Assessment of the Impact of Electronic Toll Collection on Mobile Emissions in the Baltimore Metropolitan Area

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February 2002

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ABSTRACT

This paper describes a recent study, which was conducted to assess the aggregated impact of the electronic toll collection system (locally called M-Tag) deployment at the three major toll plazas in the Baltimore Metropolitan Area. The study focused on the reduction in mobile emissions, including hydrocarbon, carbon monoxide, and nitrogen oxide, for peak hour periods. The analysis involved two major stages: (1) development of simulation and deterministic models used to generate traffic flow parameters, including speed and driving cycles for the study areas; and (2) employment of the traffic flow parameters from stage 1 to quantify the hourly emissions. Three scenarios were analyzed to quantify the air-quality associated with M-Tag deployment. The first scenario involved the pre-M-Tag deployment condition. The second scenario was based on the initial condition following the deployment of M-Tag, and involved market penetration levels ranging from 21 percent to 28 percent at the three toll plazas. The third scenario represented the current condition involving approximately 50 percent M-Tag market penetration level. A comparative analysis of the pre-M-Tag and post-M-Tag deployment scenarios showed 40 to 63 percent reduction of hydrocarbon and carbon monoxide, and approximately 16 percent reduction of nitrogen oxide in the study area. The results were similar for the simulation and deterministic models. It was also observed from the study that the performance of M-Tag system has improved significantly, because motorists are increasingly familiar with the system, resulting in fewer incidents of weaving-related problems at the toll plazas.

ACKNOWLEDMENT

This paper is based on a study sponsored by the National Transportation Center, Morgan State University. The authors thank Eunice Omaya, Andreane Johnson, Maola Masafu and Gbolahan Afonja of Morgan State University for providing assistance in data collection, simulation and data analysis. The authors also thank Keith Duerling, Howard Moore and Robert Alter of the Maryland Transportation Authority for providing the throughput and M-Tag market penetration data, and Mohamed Khan of the Maryland Department of the Environment for providing the calibrated Mobile 5b input parameters. Special thanks also go to Richard Glassco of Mitretek Systems, Inc. for providing assistance in using the Westa simulation model.

INTRODUCTION

Historically, tolls have been one of the most effective and equitable means of collecting user fees for financing and maintaining transportation infrastructure. However, toll plazas (particularly, manually operated plazas) adversely affect the throughput or capacity of roadways. The adverse effect of toll plazas is particularly evident during rush hours, when traffic is usually heavy. For manually operated toll plazas, where human attendants collect tolls, each vehicle must come to a stop in order to be processed. Past experience has revealed that the average service rate for a manual tollbooth ranges from 350 to 500 vehicles per hour (vph). Therefore, it is not surprising that toll plazas located on heavily traveled corridors experience lengthy vehicular queues, resulting in long delays and increased mobile emissions.

As the federal government's regulations on the environment (including air pollution) intensify, the metropolitan areas categorized as non-attainment areas under the Clean Air Act Amendments (CAAA) of 1990 have been aggressively exploring innovative mitigation strategies. One of such strategies involves the use of intelligent transportation system (ITS) technologies for managing traffic demand and incidents in order to minimize vehicular delays and mobile emissions. An increasing number of the non-attainment areas of the western and eastern parts of the United States have been deploying electronic toll collection (ETC) technology at toll facilities, which results in significantly higher throughputs and hence less delay than conventional (manned) tollbooths.

The Baltimore Metropolitan Area, which is the study area reported herein, has three major toll facilities (Fort McHenry Tunnel plaza on I-95, Baltimore Harbor Tunnel plaza on I-895 and Francis Scott Key Bridge plaza on I-695). In early spring 1999, the ETC system, which is locally known as M-Tag, was deployed at all three toll plazas in the Baltimore area. In summer 1999, a pilot study (1, 2) funded by the National Transportation Center (NTC) at Morgan State University was undertaken to evaluate the effectiveness of the newly deployed ETC in reducing mobile emissions in the Baltimore Metropolitan Area. Henceforth, the terms ETC and M-Tag will be used interchangeably.

The pilot study focused primarily on the Fort McHenry Tunnel toll plaza, which is the largest of the three toll facilities. The study involved two major steps. The first step involved the validation and use of microscopic simulation to analyze the traffic situation at the toll plaza. The primary output of the simulation analysis was the average time spent in the system, which was converted to the average travel speed at the toll plaza. The analysis compared the output data for the pre-M-Tag and post-M-Tag deployment scenarios. The second step involved the use of the average speed data obtained from the simulation analysis with the Mobile 5b software to estimate the respective mobile emission rates for the pre-M-Tag and post-M-Tag deployment scenarios.

The result of the pilot study showed significant decrease in mobile emission rates (i.e., 40 percent decrease for hydrocarbon [HC], 41 percent for carbon monoxide [CO], and 11 percent decrease for nitrogen oxide [NO_x]) at the vicinity of the study area (the Fort McHenry Tunnel toll plaza). The preliminary findings from the pilot study motivated a second NTC project funded to extend the scope of the study to encompass the three toll plazas in the Baltimore Metropolitan Area.

STUDY OBJECTIVES

The primary objective of this second phase of the study was to conduct a more detailed and extensive analysis in order to estimate the aggregated impacts of M-Tag usage at the three toll-plazas in the Baltimore Metropolitan Area. Specifically, this study was to estimate from combined empirical and simulated data the reduction of mobile emissions [i.e., hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxide (NO_x)] attributed to the M-Tag deployment at the toll plazas in the Baltimore area. A secondary objective was to identify, from field observations, the obvious design problems affecting the performance of the M-Tag system.

In summary, the additional contributions of this second phase of the study include:
(1) Revised current market penetration values of M-Tag technology in Baltimore;
(2) Collection of new sets of hourly volume, throughput, and delay data;
(3) Disaggregation of the simulated vehicular speed data, which describe more accurately the driving cycle at the toll plazas reported herein;
(4) Updating of local parameter values for the *Mobile 5b* emission-model;
(5) Comparative analysis of results obtained from *Mobile 5b* and a modal level (*CMEM*) emission model;
(6) Estimation of the total reduction of mobile emissions for the three toll plazas using both a deterministic model and a simulation model.

STUDY METHODOLOGY

Consistent with the pilot study, the methodology used in this second phase of the study involved three major activities: (1) literature review of related studies, (2) modeling, and (3) data collection and analysis.

Literature Review

The primary objective of this study involved quantification of mobile emissions reduction attributed to the use of ETC. The study was motivated by the following previous studies:

- Lampe and Scott (3) demonstrated from a laboratory study that the use of ETC decreased HC emissions from 0.72 g/km to 0.12 g/km, NO_x emissions from 0.66 g/km to 0.36 g/km, and CO emissions from 18.36 g/km to 5.10 g/km. The corresponding percent decrease in the three emission compounds is 500 percent, 83 percent, and 260 percent, respectively.
- Guensler and Washington (4) estimated the reductions in CO emissions attributed to ETC to range from 7 g/vehicle to 650 g/vehicle, depending on the deployment scenarios assumed.

