ESTIMATION OF THE IMPACT OF ELECTRONIC TOLL COLLECTION ON AIR POLLUTION LEVELS USING MICROSCOPIC SIMULATION MODEL OF A LARGE-SCALE TRANSPORTATION NETWORK

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ABSTRACT

This paper presents a microscopic simulation based estimation of the spatio-temporal change in air pollution levels as a result of electronic toll collection (ETC) deployment in New Jersey Turnpike (NJTPK), a large-scale traffic network. Other important features of this paper are the (1) disaggregate spatial estimation and analysis of the emissions instead of aggregate system-wide estimations, (2) the use of a vehicle-based and well-calibrated traffic simulation model of NJTPK network in PARAMICS microscopic simulation software to perform this disaggregate emission estimation, (3) the use of a unique and realistic toll plaza model with a complete mainline model to capture complex mainline-toll plaza interactions, and (4) the study of short and long term impacts of ETC systems. The simulation model is loaded with a recent network specific dataset, which includes origin-destination demand data for 1999 (before ETC deployment) and for 2005 (six years after ETC deployment) and toll plaza service times obtained from toll plaza videotapes. MOBILE 6.2 mobile source emission model developed by the Environmental Protection Agency is integrated in PARAMICS. At each time step of the simulation air pollution levels, namely CO, HC, NOx and PM10 emissions are calculated for each vehicle type based on their speeds. The simulation network is used to estimate not only the change in system-wide air pollution levels but also the spatial changes throughout the system. Results show that ETC deployment reduces the overall network air pollution level in the short term; however, in the long term its benefits are not sufficient enough to compensate the air pollution increase on the mainline because of annual traffic growth.

INTRODUCTION

Air pollution is the change in the percentage of ambient compounds in the atmosphere as a result of the activities of mankind. Highway transportation accounts for the air pollution due to the release of pollutants during motor vehicle operations. Its contribution is either through the direct emission of the pollutants from the vehicles or the resulting chemical reactions of the emitted pollutants with each other or with the existent materials in the atmosphere. On-road motor vehicle emissions accounts for 45% of the air pollutants in the US (1).

For the last 30 years United States Environmental Protection Agency (USEPA) has been applying an integrated approach to reduce air pollution due to mobile emissions. This approach includes extensive collaboration not only between USEPA and state and local governments, but also between vehicle, engine, and fuel manufacturers, transportation planners, and individual citizens (2).

Intelligent Transportation Systems (ITS), on the other hand, offer a variety of benefits to motorists through its various applications. In specific, electronic toll collection (ETC) is not only effective in reducing congestion in toll plazas, but also has been advocated in the literature as an effective system that can reduce air pollution (3, 4).

This paper stems from the interest in quantifying the impact of ETC on air pollution levels in a large-scale highway network.

However, it is often quite difficult to accurately estimate the change in air pollution levels due to ETC system. Various approaches have been proposed in the literature. Saka and Agboh (3) conducted a study that evaluates the effect of ETC on air pollution at three major toll plazas in Baltimore using both deterministic and simulation models. Klodzinski et al. (4) estimated the air quality benefits of ETC at the Holland East Toll Plaza in Orlando-Orange County Expressway using MOBILE 5a emission model using before and after data.
The methods employed in the literature for evaluating the effects of ETC in a large-scale highway network can be classified as: (1) Macroscopic traffic models, (2) Collecting vehicle emission data using emission sensors, and (3) Microscopic traffic models.

**Macroscopic Traffic Models**
In the past, system-wide effects of air-pollution have been estimated using the output of traditional aggregate planning models such as TP+, EMME/2. (5, 6). However, macroscopic traffic models are too aggregate to capture time and space-dependent changes in traffic patterns. These models are usually used also for planning purposes, and are not sufficiently disaggregate to model ITS technologies such as ETC systems. Hanley and Marshall (5) have used EMME/2 to perform a comparative analysis of various land-use patterns on air quality and transportation. Fedra and Hauri (6) have proposed a GIS-based optimization approach for design of plans of urban environment with focus on air quality. Stein and Walker (7) used EMME/2 to perform a multi-class assignment of various vehicle types and analyze the emissions. Ozbay et al. (8) estimated the air pollution level for the northern New Jersey highway network using a deterministic transportation network.

**Collecting Vehicle Emission Data**
Collecting real-time vehicle emission data can only be performed after the ETC implementation is completed. Krimmer and Venigalla (9) evaluated the impacts of high occupancy vehicle lane operation on light-duty vehicle emissions using portable emission sensors in Washington D.C. area. Krimmer and Venigalla (9) used extensive dataset obtained from sensor-equipped vehicles, which include 13 hours and 520 miles of data for both general-purpose lanes and high occupancy lanes.

