An Estimation of Mobile Emissions Reduction from Using Electronic Toll Collection in the Baltimore Metropolitan Area: A Case Study of the Fort McHenry Tunnel Toll Plaza

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16. Abstract

The Baltimore Metropolitan Area is classified as a severe nonattainment area under the Clean Air Act Amendments of 1990. Consequently, it operates on a stringent emissions budget and is mandated to embark on mitigation measures. The area has been aggressively implementing emissions control and transportation demand management programs. One of the newest emissions control schemes in the Baltimore area is the deployment of electronic toll collection (ETC) technology, locally known as M-Tag, at the three facilities (the Fort McHenry, Baltimore Harbor, and Key Bridge toll plazas). The ETC deployment, which began in spring 1999, has already enjoyed a significant market penetration. The objectives of the study described herein are twofold. First, a microscopic simulation model was used to simulate the existing traffic situations at the Fort McHenry Tunnel toll facility, which is the largest toll plaza in the State of Maryland. Observed field data were used to validate simulation results. Second, the benefits inherent in the use of ETC technology were captured by undertaking a comparative analysis of pre-ETC and post-ETC scenarios. The primary measures of effectiveness used were: (1) increased throughput and hence reduced wait time at the toll plazas; and (2) reduced mobile emissions (hydrocarbon, carbon monoxide, and nitrogen oxide). It was determined from the simulation and mobile emissions models that the current deployment level of M-Tag has improved the average travel speed by more than 125% and has decreased the mobile emissions rate by up to 41% at the Fort McHenry toll plaza.

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ABSTRACT

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ACKNOWLEDGMENTS

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INTRODUCTION

According to the criteria established in Title I of the Clean Air Act Amendments (CAAA) of 1990, the Baltimore area is categorized as a severe nonattainment area. Consequently, the area was mandated to embark aggressively on effective mitigation measures through the State Implementation Plan as commitment to meet the National Ambient Air Quality Standards attainment deadlines. The Baltimore area has been undertaking stringent inspection and maintenance programs in conjunction with other transportation control measures (e.g., transportation demand management, transportation systems management, and the use of intelligent transportation system technologies) to meet the challenging conformity requirements of the CAAA of 1990. One aspect of congestion mitigation that is very promising is the use of electronic toll collection (ETC), which belongs to the aforementioned intelligent transportation system technology group. An increasing number of areas, particularly the nonattainment areas of the western and eastern parts of the country, currently embrace this innovative technology. The State of Maryland has recently deployed ETC technology, popularly known as M-Tag, at the existing toll facilities (Fort McHenry Tunnel, Harbor Tunnel, and Key Bridge) in the Baltimore area. Henceforth, M-Tag will be used interchangeably with ETC in discussing the ETC facilities in the Baltimore Metropolitan Area. The use of ETC has been credited with a substantial increase in throughput, which translates to less traffic congestion at toll facilities and hence less air pollution (Al-Deek et al., 1997; Guensler and Washington, 1994; Lampe and Scott, 1995; Lennon, 1994). However, the potential impact on mobile emissions from the use of M-Tag has not been extensively investigated for the Baltimore Metropolitan Area. Currently, 4 of the 24 toll lanes at the Fort McHenry Tunnel toll facility, 2 of the 14 toll lanes at the Harbor Tunnel toll facility, and 2 of the 12 toll lanes at the Key Bridge toll facility are exclusively used for ETC. However, vehicles equipped with M-Tag have the flexibility to use all available (manned and ETC) tollbooths, all of which are equipped with M-Tag readers. It is estimated from field observations that approximately 28% of rush-hour commuters at the Fort McHenry Tunnel toll plaza use the designated M-Tag tollbooths.

STUDY OBJECTIVES

The primary objective of this study was to estimate from combined field data and microsimulation the potential reduction of mobile emissions [i.e., hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxide (NO_x) attributable to the use of ETC technology in the Baltimore area]. Specifically, this study investigated the potential impact of the use of ETC on average travel time and mobile emission rates at the Fort McHenry Tunnel toll plaza, which is the largest toll plaza in the State of Maryland. This toll plaza served a peak hourly volume of approximately 8,700 vehicles per hour (vph). A secondary objective was to identify from field observations the operational problems inherent in the use of ETC.

This study focused on the peak period traffic situation, during which the adverse effects of toll operations are most critical. For example, during the off-peak traffic period, there were few or no queues at the toll plazas, and most vehicles were delayed only for the duration of the toll payment, which—according to field observations—averaged 4.4 seconds for the Fort McHenry Tunnel toll plaza. Conversely, during rush-hour periods, most of the delay experienced at the toll facility is from time spent in queues.