- Lennon (5) projected from a "microscale carbon dioxide analysis" 30 percent reduction (i.e., 12.3 ppm to 8.8 ppm) in CO concentrations.
- Saka et al. (1, 2) estimated from simulation 40 percent decrease in HC and CO, and 11 percent decrease in NO_x from the use of ETC at the market penetration level of 28 percent. The study also reported a 150 percent increase in throughput for exclusive ETC lanes.
- Burris and Hildebrand (6) used microsimulation analysis to estimate up to a 60-second reduction in delay and up to a 55-vehicle reduction in queue lengths.
- Al-Deek, Mohamed, and Radwan (7) estimated a 160 percent increase in throughput and a two and half to three minute per vehicle decrease in delay from the use of ETC.

As demonstrated from past studies, the use of ETC is effective in increasing throughput and hence in decreasing mobile emissions at toll plazas. However, the magnitude of ETC effect depends on the traffic intensity at the toll plaza being studied and the market penetration level of ETC. For example, the benefit of ETC is almost negligible for light traffic and low levels of ETC usage, and vice versa. The aforementioned pilot study (1, 2), which was conducted in 1999, focused on the Fort McHenry Tunnel toll plaza in Baltimore and was based on a 28 percent market penetration level of ETC usage. The study reported herein investigated a much higher range (approximately 50 percent) of market penetration level for the three toll plazas in the Baltimore area, which resulted in significantly greater benefit of ETC usage than previously reported in the pilot study.

Modeling

A summary of the modeling framework used in the study described herein is presented in Figure 1. Two sets of models were employed: traffic model and emission model.

Traffic Model

The traffic model treated the toll plazas as multi-server queuing systems. Two (simulation and deterministic) types of models were used to generate pertinent queue and delay data. The delay or travel time data were used to estimate average vehicular travel speed at the toll facilities. Supplemental data, including the driving cycle data, were also obtained from both models. Two types of servers were modeled: Manual and Automated servers. The manual-servers category involves a composite case of human and electronic toll collection capability. Under this service category, which henceforth will be referred to as manual tollbooths/servers, the tollbooths are equipped with both human and machine attendants, and are capable of processing M-Tag and non-M-Tag equipped vehicles. The second category of servers, which will be referred to as M-Tag tollbooths/servers, involved dedicated tollbooths exclusively used for processing M-Tag equipped vehicles.

Unlike the manual-service category, vehicles using the M-Tag tollbooths do not have to stop completely but travel within the posted speed limit in order to be processed. The posted speed limit varies for the three toll plazas but ranges from 8 kilometer per hour (kph) to 25 kph approximately. Six of the available 24 tollbooths at the Fort McHenry Tunnel toll plaza, four of the available 14 tollbooths at the Baltimore Harbor Tunnel toll plaza, and two of the available 12 tollbooths at the Francis Scott Key Bridge toll plaza were exclusively used for serving M-Tag equipped vehicles. Table 1 summarizes the classification of tollbooths in the study area. Clearly, the exclusive M-Tag tollbooths have much higher throughput values than the manual tollbooths because vehicles do not stop completely at the exclusive M-Tag tollbooths.

Simulation Model

A microscopic simulation model known as Westa was used in modeling the traffic patterns during the morning peak-hour period at the three toll plazas in the Baltimore Metropolitan Area. The simulation model comprises five primary blocks. The first block reads user supplied input data, which include roadway, vehicle and driver (i.e., aggressive and normal drivers, and perception-reaction time distribution) attributes. The second block (vehicle creation model block) generates different types of vehicles based on user specified inter-arrival time and traffic composition. Vehicle types generated range from passenger cars to six-axle tractor-trailers. A subgroup of vehicles was also created to represent cars equipped with the M-Tag technology. The third simulation block executes user specified vehicle-following logic, including gap acceptance, and acceleration/deceleration criteria. The fourth simulation block facilitates the execution of the two toll collection schemes (i.e., manned tollbooths and exclusive M-Tag tollbooths) based on user specified toll transaction time and the associated probability distribution. The fifth block is associated with processing input data and providing summary statistics of output data.

Deterministic Model

The deterministic model described herein is a composite model developed from queuing and traffic-flow principles. The model was developed using the following assumed driving cycle:

(1) Toll plazas are multiple-server queuing systems, where vehicles remain in the queue to be served;
(2) Upstream vehicles travel at a uniform cruise velocity (u_c) and join the queue at "jam" velocity (u_j), which is the average speed of vehicles in the queue;
(3) Vehicles in the queue are spaced uniformly at a spacing (s_j) corresponding to the jam density (k_j); and
(4) Maximum attainable velocity for vehicles in the queue is constrained by the assumed values of jam spacing (s_j), jam vehicular acceleration rate (a_j) and jam vehicular deceleration rate (d_j).

The term "jam" is used herein to describe the traffic parameters for the over-saturated flow condition. The primary objectives of the deterministic model are two fold. First, provide a fast, inexpensive and reliable method of estimating the expected total travel time for individual vehicles at the toll facility. Secondly, determine a representative driving cycle at the toll facilities. The total travel time and the driving cycle information were used to estimate the total mobile emissions for the M-Tag deployment scenarios considered herein.

Estimation of Travel Time

The total vehicular travel time within the toll facility was determined as:

$$t_s = t_1 + t_2 + t_3 \quad (1)$$

where
t_s = total time spent in the system or toll facility,
t_1 = time spent at cruise velocity before joining the queue,
t_2 = time spent braking from cruise velocity (u_c) to queue or jam velocity (u_j),
t_3 = time spent at toll plaza (including queue time and service time).

The cruise time was determined as:

$$t_1 = [l_s - l_q - l_b]/u_c \quad (2)$$

where
l_s = length of roadway segment (m),
l_q = expected queue length (m),
l_b = expected braking distance (m),
t_1 = time spent at cruise velocity (s), and
u_c = average cruise velocity (m/s).

In Equation 2, the expected queue length was approximated as one-half of the 95th percentile queue length, which was determined as: (8)

$$N_q = (450T)\{(v/c)-1 + [(v/c - 1)^2 + [(3600n_1/c)(v/c))/(150T)]^{0.5}\}(c/(3600n_1)) \quad (3a)$$

$$l_q = l_{toll} + \max\{[s_jN_q - (l_{toll})], 0\}(n_1/n_2), \text{ for } l_{toll} \leq s_jN_q \quad (3b)$$

$$l_q = s_jN_q, \text{ for } l_{toll} \geq s_jN_q \quad (3c)$$

where
N_q = Expected total number of vehicles in the queue per lane at the toll plaza,
T = analysis period (h),
v = arrival volume (vph),
c = hourly throughput (vph),
l_q = length of queue at the toll plaza (m),
l_{toll} = length of toll service lanes,
$s_j = 1000/k_j$ = jam space headway (m),
k_j = jam density (veh./km),

n_1 = number of toll service lanes, and
n_2 = number of upstream mainline traffic lanes.

In Equation 3b, the expression $\max\{[N_q - (l_{toll}/s_j)], 0\}(n_1/n_2)$ is the length of component of the queue which overflows onto the mainline segment of the road.

In Equation 2, the required braking distance for decelerating from cruise speed to queue speed was determined as:

$$l_b = (u_c^2 - u_j^2)/2d \quad (4)$$

where
u_c = cruise velocity of upstream traffic (m/s),
u_j = final velocity of vehicles joining the queue (m/s), and
d = assumed deceleration rate of vehicles (m/s^2).