It is not always cost effective to collect and process extensive data for estimating the effects in a large-scale network. There is always a need to use a model that can estimate the impacts of such ETC applications in short period of time before implementation.

**Microscopic Traffic Models**
Microscopic traffic simulation models are effective in capturing time and space-dependent changes in traffic patterns. In the past microscopic traffic simulation models were not widely used for the emission estimations mainly due to the high initial cost of development and calibration of these models (11,12). Ozbay and Bartin (10) estimated the impacts of traveler information systems on air pollution levels in southern New Jersey highway network using micro-simulation.

**Objectives**

The objectives of this paper are:

1. **The analysis and estimation of disaggregate spatial emissions instead of disaggregate system-wide estimations** Development of disaggregate location-based emission patterns is useful in locating areas with relatively high air pollution levels. This, in turn, is useful in strategizing land development activities or health effects.

2. **The use of a vehicle-based and well-calibrated microscopic simulation model of a large-scale highway network to perform disaggregate emission estimations** The system-wide effect of ETC systems on air pollution levels for a large-scale network has not yet been widely studied using highly microscopic well-calibrated traffic simulation models such as PARAMICS, VISSIM.

3. **The use of a unique and realistic toll plaza model with a complete mainline model to capture complex mainline-toll plaza interactions** This approach provides estimates of the impacts of ETC deployment not only on the toll plazas, but also on the whole...
highway network. Most of the microscopic simulation studies in the literature have focused on individual toll plazas (3, 4).

4. **The comparison of short term and long-term impacts of ETC deployment.** Traffic demand is expected grow over the years. Moreover, induced traffic demand will be generated owing to the increased efficiency as a result of ETC deployment. Therefore, the effect of ETC needs be analyzed over a longer period.

**Research Methodology**

This paper focuses on the impacts of ETC system on air pollution levels in the NJTPK network during the morning peak period (7 a.m. – 9 a.m.). Short-term and long-term (six years after deployment) impacts of ETC system are compared. In addition to the overall impacts of ETC, this paper investigates the location-based (i.e. toll plaza links and mainline links) air pollution levels within the system. The knowledge of the most dense air pollution levels within the network can be helpful to the agency in various policy and operational decisions. Hence a spatio-temporal comparison of emission levels is also performed towards the end.

Analyses in this paper are performed using the PARAMICS micro simulation model of the New Jersey Turnpike (NJTPK). The NJTPK simulation model is an invaluable tool for evaluating the effect of ETC on air pollution for a large-scale highway network. This simulation model was developed and validated by Ozbay et al. (13) and Mudigonda et al. (14). It consists of 4244 nodes, 8800 links, and 26 zones.

Most of the microscopic simulation softwares including PARAMICS do not have any built-in toll plaza model. Although, PARAMICS has some of the basic features that can be used to build a toll plaza model, additional work using the Application Programming Interface (API) has to be performed to represent toll plaza operations accurately. A heuristic lane-choice model was developed and tested by Ozbay et al. (13) and Mudigonda et al. (14).

MOBILE 6.2 mobile source emission factor model that was developed by the USEPA is adopted for estimating air pollution levels using the simulation model.

**STUDY NETWORK AND DATA DESCRIPTION**

**Study Network**

NJTPK is a 148-mile toll facility. There exist 26 operational interchanges in NJTPK with average daily traffic exceeding 500,000 vehicles. Figure 1 shows the configuration and the exit numbers on NJTPK.

Entry and exit toll plazas on the NJTPK areas are not located en route, but they are located at separate areas at each intersection where the users enter or exit the freeway. Vehicles entering the network go through an entry toll plaza. Cash users get a ticket and ETC users (locally named as E-ZPass1) drive through the tollbooths with five mph speed. Vehicles exiting the toll plaza go through an exit toll plaza. Cash users have to make a complete stop and pay the toll E-ZPass vehicles drive through the toll plaza with five mph speed without having to stop for payment.

This type of toll plaza configuration does not impede the traffic flow on the freeway. However, they are important features of the network because they affect the travel time between origin-destination (OD) pairs. Therefore, it is essential to develop an accurate model of the toll plaza operations to obtain a realistic simulation model of the network.

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1 Note that E-ZPass and ETC have been used interchangeably in this study.
ETC system was implemented and became fully functional in 2001 in all toll plazas at the NJTPK. Currently, E-ZPass users form 63 percent of the total users; and for a typical workday 88 percent of all the vehicles are passenger cars. In addition, during peak hours more than 90 percent of the vehicles are passenger cars.

**Data Description**

The following is list of datasets that are used for the analyses presented in this paper.
(1) The first dataset is the vehicle transaction data for July 27, 2005. This dataset includes vehicle-by-vehicle entry and exit time data, such as origin index (interchange index), entry tollbooth lane index, entry time, entry date, destination index, exit tollbooth lane index, exit time, exit date, vehicle type (cars, trucks, buses), transaction type (E-ZPass or cash).