DESCRIPTION OF MODELS

Two primary models were used in this study. The first model was a microscopic simulation model used in analyzing the traffic behavior at the Fort McHenry Tunnel toll facility. The second model was a mobile emissions model used in generating representative emission factors for the analysis scenarios (pre–M-Tag and post–M-Tag) considered. The two models are briefly described below.

Simulation Model

A microscopic simulation model, known as Westa (Saka and Glassco, 1999), was used in modeling the critical peak traffic flow patterns at the Fort McHenry Tunnel toll plaza. Figure 1 depicts the modeling framework assumed in Westa, which comprised five primary blocks. The first block read user-supplied input data, which included roadway, vehicle, and driver attributes. The second block (vehicle creation block) generated different types of vehicles based on user-specified interarrival 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 with M-Tag and distinguish them from vehicles using manned tollbooths. The third simulation block executed user-specified vehicle-following logic, including gap acceptance and acceleration/deceleration criteria. The fourth simulation block facilitated the execution of the two toll collection schemes (i.e., manned tollbooths versus M-Tag tollbooths) addressed in the study, based on user-specified toll transaction time and the associated probability distribution. As discussed later, under data collection and analysis, the exponential probability distribution was used to model the toll transaction time at the manned tollbooths. The M-Tag vehicles' toll transaction time was based on an average speed of 16 km/hr (10 mph) within the ETC tollbooths. The fifth block was associated with processing input data and providing summary statistics of output data.

Mobile Emissions Modeling

Mobile 5b, a mobile emissions modeling software, was used to analyze the anticipated impact of M-Tag on the air quality at the toll plaza. The Maryland Department of the Environment, which is the state's oversight agency for air quality compliance, uses Mobile 5b. The Maryland Department of the Environment provided most of the input data and the local model parameters used in this study for estimating the mobile emission (HC, CO, and NO_x) rates at the Fort McHenry toll plaza.

The rationale for using Mobile 5b emissions model was that it is currently the only accepted method of determining air quality compliance in the nonattainment areas, which include the study area described herein. It must be noted that Mobile 5b is not the most effective modeling tool at toll facilities, because it does not capture additional impact of frequent stops, and accelerations and decelerations on mobile emissions productions. There are modal models (e.g., the Virginia Tech mobile emissions model) that have the capability of capturing mobile emissions impact engendered by the aforementioned exogenous variables (e.g., frequency and duration of acceleration, deceleration, and stops). These modal emissions models were not considered in the study described herein, because they are still at the prototype stage and have not been widely accepted in analyzing air quality in the nonattainment areas. In addition, the Westa microscopic simulation model used herein was effective in capturing the creeping speed of vehicles in the traffic stream at the toll facility. Notwithstanding, generating the required input data (including the frequencies, magnitude, and duration of acceleration and deceleration of individual vehicles) for the aforementioned modal emission models will require a number of assumptions that would compromise their robustness in estimating the mobile emissions in the study area.

The emission results from Mobile 5b, which does not capture effectively the typical drive cycle at toll facilities, should be interpreted as indicators (indexes) based on cursory estimates of mobile emissions reduction from using ETC. The estimated emission results are expected to serve as decision-making tools for ETC deployment and operations.

STUDY METHODOLOGY

The study methodology consists of three major activities: (1) literature review of related studies, (2) data collection and analysis, and (3) modeling.

Literature Review

A review of literature on related studies was undertaken. The purpose of the literature review was to uncover information on past experience with ETC programs and lessons learned. The number of publications directly related to this study (i.e., mobile emissions at ETC toll facilities) was small vis-à-vis the increasing popularity of ETC nationwide. Lamp and Scott (1995) demonstrated from a laboratory study that the use of ETC decreased HC emissions from 1.2 g/mile to 0.2 g/mile, NO_x emissions from 1.1 g/mile to 0.6 g/mile, and CO emissions from 30.6 g/mile to 8.5 g/mile. Guensler and Washington (1994) 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 (1994) projected from a "microscale carbon dioxide analysis" 30% reduction (i.e., from 12.3 ppm to 8.8 ppm) in CO concentrations.

Other related studies that focussed on increased throughput attributed to ETC include:

- Burris and Hildebrand (1996), who 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 (1997), who estimated a 160% increase in throughput and a 2.5 to 3-minute per vehicle decrease in delay from the use of ETC.

As previously documented, the majority of previous studies on ETC deployment focused on either the throughput or the mobile emissions issue. The study described in this paper addressed both issues, as well as the critical operational issues inherent in the use of ETC.

Data Collection and Analysis

Data collection activity involved two primary tasks: (1) collection of service time (i.e., toll payment time) data and (2) collection of travel time data within the road network at the toll plaza.

Service Time Data

Service time and throughput data were collected for manned tollbooths and M-Tag booths. Data were collected in the evening peak direction (i.e. northbound) between 5 P.M. and 6 P.M. on Mondays, Tuesdays, Wednesdays, and Thursdays in June and July. Fridays and the weekends were excluded, because the traffic pattern during these periods was not considered a typical representation of the weekday traffic pattern. Service time and throughput data were collected using a videocamera. Data were collected on a minimum of two manned tollbooths and on a designated M-Tag booth(s).