In Equation 1, the braking time of upstream vehicles from cruise speed to queue speed is

$$t_2 = (u_c - u_j)/d \quad (5)$$

and the time vehicles spent at the toll plaza is

$$t_3 = l_q/u_j \quad (6a)$$

and using the fundamental traffic-flow principle,

$$u_j = c/(n_1 k_j) \quad (6b)$$

where
u_j = average speed under jam density condition,
k_j = jam density, and
c = throughput.

In Equation 1, the total time spent at the toll plaza was determined as:

$$t = \{[l_s - l_q - (u_c^2 - u_j^2)/2d]/u_c\} + \{(u_c - u_j)/d\} + \{l_q n_1 k_j/c\} \quad (7)$$

In Equation 7, each of the time components as defined in Equation 1 is enclosed in braces {}. The average vehicular speed at the toll plaza was determined as:

$$u_{ave} = l_s/t \quad (8)$$

Emission Model

The second step of the modeling process involved the use of mobile emission models to quantify the quantities of CO, HC, and NO_x produced for the pre-M-Tag and post-M-Tag deployment scenarios. The analysis was performed for pre-M-Tag and post-M-Tag scenarios, in order to determine the contributions of M-Tag deployment in reducing mobile emissions in the study area. The difference in the values of the mobile emissions for the pre-M-Tag and post-M-Tag scenarios was attributed to the effect of the M-Tag deployment.

Two categories of models (*Mobile 5b* and *CMEM* [Comprehensive Modal Emissions Model]) were considered and used in the study. Mobile 5b is a planning-type model, which uses a set of fixed driving cycles to estimate mobile emissions. CMEM is a modal-level emission model that captures the effects of vehicular acceleration and deceleration on mobile emissions.

Only the results obtained from Mobile 5b are presented in detail herein, because it is used as the official mobile emission model for the Baltimore Metropolitan Area. However, a comparison analysis was undertaken for Mobile 5b and CMEM, using a sample problem.

Data Collection & Analysis

The following sets of data were collected at the three toll plazas in order to estimate mobile emissions reduction attributed to M-Tag usage:

1. Peak arrival volumes;
2. Peak departure volumes (throughputs);
3. Average time spent in the system (including service time); and
4. Local parameters for emission models.

Peak Hourly Arrival Data

Two-way arrival volume data for the morning peak period, from 7 am to 8 pm, were collected at the three toll plazas for three weekdays (Tuesday through Thursday) in spring 2001. The average flow data, which are rounded to the nearest hundred, are summarized as:

- 6500 vph for southbound Fort McHenry Tunnel Toll Plaza (SB FMT)
- 2700 vph for northbound Fort McHenry Tunnel Toll Plaza (NB FMT)
- 4000 vph for southbound Baltimore Harbor Tunnel Toll Plaza (SB BHT)
- 2500 vph for northbound Baltimore Harbor Tunnel Toll Plaza (NB BHT)
- 2000 vph for southbound Francis Scott Key Bridge Toll Plaza (SB FSK)
- 1500 vph for northbound Francis Scott Key Bridge Toll Plaza (NB FSK)

Based on the observed throughput data obtained from the Maryland Transportation Authority (MdTA), the current market penetration of M-Tag was estimated to be approximately 50 percent for peak hour traffic at the three toll plazas. It was also estimated from the observed throughput data that the exclusive M-Tag lanes process up to 1350 vehicles per hour per lane (vphpl). Regular toll lanes with human servers are capable of processing between 450 vphpl and 500 vphpl, depending on the number of M-Tag vehicles using the regular lanes.

Throughput Volumes

For the study described herein, the capacity throughput assumed for manned toll lanes and exclusive M-Tag lanes were 475 vphpl and 1350 vphpl, respectively. For the pre-M-Tag scenario, a slightly lower capacity (450 vphpl) was assumed for manned toll lanes. The capacity of manned toll lanes was higher for the post-M-Tag scenario because some M-Tag vehicles, usually those unable to weave to the exclusive M-Tag lanes, use the manned tolls, which are also equipped to process M-Tag vehicles.

Travel Time Data

Peak hourly travel time data were collected in spring 2001 at the three toll plazas for the manned toll lanes and the exclusive M-Tag lanes. The travel-time data was collected from observing randomly selected vehicles at established reference locations (usually at the location where the mainline lanes widen to form the toll lanes) until the vehicles exit the tollbooths. The southbound average travel times were determined as follows:

- For Fort McHenry Tunnel (FMT) Toll Plaza, the average travel time was 23 sec and 81 sec for the exclusive M-Tag lanes and the manned lanes, respectively. The travel distance was 310 m.
- For Baltimore Harbor Tunnel (BHT) Toll Plaza, the average travel time was 20 and 47 sec for the exclusive M-Tag lanes and the manned lanes, respectively. The travel distance was 175 m.
- For Francis Scott Key Bridge (FSK) Toll Plaza, the average travel time was 15 and 30 sec for the exclusive M-Tag lanes and the manned lanes, respectively. The travel distance was 278 m.

Model Parameters

The local model parameters, including ambient temperature, and vehicle-fleet categorization by age and type, were obtained from Maryland Department of the Environment (MDE) for the mobile 5b emission models. The fleet data used in mobile 5b were also mapped for application in CMEM modal emission model.

Validation of Models

The two (simulation and deterministic) categories of models used in estimating the mobile emissions at the three toll plazas in Baltimore were validated using the speed data determined from the observed travel time data for the current M-Tag market penetration level of 50 percent. The maximum difference between the observed average speed and the average speed obtained from both simulation and deterministic model is 15 percent approximately for the three toll plazas. The maximum difference between the average speed obtained from simulation and the deterministic model is 10 percent approximately for the three toll plazas. Samples of the validation results are presented in Figures 2a and 2b.

SUMMARY OF RESULTS

The results obtained from analyzing the different scenarios of M-Tag market penetration level using the deterministic and simulation model are presented in Tables 2 and 3, respectively. The results in Tables 2 and 3 were determined using a zone of influence spanning 630 m for the Fort McHenry Tunnel toll plaza, 395 m for the Harbor Tunnel toll plaza, and 455 m for the Francis Scott Key Bridge toll plaza. The zones of influence used represent the distance from the point of transition for upstream traffic lanes to the point of transition for downstream traffic lanes. The analysis showed significant decrease in mobile emissions, ranging from 40 percent to 63 percent approximately for HC and CO, and 16 percent approximately for NO_x, at the three toll plazas, from pre-M-Tag to the current 50 percent market penetration level of M-Tag. Summaries of the percent reduction of mobile emissions are presented in Table 4.

DRIVING CYCLES

The operational benefit of M-Tag deployment is also captured from the driving cycle data obtained from the simulation for different scenarios of M-Tag market penetration level. Figures 3a, 3b, and 3c, were generated from the microscopic simulation model for the pre-M-Tag and post-M-Tag scenarios. For example, Figure 3a (the pre-M-Tag scenario) shows a much higher frequency of stops than Figure 3b (the post-M-Tag scenarios). Figure 3c, which represents an exclusive M-Tag lane, shows no stops.

