make it convenient to spatially assess congestion level and guide project planning and management. The LOS maps of the PM peak period before and after ICC are displayed in Fig. 5 as an example of corridor level analysis. LOS A, B, and C indicate free, stable, and uncongested flow, respectively; D is an indicator of approaching unstable flow; E means that the flow is operating at capacity; F suggests a breakdown flow.

Predicted by the model, ICC will affect traffic on crossing and parallel arterials. For crossing corridors such as US-29, MD-182, and MD-97, the situation grows slightly worse. This is attributable to the disturbance caused by the new-build junctions with ICC. For instance, for MD-97, two signalized intersections are constructed to accommodate on-ramp and off-ramp traffic of the ICC roadway. This is simulated accordingly in the ICC scenario and leads to the additional delay on MD-97. Additionally, initially heavy congestion on segments of the parallel corridors (MD-355, I-270, and I-495) has been mitigated to some extent. The model suggests that more vehicles have been diverted from MD-355 and I-495/I-95 corridors, which are the most severely congested corridors in the DC metropolitan area, to ICC heading toward northeastern suburban areas during PM peak.

The unique features of 24-h simulation allow the authors to conduct a within-day freeway level analysis of highway congestion assessment, traffic speed, and LOS. Before the construction of ICC, I-495, the Capital Beltway, was a highly congested corridor that carries intrastate and interstate travel demand from, via, and to Maryland, Virginia, and Washington, DC. Once fully operational, ICC is believed to serve as a useful alternative corridor to remit I-495 congestion. Judged by the LOS maps in Fig. 4, ICC does reduce congestion on the I-495 corridor. Quantitative measurement of this reduction is obtained by the traffic simulation. This study presents a comparison between space-time diagrams of speed (Fig. 6). The simulation model predicts that ICC will cause noticeable effects to remit the congestion level on I-495. A spatial-temporal

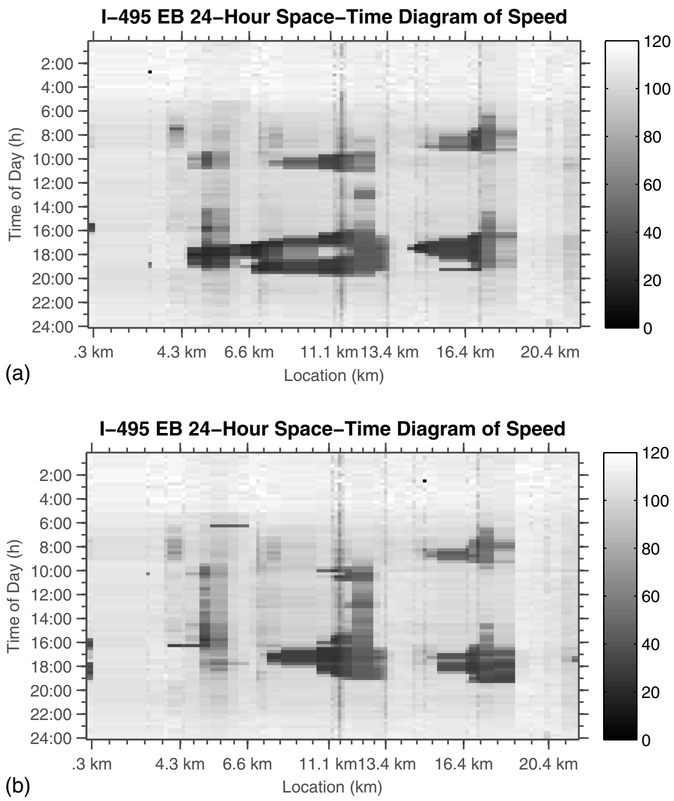

Fig. 6. I-495 EB space-time diagram of speed for the two scenarios: (a) space-time diagram of speed for the no-build scenario; (b) space-time diagram of speed for the ICC scenario

comparison implies that the most significant improvements on I-495 eastbound (EB) are at the joints of I-270 [5.2 km in Figs. 6(a and b)], MD355 (6.8 km), and I-95 (16.4 km). The most significant effects take place during PM peak (the most congested period on I-495 EB, caused by the tidal commuting phenomenon in the area), whereas AM peak and midday also show noticeable improvement. This before-and-after comparison implies an important role of ICC in mitigating congestion, particularly the PM peak congestion, on the Capital Beltway. In the future, this analysis can be extended to other arterial/freeway corridor scenarios, and a similar analysis for intersection queue length can be conducted.