The Fort McHenry Tunnel toll facility has a total of 24 tollbooths (12 tollbooths per traffic direction). Two of the 12 tollbooths are designated M-Tag booths per traffic direction. The configuration of the Fort McHenry Tunnel toll facility is depicted in Figure 2.

Travel Time Data

Travel time data were collected at manned tollbooths and M-Tag booths. Data were collected on at least two manned tollbooths and on the designated M-Tag booths. Travel time data were collected by randomly selecting and tracking the vehicles at the plaza from a fixed reference point to the exit point of the tollbooth. The total travel time (including the time spent in the queue and service time) from the reference point to exit point was determined using a stopwatch. Knowing the distance from the point of tracking to the point of exit, the corresponding average speed was determined from distance, time, and speed relationships.

Data Analysis

The observed mean service time at the manned tollbooths was 4.4 seconds at the Fort McHenry toll plaza. The service times represented a composite case (a combination of M-Tag, commuter tickets, and cash) of toll payment options.

M-Tag–equipped vehicles have the flexibility to use manned tollbooths or exclusive M-Tag booth(s), because all tollbooths are equipped with M-Tag readers. It was estimated from field observations that approximately 28% (1,500 vph) of the traffic used M-Tag–designated lanes at the Fort McHenry Tunnel toll plaza. In Table 1, the average travel speed on lanes serving M-Tag tollbooths is at least twice the average travel speed on lanes serving manned tollbooths, which translates to a significant increase in throughput attributed to the use of the M-Tag toll payment scheme.

Service time data were also analyzed for representative probability distributions for input into the simulation model. The Kolmogorov-Smirnov goodness-of-fit test was undertaken as an attempt to fit the service times to probability distributions at the 95% confidence level. None of several probability distributions (including the Normal, Weibull, Exponential, Lognormal, and Uniform distributions) considered in the study matched the observed service time data at 95% confidence level. The difficulty in fitting the service times at the 95% confidence level was the motivating factor for using microscopic simulation modeling in lieu of analytical queue and delay models. Reasonable results were obtained through the calibration of the simulation model parameters. The process followed in calibrating and validating the simulation model is described below. For this study, the exponential probability distribution, which provided the best fit in the aforementioned Kolmogorov-Smirnov goodness-of-fit test, was used in simulating the service times at the toll facilities. Figure 3 depicts sample comparison of the observed cumulative service time distribution and the theoretical exponential cumulative probability distribution.

Modeling

The study described herein consists of two stages of modeling. The first stage involved micro-simulation modeling of the Fort McHenry Tunnel toll plaza to estimate the average operating speed and throughput that are associated with the two M-Tag utilization (market penetration) scenarios considered in the study. The second stage of the modeling process involved the use of the aforementioned Mobile 5b with the output data from the microscopic simulation in estimating the mobile emissions rates associated with the two scenarios (pre–M-Tag and current M-Tag market penetration) considered. A summary of the modeling framework used in the study described herein is depicted in Figure 4.

Model Calibration and Validation

The average observed peak-hour throughput data (424 vph for manned tollbooths and 755 vph for M-Tag–designated tollbooths) were used in calibrating the simulation model. The calibration process involved adjustment of the parameter for the exponential distribution model. The adjustment process continued until a close match was obtained between the simulated throughput data and the observed throughput data at the tollbooths. Table 1 provides a summary of the data used in validating the simulation model for the Fort McHenry Tunnel toll plaza. The difference between the observed throughput and the simulated throughput values is less than 2% for the M-tag–designated lanes and less than 4% for the manned tollbooth lanes.

Scenario Evaluation

Two scenarios were evaluated. The first scenario was the baseline case, which did not involve the use of M-Tag technology (i.e., all tollbooths operate manually). The second scenario represented the current market penetration level of M-Tag technology, which is approximately 28%, as estimated from field observations of vehicles using the exclusive M-Tag lanes. In addition to these two scenarios, a third scenario was undertaken solely to estimate the maximum throughput associated with exclusive M-Tag tollbooths and comparing the results with that of manned tollbooths at the Fort McHenry Tunnel toll plaza.

For each of the previously described scenarios, the weighted-average travel time was estimated from the validated simulation model, and the associated mobile emissions (HC, CO, and NO_x) rates were determined from the Mobile 5b model. Table 2 gives a comparative summary of the estimated peak- hour mobile emissions for the two scenarios at the Fort McHenry Tunnel toll plaza. For an assumed zone of influence of 610 m, the estimated decrease in peak-hour mobile emissions attributed to M-Tag deployment were 3.77 kg (40% decrease) for HC, 36.04 kg (41% decrease) for CO, and 0.85 kg (11% decrease) for NO_x. The maximum throughput obtained from the simulation model was estimated to be approximately 1,025 vph/tollbooth for M-Tag tollbooths (compared with maximum simulated throughput of approximately 408 vph/tollbooth for manned tollbooths).