The deterministic model described herein was also used to develop the driving cycle data. As an illustration, a sample driving cycle data is presented in Figure 4a for the case problem in Example 1. The generation of the driving cycle from the deterministic model was based on the following rules:

- Vehicles approaching the toll plaza maintain a constant cruise speed (u_c).
- At a distance corresponding to the braking distance from the back of the queue, vehicles decelerate uniformly from the initial cruise speed (u_c) and join the queue at the final speed (u_j). For exclusive M-Tag lanes, where queues are seldom formed, the final approach speed (u_a) used was based on field observations as opposed to the posted speed limit at the tollbooths.

- In the queue, vehicles travel in a stop-and-go pattern, until exiting the toll plaza.
- The average number of acceleration and deceleration maneuvers undertaken by individual vehicles corresponds to the average queue size.

The maximum speed of the vehicles in the queue is constrained by the assumed value of the jam density (k_j) and hence the spacing (s_j) between vehicles, and the assumed jam acceleration (a_j) and deceleration (d_j) rates.

The following calibrated and validated parameter values were used:

- u_c = 90 kph (25 m/s)
- u_j = 4.7 kph (1.3 m/s) and 40 kph (11 m/s) for the manned toll lanes and the exclusive M-Tag toll lanes, respectively
- k_j = 96 veh/km or 0.96veh/m; (s_j = 10 m)
- a = 1.5 m/s^2 for normal traffic flow; a_j = 0.25 m/s^2 for jam traffic condition
- d = 4.5 m/s^2 for normal traffic flow; d_j = 1.0 m/s^2 for jam traffic condition
- c = 450 vphpl for pre-M-Tag scenario, and 475 vphpl and 1350 vphpl for manned toll lanes and exclusive M-Tag lanes, respectively, for post-M-Tag scenario.

Example 1: Determination of Driving Cycle

This example illustrates the determination of a driving cycle for a pre-M-Tag scenario, using the deterministic approach described herein. The supplemental data used for the illustration are:

- v = 5700 vph
- n_1 = 12 lanes
- n_2 = 4 lanes
- l_s = 310 m
- l_{toll} = 310 m
- T = 1 h

Problem 1

1. Determine the average travel time and travel speed at the toll plaza.
2. Develop a representative driving cycle for the scenario analyzed using the deterministic model and the simulation model, respectively.
3. Compare the estimated mobile emissions from Mobile 5b and CMEM for the deterministic model and the simulation model, respectively.

Analysis 1

- Step 1. Given: $c = (12)(450) = 5400$ vph or 1.5 vps; $k_j = 100$ veh/km or 0.1 veh/m; Therefore, $t = \{[310 - l_q - (25^2 - 1.3^2)/2(4.5)]/25\} + \{(25-1.3)/4.5\}$

  $+ \{l_q(12)(0.1/1.5)\} = (310 - l_q - 69.3)/25 + 5.3 + 0.8\ l_q$ from Equation 7.
- Step 2. To determine the appropriate expression for l_q, it is first necessary to calculate N_q.

$N_q = (450)(1)\{(5700/5400) -1 + [(5700/5400 -1)^2 + [(3600(12)/5400)(5700/5400)]/((150)(1))]^{0.5}\}(5400/(3600(12))$
$= 16.8$ or 17 veh (from Equation 3a); and $l_q = 170$ m, because $s_jN_q \leq l_{toll}$ from Equation 3c.

- Step 3. Therefore, $t = (310 - 170 - 69.3)/25 + 5.3 + (0.8)(170) = 144$ sec or 2.4 min; and the average travel speed from upstream distance of 310 m is estimated as:

  $u_{ave} = 310/144 = 2.2$ m/s or 7.8 kph from Equation 8. It can be verified that the average travel time in the queue is the third component (i.e., 136 sec) of the total travel time, which corresponds to average speed of $u_{ave} = 170/136 = 1.3$ m/s or 4.5 kph. Based on flow, density, and speed relationship, the hourly throughput of 450 vphpl is obtained, which was the assumed capacity.
- Step 4. The driving cycle within the segment being analyzed was determined using the three components (t_1, t_2, and t_3) of travel time computed above. For t_1, the speeds used were determined as:

  $$u_1(t) = u_c \quad (9a)$$

  For t_2, the speeds used were determined as:

  $$u_2(t) = u_c - (d)(t) \quad (9b)$$

  For t_3, vehicles are assumed to accelerate uniformly from stop position to the maximum velocity (u_3) allowed by s_j (the jam spacing) and decelerate back to stop position. The acceleration-deceleration cycle, which is assumed to have a cycle-length equivalent to the average service (toll processing) time, is repeated for the duration of t_3.

  $$u_3 = [(2a_jd_js_j/(a_j + d_j)]^{0.5} \quad (9c)$$

  $$x_a = u_3^2 /2a_j \quad (9d)$$

$$x_d = u_3^2 / 2d_j \tag{9e}$$

$$t_a = u_3 / 2a_j \tag{9f}$$

$$t_d = u_3 / 2d_j \tag{9g}$$

$$t_{a,d} = u_3(a_j + d_j)/2a_jd_j \tag{9h}$$

where

x_a = distance traveled from the stop position to u_3, and x_d = distance traveled from u_3 back to the stop position, t_a = acceleration time from the stop position to u_3, t_d = deceleration time from u_3 back to the stop position, and

$$s_j \geq x_a + x_d. \tag{9i}$$

The elapsed time between acceleration-deceleration cycles was determined as:

$$t_e = (3600n_1/c) - t_{a,d} \tag{9j}$$

where

t_e = elapsed time between acceleration-deceleration cycles, during which vehicles are in stop position, and

$(3600n_1/c)$ in Equation 9j is the average inter-service (toll processing) time.

The cycle length, τ, which is the elapsed time between two successive acceleration or deceleration is determined as:

$$\tau = t_{a,d} + t_e \tag{9k}$$

- Step 4.1 Time to decelerate from u_c to u_j is $t_2 = (25 - 1.3)/4.5$ or 5.3 sec (from Equation 5).
- Step 4.2 Vehicles joining the queue at speed u_j will accelerate to speed u_3 or decelerate to a complete stop (i.e., $u = 0$). Assuming that vehicles decelerate to a complete stop upon joining the queue, the time of deceleration from u_j is $t_d = (u_j - 0)/d_j = 1.3/1.0$ or 1.3 sec. Therefore, the total time of deceleration from u_c to u_j and from u_j to $u = 0$ is $t_2 + t_d$ or 6.6 sec.

- Step 4.3 Vehicles remain at the stop position for time t_e or (3600)(12)/5400 - 5 or 3 sec (from Equations 9h and 9j).
- Step 4.4 Vehicles from the stop position, after time t_e, accelerate to speed u_3 = $[(2)(0.25)(1.0)(1.0)/(1 + 2.5)]^{0.5}$ = 2 m/s or 7.2 kph (from Equation 9c). The time to achieve u_3 is determined as $u_3/2a_j$ = 2/2(0.25) or 4 sec (from Equation 9f).
- Step 4.5 Vehicles from u_3 decelerate back to the stop position, and the time used is determined as $u_3/2d_j$ = 2/2(1.0) or 1 sec (from Equation 9g).
- Step 4.6 The time to complete one cycle of acceleration and deceleration in the queue is determined as $t_{a,d} = t_a + t_d$ or 5 sec (from Equation 9f – 9h).
- Step 4.7 The cycle length (i.e., the elapsed time between two successive acceleration or deceleration) is determined as $\tau = t_{a,d} + t_e$ or 8 sec (from Equation 9k).
- Step 4.8 Number of acceleration-deceleration cycles for individual vehicles in the queue at the toll plaza is determined as $\eta = t_3 / \tau$ = 136/8 or 17 (from Equations 6a, 6b, and 9k).