Conclusions

This case study develops a 24-h large-scale microscopic traffic simulation model for the northern Washington, DC, metropolitan area in which a new-build toll road influences daily travel patterns. The case study extends a regional planning model with capabilities for microscopic traffic simulation and emission estimation, both at network and corridor levels. The microscopic traffic simulation model is built in the *TransModeler* environment. The model consists of over 7,000 links, 3,500 nodes, over 40,000 OD pairs, and over 2 million travelers. Three freeway corridors, one new highway with time-of-day pricing, and all major/minor arterials are included in the simulation network. In addition, more than 400 signalized intersections are included to simulate real-world dynamic signal control. This case study represents the largest application of its kind, as confirmed by the software developers.

Multiple ground truth data sources are the prerequisite to model development, such as intersection types, real-world signal timing plans, and speed limits. A complete set of information about traffic control strategies is crucial because it reduces the problem dimension of model calibration such that when calibrating the model, signal timing allocations are no longer confounding variables. The same reason holds for the needs of great quantities of GIS data, which ensures that the nodes, links, lanes, and intersections match the actual geography. Directly converting a regional planning network shape file has not been successful for microscopic simulation.

Based on multiple data sources, comprehensive calibration and validation have been conducted for the robustness and reliability of the model. Data of 24-h field counts at 62 sensor stations are obtained for calibration. Next, the microscopic traffic simulation with simulation-based DTA is applied to obtain simulated volumes. Eight rounds of calibration cost approximately 400 h of computational time for calibrating the 24-h model, using an Intel Xeon 24-Core CPU with 12 GB memory. The overall NRMSE for the calibration falls to 16.77%. This quality of calibration is comparable to many corridor-level simulation studies. An independent validation has also been conducted via comparing simulated and observed corridor travel times. Although countless factors may affect the simulation/calibration results (e.g., OD demand, driving behavior, travel behavior, control strategies, and traffic pattern), this study strives to calibrate a subset of these factors. Calibrating other factors, such as the behavior model parameters, requires high-quality data and modeling techniques to separate different effects, and thus is a subject for future research.

The case study quantifies the traffic and environmental impact of a new-build toll road, ICC, in the Washington, DC–Baltimore metropolitan area, both at corridor and network-wide levels, with respect to delay times, average speeds, and emissions by using microscopic traffic simulation and emission modeling. It contributes to the state-of-the-practice of large-scale microscopic simulation with a unique real-world application. Developing a 24-h large-scale simulation model can be challenging. Major procedures are reported and discussed in the paper, including data preparation, development and integration of traffic and emissions models, calibration of dynamic OD matrices, and model validation. Another highlight of this case study is the emissions estimation, which links simulation outputs and EPA's *MOVES* emission simulator. Different levels of emission estimation have been conducted for environmental impact analysis of ICC using instantaneous link speeds and volumes extracted from the traffic model. Four different types of emissions are quantified, including GHG emissions (CO_2, NO_x, and CH_4), poisonous emissions (CO, NH_3, and SO_2), PM contamination ($PM_{2.5}$ and PM_{10}), and energy consumptions (fossil fuel and petrol fuel). The results provide important insights into the impacts of ICC on air pollutant emissions. The measures suggest moderate improvement in network-wide emissions (on average, −0.40% in CO_2, −0.41% in NO_x, −0.72% in CO, −0.22% in $PM_{2.5}$, and −0.40% in fuel consumption). Corridor-level results suggest that although it generally helps mitigate area-wide congestion level, ICC has a negative influence on crossing arterials. One meaningful reason may be the disturbance (e.g., extra intersection delays) introduced by the highway junctions of those arterials and ICC. On the other hand, ICC induces noticeable benefits to the performance of parallel links, especially during the peak hours. The LOS changes on I-495, the Capital Beltway, which is already one of the busiest corridors in the region, are quantified as an example in which one can magnify each spatial/temporal point to evaluate the impact of ICC.

This calibrated model showcases a case study of 24-h large-scale microscopic traffic simulation model, which is the largest application of its kind. The spatial/temporal scale of the model allows MOEs on different levels of details to be obtained for the case study to investigate the impact of ICC on daily dynamic traffic patterns. Second, as a case study that links 24-h large-scale simulation with emission models such as MOVES, this work demonstrates the feasibility of employing a popular emissions simulator as a post-processor to quantify environmental impacts attributable to the introduction of new infrastructure.

The 24-h large-scale simulation model can serve as a test bed in the analysis of a wide range of policies, control and management strategies, and driving/travel behavior decision-making processes. It can be used to analyze active traffic management schemes (e.g., ramp metering, dynamic lane controls, and en-route diversion), because the model can capture the dynamic traffic conditions on multiple corridors. With the 24-h traffic simulation, within-day and day-to-day behavioral dynamics can also be researched once agent-based behavioral models are integrated. In this sense, the dynamic traffic patterns are coupled with fine-grained demand-side dynamics, because the simulated agents will not only determine routes through simulation-based DTA but also dynamically choose the destinations, travel modes, and departure times. This may become a promising research direction for microscopically, dynamically, and behaviorally forecasting the future.

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