The simulated maximum throughput for manned tollbooths is within the 400 vph to 500 vph threshold estimated by the Maryland Transportation Authority staff from past experience, which underscores the robustness of the validated simulation model used in the study described herein.

CONCLUSIONS

This paper describes a recent study of the estimated impact of the use of ECT scheme (M-Tag) at the Fort McHenry Tunnel toll plaza. The use of M-Tag is one of the various mobile emissions mitigation programs in the Baltimore Metropolitan Area, which is classified as a severe nonattainment area under the CAAA of 1990.

The Fort McHenry Tunnel toll facility, which is considered herein, is the largest in the State of Maryland and is used extensively by local commuters and Interstate I-95 traffic. The observed hourly throughput at the Fort McHenry Tunnel toll facility is approximately 8,700 vph, and the directional split is 60/40. The microscopic simulation model, which was validated with observed field data, was used to estimate the traffic situation for pre–M-Tag and post–M-Tag scenarios. Specifically, the average travel time and hence the travel speed were estimated for the aforementioned two scenarios. The associated impact on mobile emissions in the vicinity of the Fort McHenry Tunnel toll plaza was estimated using results from the Mobile 5b emissions model.

The following observations were made from the simulation and emissions analyses:

1. Maximum throughput (effective capacity) of manned and M-Tag tollbooths was estimated to be 408 vph/tollbooth and 1,025 vph/tollbooth, respectively.
2. Changes in estimated mobile emissions (for pre–M-Tag and current M-Tag deployment levels) ranged from an 11% decrease for NO_x to more than a 40% decrease for HC and CO.
3. One of the problems experienced by M-Tag–equipped vehicles is occasional difficulty in accessing the exclusive M-Tag lanes as a result of lane blockage engendered by the spillover of queues from manned tollbooth lanes and difficulty in weaving to the designated lanes.
4. The effective capacity of the exclusive M-Tag lanes will be significantly increased if motorists are p ovided adequate advance warnings regarding designated M-Tag lanes, and also by properly delineating and designating lanes to manned tollbooths and M-Tag tollbooths to minimize the aforementioned spillover and weaving incidents.
5. Proper positioning of M-Tag–designated lanes and providing an adequate merge area will

result in increased capacity at the toll facility, because merging incidents that occur downstream of the toll facility impede the flow of M-Tag traffic.

Estimated mobile emission results summarized in Table 2 can serve as a guide in estimating emissions for different analysis scenarios (peak periods, daily condition, etc.). For example, the total mobile emissions for both morning and evening peak periods can be estimated by applying the emission rates per vehicle to the total number of vehicles considered, because the traffic flow pattern does not vary significantly within the peak periods at the Fort McHenry Tunnel toll plaza. In addition, the methodology described herein can also be applied to the two other toll plazas (Baltimore Harbor Tunnel toll plaza and Francis Scott Key Bridge toll plaza) in the Baltimore Metropolitan Area.

Thus, the study described herein is expected to motivate a more extensive study that will investigate the aggregated impacts of M-Tag usage at all toll plazas in the Baltimore Metropolitan Area, and possibly to quantify the overall impacts of M-Tag deployment on regional air quality.

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TABLE 1. Validation Data for Simulation Model

Tollbooth Type	Observed Data	Random Seed #47 Simulated Data	Random Seed #67 Simulated Data	Random Seed #107 Simulated Data	Random Seed #117 Simulated Data	Average Simulated Data
Manned tollbooth throughput (vph/booth)	424	408	407	407	405	407
M-Tag tollbooth throughput (vph/booth)	755	761	774	781	773	772
M-Tag traffic lane average travel speed (km/hr)	N/A*	43.0 km/hr (26.9 mph)	39.8 km/hr (24.9 mph)	43.0 km/hr (26.9 mph)	41.4 km/hr (25.9 mph)	41.8 km/hr (26.1 mph)
Manned tollbooth traffic lane average travel speed (km/hr)	N/A*	9.3 km/hr (5.8 mph)	9.3 km/hr (5.8 mph)	9.8 km/hr (6.1 mph)	9.3 km/hr (5.8 mph)	9.4 km/hr (5.9 mph)

Abbreviations used: vph = vehicles per hour; N/A = not applicable.
*The observed average speed was determined by randomly tracking vehicles from a reference point, which was 91 meters upstream of the tollbooths, to the point of exit from tollbooth and using the travel time to estimate the average operating speed. A similar scheme was used in validating the simulation model. The observed average speeds from the aforementioned point of reference to point of exit were estimated as 4 km/hr (2.5 mph) and 18.1 km/hr (11.3 mph) for the manned tollbooth lanes and M-Tag exclusive lanes, respectively. The corresponding simulated average travel speeds were 5.4 km/hr (3.4 mph) and 20.6 km/hr (12.9 mph) for manned tollbooths and M-Tag exclusive lanes, respectively.