The resulting driving cycle for Example 1 obtained from the above computational steps is presented in Figure 4a. The driving cycle obtained from the simulation model for the same problem is presented in Figure 4b. For the purpose of comparison, two additional driving cycles (see Figures 4c and 4d) were generated from the Poisson distribution using a parameter (λ = 7.8) value equivalent to the average speed determined from Example 1. The mobile emissions, obtained from CMEM and Mobile 5b, associated with the four driving cycles depicted in Figure 4 are presented in Table 5. As expected, the two emission models showed significantly different results, particularly for NO_x. The significant difference in the emission results may be attributed to the fact that CMEM uses as its input data the site specific driving cycle data, which is known to vary significantly even for the same average speed. The Mobile 5b model, however, is based on fixed driving cycles for the individual speed categories.

The fixed driving-cycle property of Mobile 5b affects its robustness in estimating the mobile emissions for driving cycles significantly different from those assumed in the model. For example, the driving cycles in Figure 4, albeit different, correspond to the same average speed of 7.8 kph approximately. As shown in Table 5, Mobile 5b gave the same values of mobile emissions for all four of the driving cycles, because the model uses the average speed as part of its input data. Conversely, CMEM gave different values of mobile emissions for all four of the driving cycles, because the model uses the vehicle's acceleration-deceleration activity data as part of its input data. In Table 5, the significant difference in the estimated values of NO_x for CMEM and Mobile 5b needs a more careful scrutiny in order to determine which of the two emission models gives a more accurate estimate of this category of emission. Empirical studies are required in order to demonstrate, for the same average speed, the level of contribution of different scenarios of vehicular acceleration-deceleration activities on NO_x production.

CONCLUSIONS

This paper describes a recent study of the operational benefits associated with the deployment of M-Tag (electronic toll collection) technology at the three major toll plazas in the Baltimore Metropolitan Area. Specifically, the study focused on the air quality benefit component, and it's considered the first complete study to assess the aggregated reduction in mobile emissions from the use of M-Tag. Two different modeling (simulation and deterministic) approaches were adopted to generate the traffic input data (speed and driving cycle) used for estimating the mobile emissions. The rationale for developing a deterministic model was to streamline and simplify the process of generating the required traffic parameters for estimating traffic delay and hence mobile emissions. Unlike simulation, which involves a tedious and costly process, all the computational steps required for the deterministic modeling process can be completed with a simple hand-held calculator. The comparative analysis undertaken for the results obtained from the simulation and deterministic models showed similar patterns of benefits from the use of electronic toll collection. However, the two emission models (CMEM and Mobile 5b) used in the analysis gave different results, which may be attributed to the heterogeneity of their parameters and required input data.

Based on the study results, it can be postulated that the use of electronic toll collection is an effective strategy for mitigating air-quality related problems, particularly in the regions classified as non-attainment areas. The current market penetration level of 50 percent of M-Tag usage resulted in the reduction of HC and CO emissions by 40 to 63 percent, and the reduction of NO_x emission by 16 percent approximately, in the vicinity of the toll plazas. The peak-hourly reduction in mobile emissions (approximately 4.8 kg of HC, 43.3 kg of CO, and 1.4 kg of NO_x) obtained from Mobile 5b is considered significant. The traffic pattern at the three toll plazas analyzed, which serve the majority of peak-hour commuters and out-of-state traffic in the Baltimore Metropolitan Area, is similar for the morning and evening peak periods, which last approximately four hours daily. The aggregated reduction attributed to the current level of M-Tag usage for the morning and evening rush periods can be estimated by increasing the hourly quantity by a factor of 4; i.e., 19.2 kg of HC, 173 kg of CO, and 5.6 kg of NO_x. As demonstrated in Table 5, the values obtained from Mobile 5b are considered conservative, because results obtained from CMEM are likely to show much higher benefits, particularly for NO_x reduction, which appears to be sensitive to vehicular acceleration-deceleration activities.

From field observations and current throughput data, the M-Tag system is much more effective now than it was in the early phase of deployment. As users' familiarity with the system increases with time, less operational problems (including inability to access the exclusive M-Tag lanes) are encountered. For example, the exclusive M-Tag lanes at BHT toll plaza experienced longer queues than the lanes serving the manned tollbooths at the early period of deployment, because non-M-Tag equipped vehicles frequently blocked the exclusive M-Tag lanes. This problem has been reduced, because motorists are provided with adequate advance notice to weave to the appropriate lanes.

Finally, the use of electronic toll collection technology is spreading rapidly, particularly along the congested corridors of the western and eastern parts of the United States, where manned tolls have been in use for several years. The methodology and results presented herein are expected to serve as a guide for making decisions and estimating benefits relating to the use of electronic toll collection technology.

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TABLE 1 Classification of Tollbooths in the Study Area

Toll Plaza	Total number of exclusive M-Tag tollbooths in peak periods	Number of exclusive M-Tag tollbooths in the peak direction	Total number of tollbooths in both directions of travel
Fort McHenry Tunnel on I-95	3	2	24
Baltimore Harbor Tunnel on I-895	3	2	14
Francis Scott Key Bridge on I-695	2	1	12

TABLE 2 Summary of Mobile Emission Results for Deterministic Model

NAME OF TOLL PLAZA	SPEED (KPH)	VOLUME (VPH)	TOTAL HC (KG)	TOTAL CO (KG)	TOTAL NOx (KG)	TWO-WAY TOTAL HC (KG)	TWO-WAY TOTAL CO (KG)	TWO-WAY TOTAL NOx (KG)
SB FMT_PRE-M-TAG	6.7	6300	6.0	52.9	3.5	6.7	58.5	4.5
NB FMT_PRE-M-TAG	35.0	2700	0.7	5.6	1.1			
SB FMT_MANUAL	9.0	4536	2.9	27.2	2.3	3.5	31.3	3.6
NB FMT_MANUAL	41.7	756	0.2	1.5	0.3			
SB FMT_MTAG_28%	65.8	1764	0.3	2.1	0.7			
NB FMT_MTAG_28%	87.0	529	0.1	0.5	0.3			
SB FMT_MANUAL	15.0	3150	1.5	12.9	1.5	2.6	21.7	3.8
NB FMT_MANUAL	47.5	1755	0.4	3.2	0.7			
SB FMT_MTAG_50%	52.5	3150	0.6	4.7	1.2			
NB FMT_MTAG_50%	87.0	945	0.1	0.9	0.4			
SB BHT_PRE-M-TAG	6.5	3600	2.0	18.5	1.2	2.7	24.1	1.9
NB BHT_PRE-M-TAG	16.0	2400	0.6	5.6	0.6			
SB BHT_MANUAL	6.5	2844	1.6	14.6	1.0	2.2	19.4	1.8
NB BHT_MANUAL	18.5	1896	0.5	4.0	0.5			
SB BHT_MTAG_21%	68.7	756	0.1	0.5	0.2			
NB BHT_MTAG_21%	83.8	504	0.0	0.3	0.1			
SB BHT_MANUAL	14.0	1800	0.5	4.6	0.5	1.1	8.8	1.6
NB BHT_MANUAL	23.5	1200	0.3	2.2	0.3			
SB BHT_MTAG_50%	57.5	1800	0.2	1.3	0.4			
NB BHT_MTAG_50%	87.0	1200	0.1	0.7	0.4			
SB FSK_PRE-M-TAG	15.0	2000	0.7	5.9	0.7	1.1	9.4	1.2
NB FSK_PRE-M-TAG	20.5	1500	0.4	3.5	0.5			
SB FSK_MANUAL	19.3	1520	0.5	4.4	0.5	0.9	7.6	1.2
NB FSK_MANUAL	22.0	1140	0.3	2.6	0.4			
SB FSK_MTAG_24%	86.2	480	0.1	0.3	0.2			
NB FSK_MTAG_24%	83.8	360	0.0	0.3	0.1			
SB FSK_MANUAL	31.5	1000	0.2	1.9	0.3	0.6	5.5	1.0
NB FSK_MANUAL	26.3	750	0.2	1.6	0.2			
SB FSK_MTAG_50%	55.0	1000	0.1	1.1	0.3			
NB FSK_MTAG_50%	48.3	750	0.1	0.9	0.2			