TABLE 2. Summary of Estimated Mobile Emissions for M-Tag Deployment Scenarios

M-Tag Deployment Scenarios	Weighted Average Operating Speed (km/hr)*	Estimated Peak Hour Quantity of HC Emissions (g/km)*	Estimated Peak Hour Quantity of CO Emissions (g/km)*	Estimated Peak Hour Quantity of NO_x Emissions (g/km)*
Baseline (no M-Tag) for critical direction of traffic flow	8.0 km/hr (5.0 mph)	2.5 g/km/veh (3.94 g/mile/veh)	21.8 g/km/veh (34.88 g/mile/veh)	1.5 g/km/veh (2.47 g/mile/veh)
Baseline for non-critical direction of traffic flow	30.1 km/hr (18.8 mph)	0.73 g/km/veh (1.17 g/mile/veh)	8.54 g/km/veh (13.66 g/mile/veh)	1.18 g/km/veh (1.88 g/mile/veh)
Current market penetration level (approximately 28%) of M-Tag for critical direction of traffic flow	18.6 km/hr (11.6 mph)	1.4 g/km/veh (2.20 g/mile/veh)	11.8 g/km/veh (18.80 g/mile/veh)	1.3 g/km/veh (2.07 g/mile/veh)
Current market penetration level of M-Tag for non-critical direction of traffic flow	38.7 km/hr (24.2 mph)	0.59 g/km/veh (0.94 g/mile/veh)	6.64 g/km/veh (10.62 g/mile/veh)	1.15 g/km/veh (1.84 g/mile/veh)
Weighted total (both direction of traffic) for baseline	N/A	1.77 g/km/veh (2.83 g/mile/veh)	16.50 g/km/veh (26.39 g/mile/veh)	1.40 g/km/veh (2.23 g/mile/veh)
Weighted total for current market penetration level of M-Tag	N/A	1.06 g/km/veh (1.70 g/mile/veh)	9.71 g/km/veh (15.53 g/mile/veh)	1.24 g/km/veh (1.98 g/mile/veh)
Weighted reduction (based current market penetration level)	N/A	0.71 g/km/veh (1.13 g/mile/veh)	6.79 g/km/veh (10.86 g/mile/veh)	0.16 g/km/veh (0.25 g/mile/veh)
Weighted reduction based on assumed 0.61 km (0.38 mile) zone of influence*	N/A	3.77 kg (40% decrease)	36.04 kg (41% decrease)	0.85 kg (11% decrease)

Abbreviations used: HC = hydrocarbon; CO = carbon monoxide; NO_x = nitrogen oxide; N/A = not applicable; veh = vehicle; ETC = electronic toll collection; vph = vehicles per hour.
*The estimated quantity of the mobile emissions reduction depends on the assumed zone of influence of ETC deployment at the toll facility for the scenario analyzed. Data emissions information is determined using a zone of influence rates of 610 m (2,000 ft), which is the distance from point of transition for upstream traffic lanes to the point of transition for downstream traffic lanes. The observed two-way hourly throughput is approximately 8,700 vph (5,220 vph

assumed for the peak direction based on a 60%-40% split).

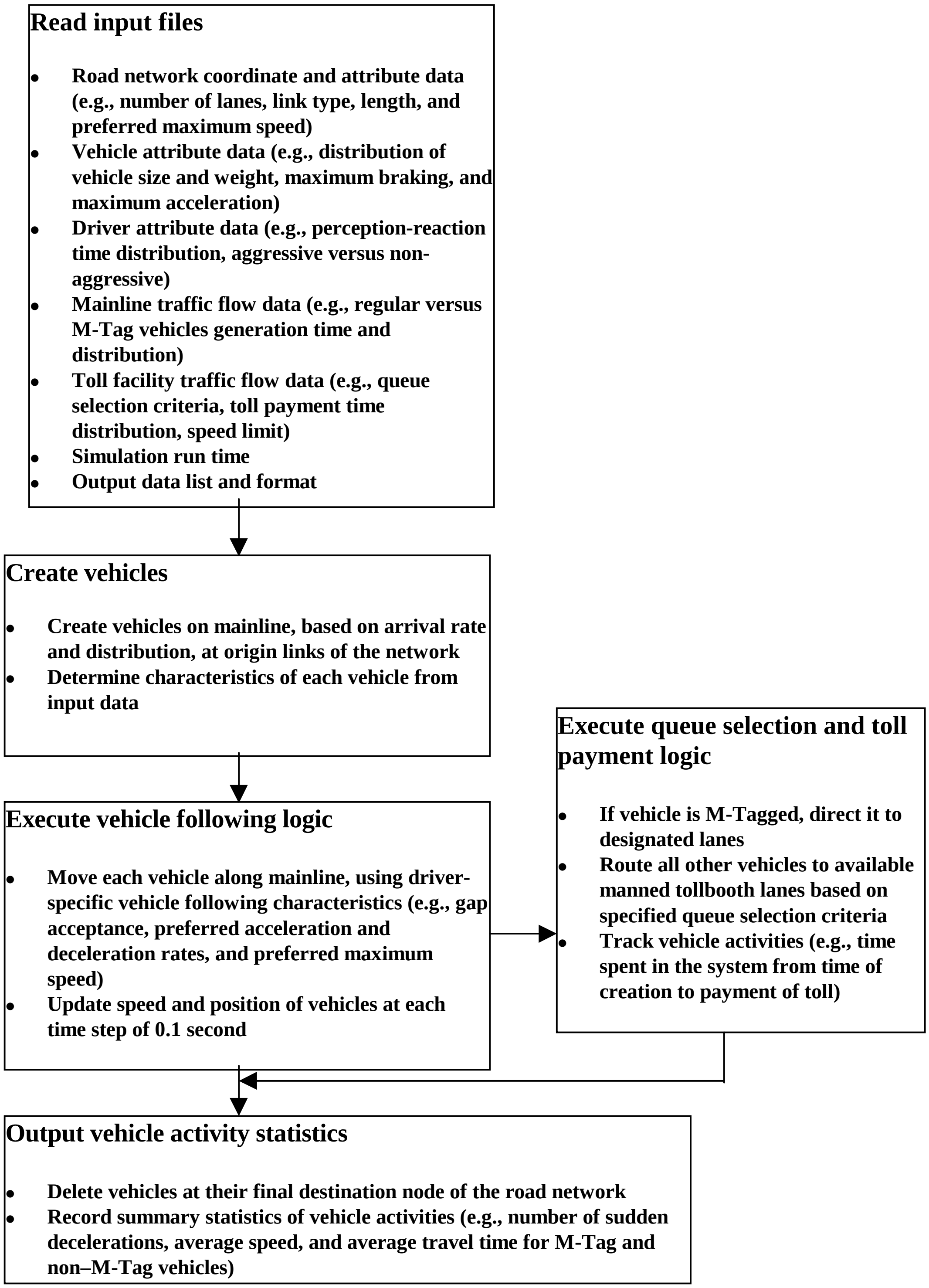

FIGURE 1. Simplified block diagram of the simulation model.