TABLE 3 Summary of Mobile Emission Results for Simulation Model

NAME OF TOLL PLAZA	SPEED (KPH)	VOLUME (VPH)	HC (KG)	CO (KG)	NOx (KG)	TWO-WAY TOTAL HC (KG)	TWO-WAY TOTAL CO (KG)	TWO-WAY TOTAL NOx (KG)
SB FMT_PRE-M-TAG	7.0	6300	5.2	48.2	3.5	6.1	52.8	4.5
NB FMT_PRE-M-TAG	33.3	2700	0.9	4.7	1.1			
SB FMT_MANUAL	6.8	4536	3.9	35.2	2.5	4.5	39.3	2.7
NB FMT_MANUAL	36.4	756	0.2	1.7	0.3			
SB FMT_MTAG_28%	72.3	1764	0.3	1.9	0.9			
NB FMT_MTAG_28%	85.8	529	0.1	0.5	0.2			
SB FMT_MANUAL	7.9	3150	2.4	21.7	1.5	3.6	30.8	3.8
NB FMT_MANUAL	37.6	1755	0.5	3.9	0.7			
SB FMT_MTAG_50%	57.8	3150	0.6	4.2	1.2			
NB FMT_MTAG_50%	72.3	945	0.1	1.0	0.4			
SB BHT_PRE-M-TAG	5.2	3600	2.5	21.7	1.3	3.1	27.1	2.0
NB BHT_PRE-M-TAG	19.5	2400	0.6	5.4	0.6			
SB BHT_MANUAL	6.5	2844	1.6	12.2	1.0	2.3	17.6	1.8
NB BHT_MANUAL	17.8	1896	0.5	4.2	0.5			
SB BHT_MTAG_21%	54.5	756	0.1	0.7	0.2			
NB BHT_MTAG_21%	50.7	504	0.1	0.5	0.1			
SB BHT_MANUAL	13.6	1800	0.6	5.2	0.5	1.3	10.7	1.5
NB BHT_MANUAL	23.5	1200	0.3	2.4	0.3			
SB BHT_MTAG_50%	51.0	1800	0.2	1.8	0.4			
NB BHT_MTAG_50%	47.0	1200	0.2	1.3	0.3			
SB FSK_PRE-M-TAG	15.2	2000	0.7	6.2	0.7	1.1	10.0	1.2
NB FSK_PRE-M-TAG	20.0	1500	0.4	3.8	0.5			
SB FSK_MANUAL	19.7	1520	0.4	3.9	0.5	0.9	7.4	1.1
NB FSK_MANUAL	20.5	1140	0.3	2.8	0.4			
SB FSK_MTAG_24%	69.5	480	0.1	0.4	0.1			
NB FSK_MTAG_24%	59.8	360	0.1	0.3	0.1			
SB FSK_MANUAL	31.7	1000	0.2	1.9	0.3	0.6	5.1	1.0
NB FSK_MANUAL	26.3	750	0.2	1.6	0.2			
SB FSK_MTAG_50%	52.6	1000	0.1	0.9	0.3			
NB FSK_MTAG_50%	59.8	750	0.1	0.7	0.2			

TABLE 4 Percent Reduction in Mobile Emissions from Pre-M-Tag to Post-M-Tag Period

	Results from Deterministic Model			Results from Simulation Model		
Toll Plaza	HC	CO	NO_X	HC	CO	NO_X
FMT	61.2%	62.9%	15.6%	40.1%	41.7%	15.6%
BHT	59.3%	63.5%	15.8%	58.1%	60.5%	25.0%
FSK	45.6%	41.5%	16.7%	45.5%	49.0%	16.7%

TABLE 5 Comparative Analysis of Mobile 5b and CMEM Results

Vehicle Category	Proportion	HC (kg)[1]	CO (kg)[1]	NO_x (kg)[1]	HC (kg)[2]	CO (kg)[2]	NO_x (kg)[2]	HC (kg)[3]	CO (kg)[3]	NO_x (kg)[3]	HC (kg)[4]	CO (kg)[4]	NO_x (kg)[4]
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.01	0.03	0.47	0.06	0.03	0.69	0.08	0.05	0.17	0.08	0.07	0.43	0.09
3	0.04	0.04	1.52	0.14	0.04	1.20	0.22	0.03	0.71	0.21	0.05	1.45	0.25
4	0.05	0.03	0.61	0.10	0.05	0.89	0.17	0.05	0.84	0.18	0.06	1.06	0.23
5	0.04	0.03	0.52	0.05	0.03	0.86	0.08	0.03	0.60	0.08	0.05	1.28	0.10
6	0.01	0.00	0.16	0.02	0.01	0.25	0.04	0.01	0.09	0.04	0.01	0.12	0.05
7	0.01	0.01	0.05	0.01	0.00	0.43	0.01	0.00	0.62	0.01	0.01	0.91	0.01
8	0.01	0.00	0.02	0.00	0.00	0.06	0.00	0.00	0.03	0.01	0.00	0.04	0.01
9	0.01	0.00	0.01	0.00	0.00	0.02	0.01	0.00	0.01	0.01	0.00	0.08	0.01
10	0.06	0.01	0.19	0.04	0.01	0.29	0.06	0.01	0.27	0.07	0.03	0.35	0.09
11	0.06	0.01	0.09	0.03	0.01	0.19	0.06	0.00	0.13	0.07	0.01	0.16	0.09
12	0.01	0.11	1.37	0.06	0.12	1.77	0.08	0.13	1.49	0.07	0.18	1.70	0.09
13	0.01	0.12	1.62	0.10	0.14	1.86	0.16	0.14	1.58	0.14	0.17	1.82	0.18
14	0.01	0.02	0.55	0.05	0.02	0.67	0.07	0.03	0.55	0.07	0.03	0.67	0.09
15	0.08	0.11	3.13	0.17	0.11	2.47	0.24	0.16	1.60	0.25	0.19	3.59	0.32
16	0.16	0.23	3.06	0.50	0.23	2.54	0.82	0.32	2.38	0.86	0.37	2.93	1.07
17	0.06	0.02	1.00	0.07	0.02	0.42	0.10	0.02	0.27	0.11	0.02	0.34	0.14
18	0.07	0.02	0.39	0.09	0.03	0.52	0.16	0.03	0.50	0.17	0.03	0.63	0.21
19	0.01	0.01	0.12	0.07	0.02	0.19	0.09	0.02	0.15	0.09	0.03	0.18	0.11
20	0.01	0.06	0.79	0.05	0.06	1.19	0.07	0.10	0.68	0.07	0.13	1.09	0.09
21	0.02	0.13	1.04	0.03	0.16	1.35	0.04	0.17	1.26	0.04	0.24	2.51	0.06
22	0.01	0.10	0.62	0.07	0.09	0.56	0.10	0.15	0.40	0.09	0.17	0.66	0.11
23	0.01	0.07	0.00	0.01	0.09	3.22	0.01	0.10	2.90	0.01	0.12	3.62	0.01
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	0.12	0.06	1.13	1.23	0.09	1.68	1.80	0.09	1.63	1.68	0.11	2.05	2.12
40	0.14	0.45	0.82	9.41	0.58	1.12	4.06	0.48	0.93	3.41	0.54	1.05	3.91
CMEM TOTAL	1.00	1.7	19.3	12.4	1.9	24.4	8.5	2.1	19.8	7.8	2.6	28.7	9.4
MOBILE 5B	1.00	2.2	20.3	1.5	1.8	18.6	1.5	1.8	18.6	1.5	1.8	18.6	1.5

[1]The results obtained from the deterministic model were based on the average driving cycle (see Figure 4a).
[2]The CMEM results obtained from the simulation model were based on the driving cycle depicted in Figure 4b.
[3]The CMEM results for the driving cycle depicted in Figure 4c.
[4]The CMEM results for the driving cycle depicted in Figure 4d.

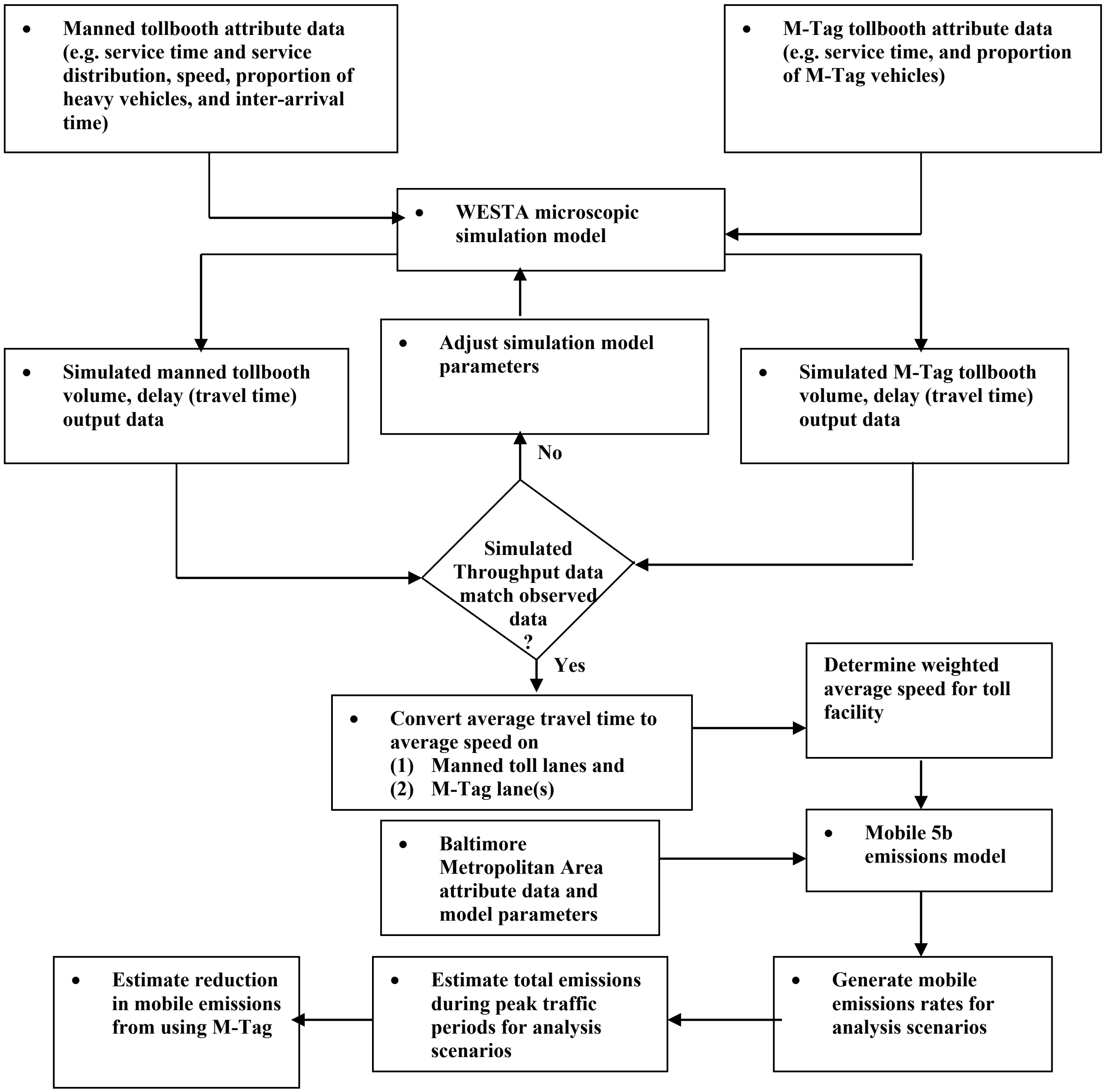

FIGURE 1. Summary of the Simulation Modeling Process

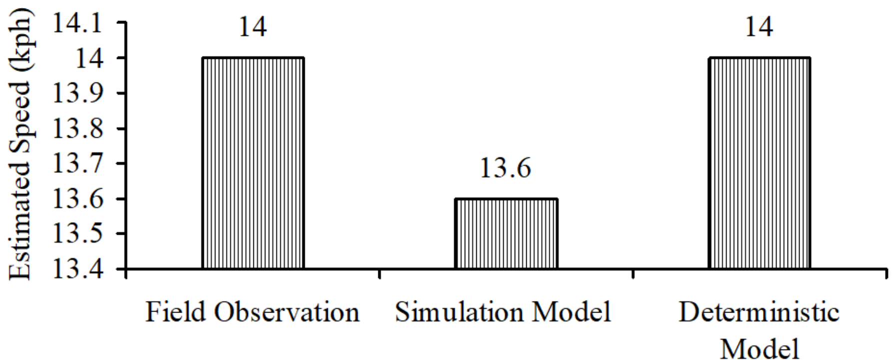

FIGURE 2a. Comparative Analysis of Travel Speed Data for BHT Toll Plaza

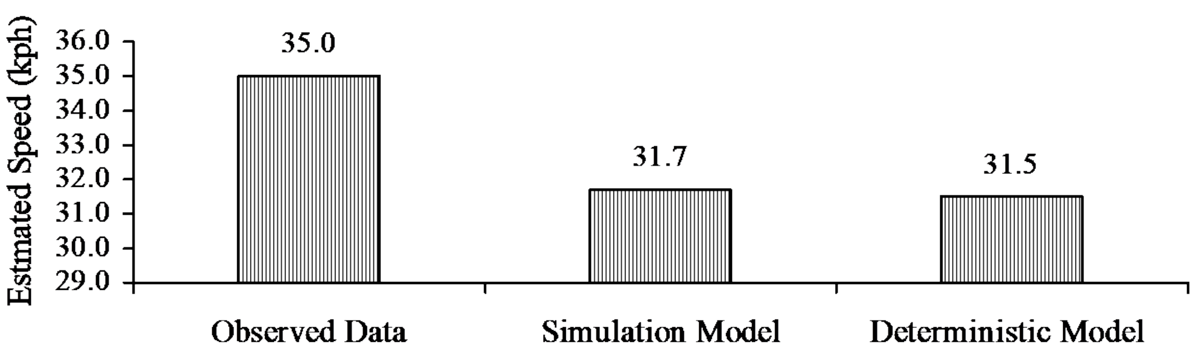

FIGURE 2b.Comparative Analysis of Travel Speed Data for FSK Toll Plaza

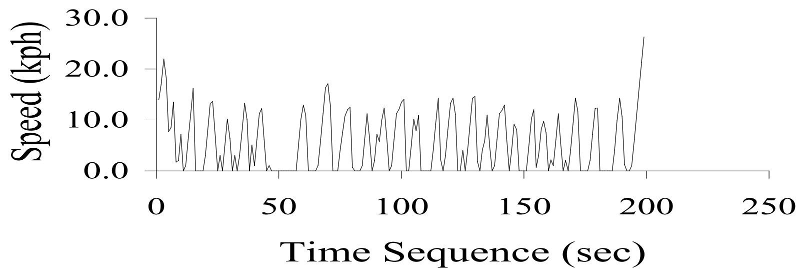

FIGURE 3a. Simulated Pre-M-Tag Driving Cycle at FMT Toll Plaza