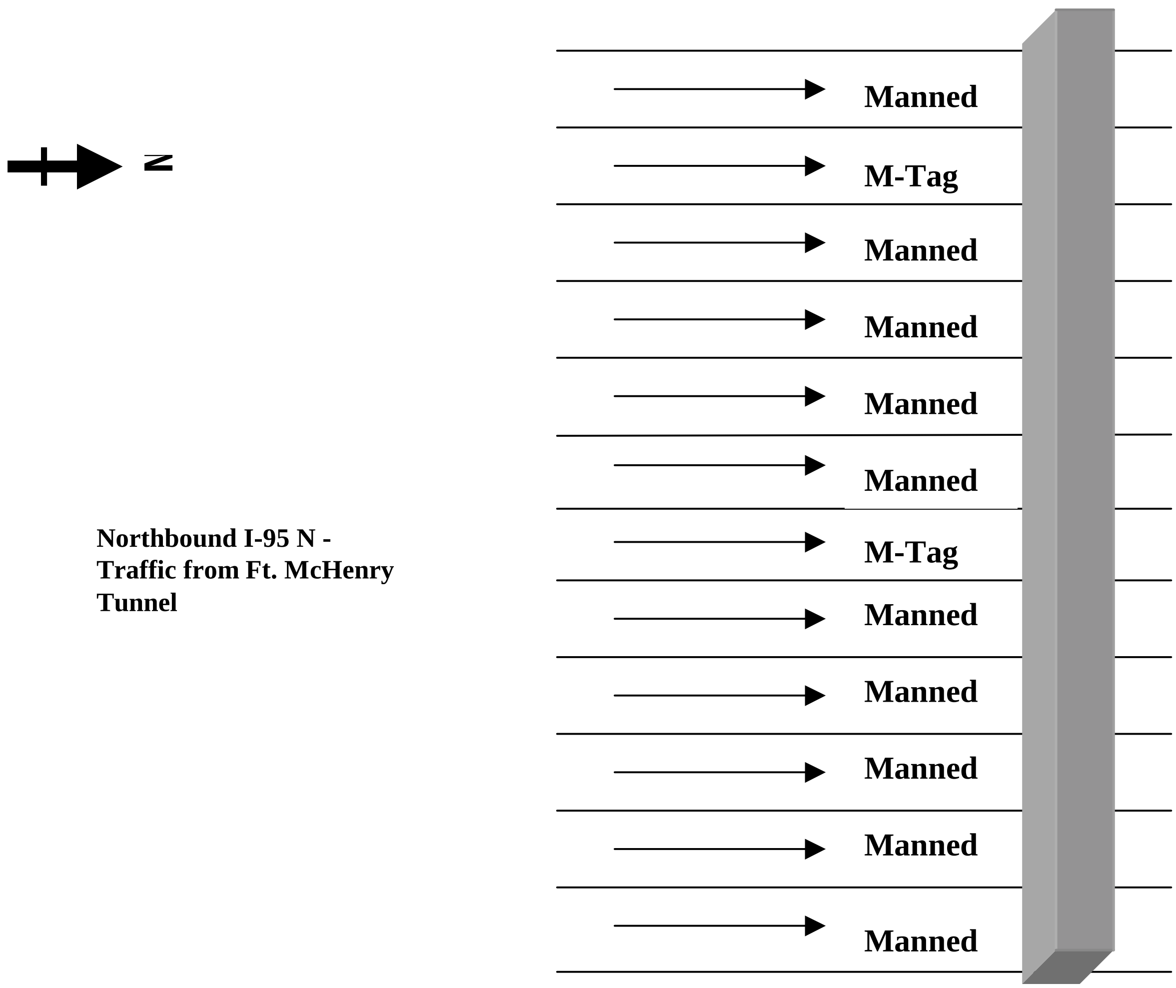

FIGURE 2. Graphical illustration of the Fort McHenry Tunnel toll facility.

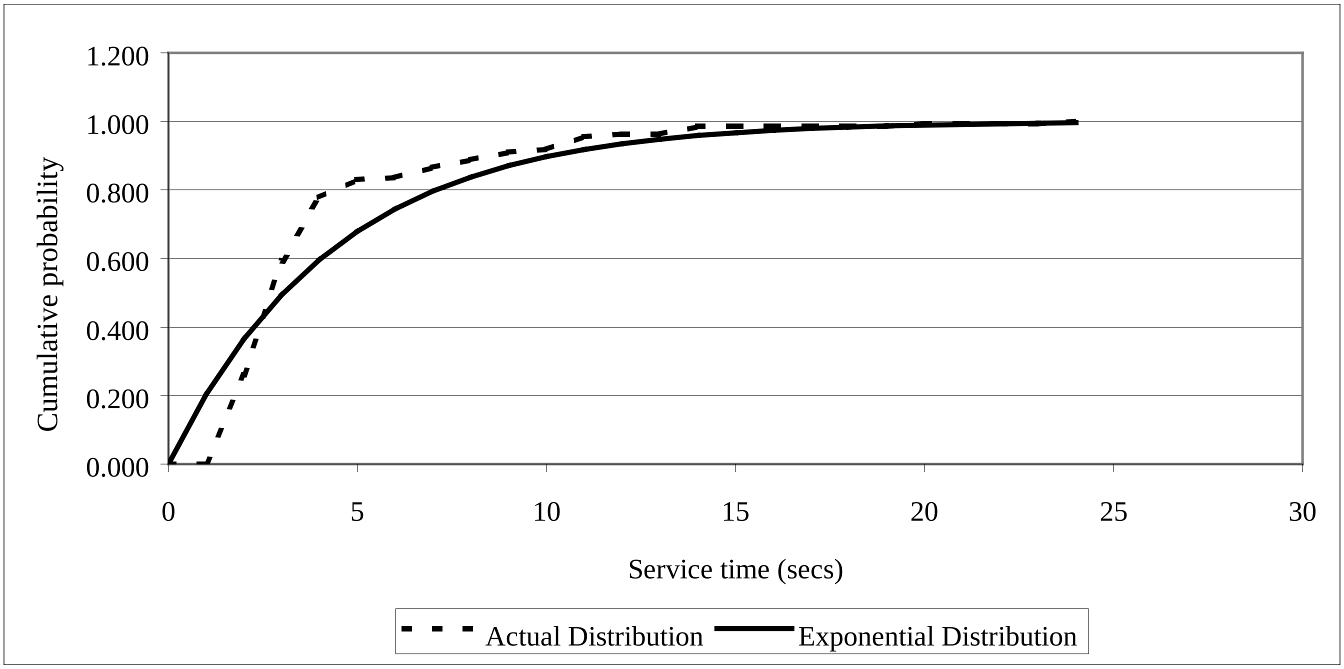

FIGURE 3. Graph of observed service-time distribution versus exponential probability distribution.