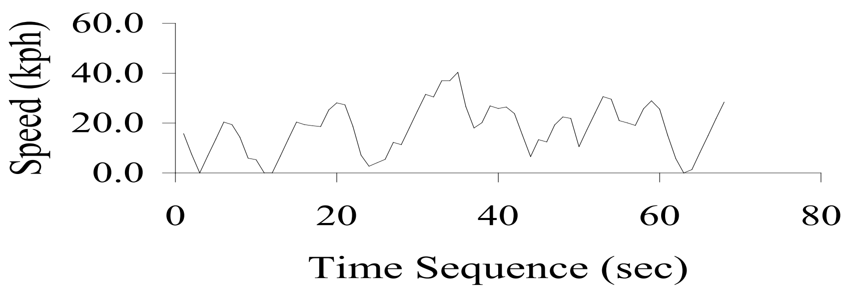

FIGURE 3b. Simulated Post-M-Tag Driving Cycle for Manned Toll Lane at FMT Toll Plaza

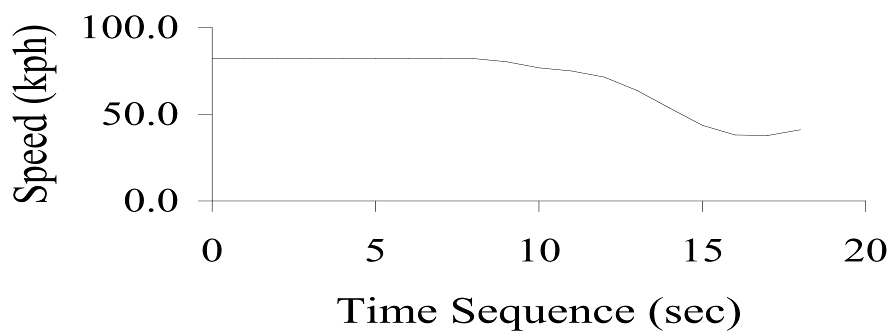

FIGURE 3c. Simulated Driving Cycle for Exclusive M-Tag Lane at FMT Toll Plaza

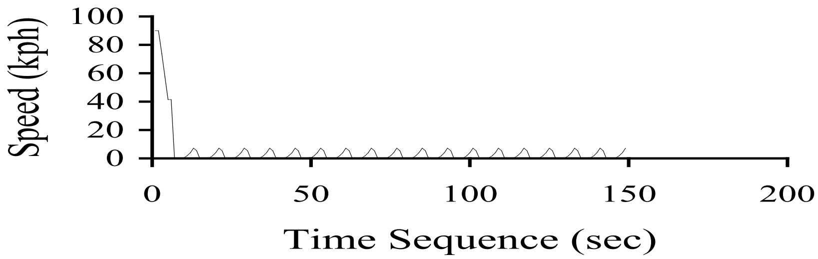

Figure 4a Driving Cycle #1 Developed from Deterministic Model

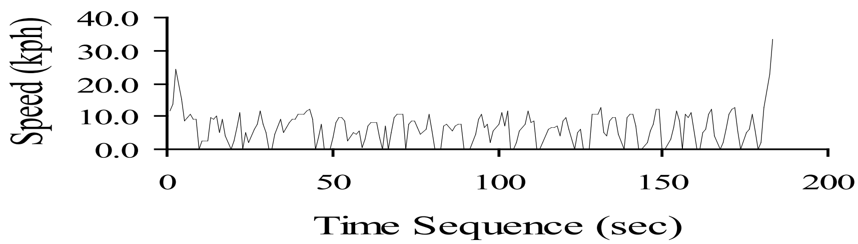

Figure 4b Driving Cycle #2 Developed from Simulation for a Randomly Selected Vehicle

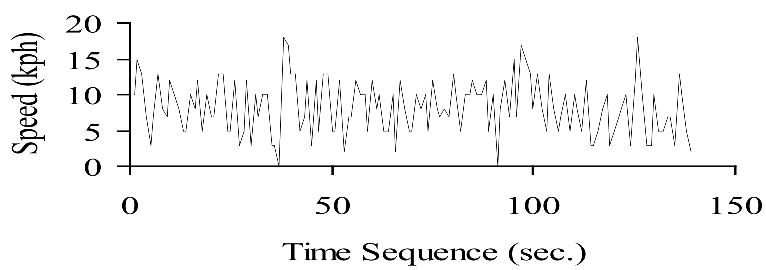

Figure 4c Driving Cycle #3 Generated from Poisson (λ = 7.8 kph) Distribution and Stream 1

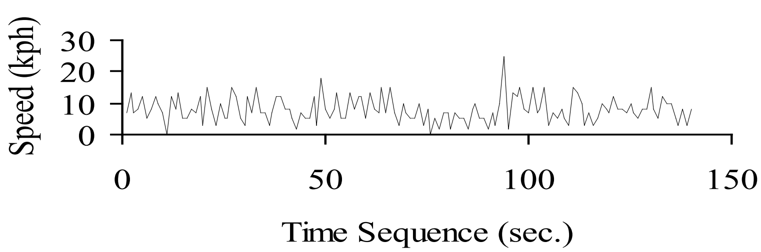

Figure 4d Driving Cycle #4 Generated from Poisson (λ = 7.8 kph) Distribution and Stream 2