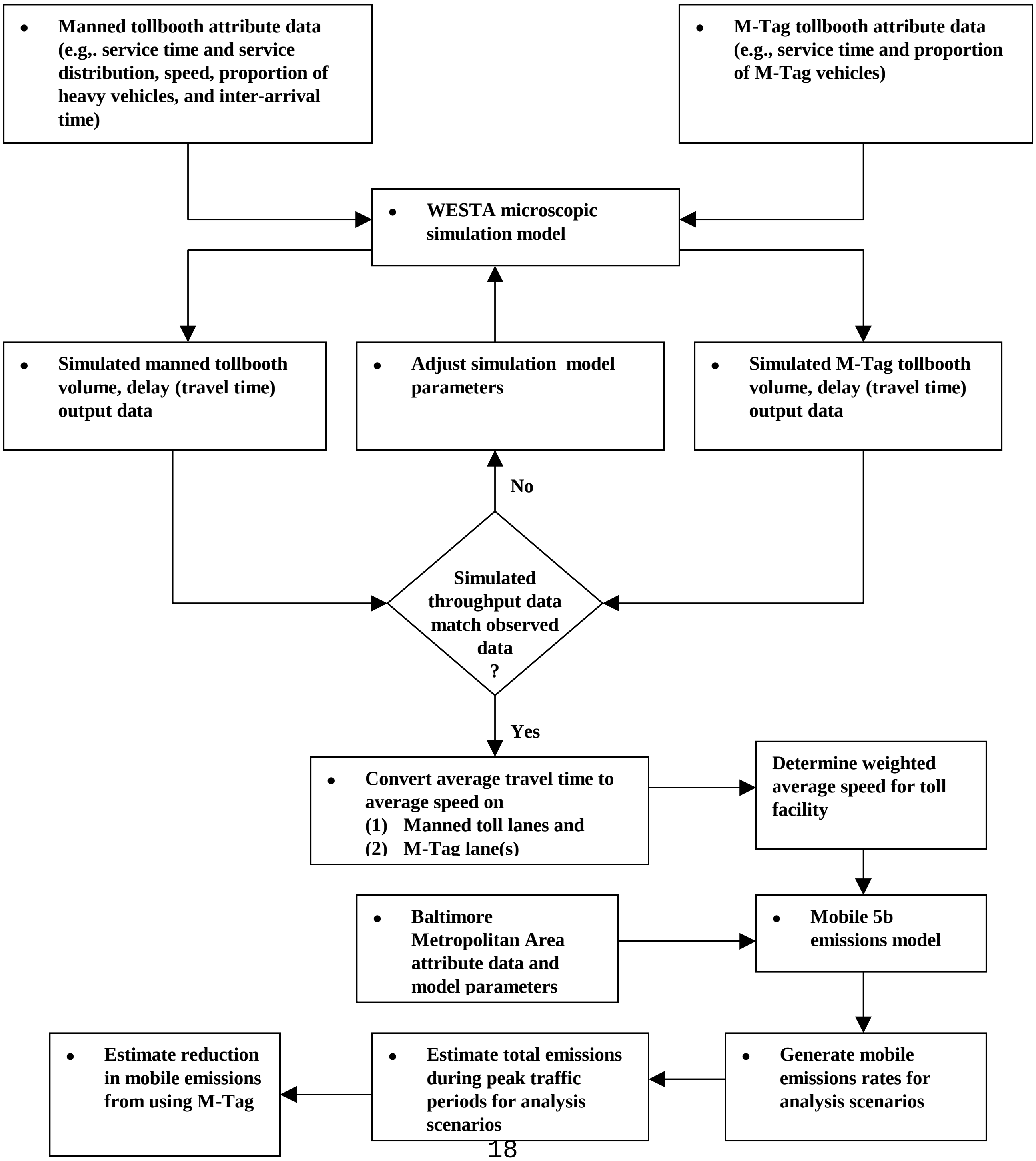
Manned tollbooth attribute data (e.g,. service time and service distribution, speed, proportion of heavy vehicles, and inter-arrival time)
M-Tag tollbooth attribute data (e.g., service time and proportion of M-Tag vehicles)
WESTA microscopic simulation model
Simulated manned tollbooth volume, delay (travel time) output data
Adjust simulation model parameters
Simulated M-Tag tollbooth volume, delay (travel time) output data
No
Simulated throughput data match observed data ?
Yes
Convert average travel time to average speed on
(1) Manned toll lanes and
(2) M-Tag lane(s)
Determine weighted average speed for toll facility
Baltimore Metropolitan Area attribute data and model parameters
Mobile 5b emissions model
Estimate reduction in mobile emissions from using M-Tag
Estimate total emissions during peak traffic periods for analysis scenarios
Generate mobile emissions rates for analysis scenarios

FIGURE 4. Summary of the modeling process.