From this raw data 6 separate OD demand matrices are generated for the morning peak period. These matrices are for (i) E-ZPass users - cars, (ii) E-ZPass users - trucks, (iii) E-ZPass users - buses, (iv) Cash users - cars, (v) Cash users - trucks and (vi) Cash users - buses. These exact demand data are invaluable for a credible simulation model.

(2) The second dataset is the daily OD demand data for June 30, 1999. This dataset represents a typical weekday before the ETC implementation. This dataset is copied from the 1999 record book that shows daily traffic data between each OD pair. The dataset includes the traffic volume between each OD pair by vehicle type (i.e. passenger cars, trucks and buses). Using this dataset, 3 OD demand matrices are generated for the morning peak period: (i) cars, (ii) trucks, and (iii) buses. It should be noted that all vehicles are cash users before the ETC system deployment.

In order to convert the daily OD volumes to the morning peak period volumes, the first dataset from 2005 is utilized. Two peak hour conversion matrices are generated separately for 7 a.m. – 8 a.m. and 8 a.m. – 9 a.m. For example, the cell (i, j) in the 7 a.m. – 8 a.m. peak hour conversion matrix indicates the proportion of traffic volume during this hour to the daily traffic between the OD pair (i, j). Multiplying the daily OD demand matrices for 1999 by these conversion matrices yield the morning peak period demand matrices for 7 a.m. – 8 a.m. and 8 a.m. – 9 a.m. for the 1999 data.

(3) The third dataset is the video recording of the exit plaza of the interchange 16E, and the entry plaza of interchange 15W between 7 a.m. – 9 a.m. on April 28, 2006. From this dataset, entry and exit toll processing times are extracted. Toll processing time of 119 exiting cars, 45 exiting trucks and buses, 179 entry cars and 54 entry trucks are extracted. Kolmogorov-Smirnov and Anderson-Darling goodness-of-fit tests show that toll processing times follow a lognormal probability distribution for $\alpha = 0.05$. Table 1 shows the summary of goodness of fit analysis.

<table>
<thead>
<tr>
<th>Sample Size</th>
<th>Mean Value ($\mu$)</th>
<th>Standard Deviation ($\sigma$)</th>
<th>K-S Test Statistics</th>
<th>A-D Test Statistics</th>
<th>Reject Lognormal at $\alpha =0.05$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry - Cars</td>
<td>179</td>
<td>0.328</td>
<td>1.469</td>
<td>0.095</td>
<td>1.519</td>
</tr>
<tr>
<td>Entry – Trucks/Buses</td>
<td>54</td>
<td>0.443</td>
<td>1.846</td>
<td>0.130</td>
<td>1.167</td>
</tr>
<tr>
<td>Exit - Cars</td>
<td>119</td>
<td>0.539</td>
<td>2.182</td>
<td>0.039</td>
<td>0.240</td>
</tr>
<tr>
<td>Exit – Trucks/Buses</td>
<td>45</td>
<td>0.545</td>
<td>3.001</td>
<td>0.097</td>
<td>0.533</td>
</tr>
</tbody>
</table>

These observed service time data are incorporated in the toll plaza simulation using the API feature of PARAMICS. It is assumed in this paper that the service times obtained from these toll plazas can be representative for the other toll plazas in the system.

\[1999\text{ data are used to represent before ETC deployment, because it was learnt from our communications with the NJTPK personnel that 2000 was a transition year due to construction of the ETC lanes.}\]
ESTIMATION OF AIR POLLUTION

There are many studies in the literature that estimate vehicle emissions based on vehicle type, vehicle speed and acceleration (15, 16). For the air pollution estimation analysis presented here, MOBILE 6.2, a mobile source emission factor model designed by the USEPA, is used.

MOBILE 6.2

MOBILE6 is a computer program that estimates hydrocarbon (HC), carbon monoxide (CO), oxides of nitrogen (NOx), exhaust particulate matter (which consists of several components), tire wear particulate matter, brake wear particulate matter, sulfur dioxide (SO2), ammonia (NH3), six hazardous air pollutant (HAP), and carbon dioxide (CO2) emission factors for gasoline-fueled and diesel highway motor vehicles, and for certain specialized vehicles such as natural-gas-fueled or electric vehicles that may replace them (1).

The final output of MOBILE6.2 is the emission factors for various vehicle types. PARAMICS has an air pollution estimation feature called PARAMICS Monitor. It is used to estimate the amount of emissions that vehicles emitted at each simulation time step using the emission factors given by MOBILE 6.2. Thus for the simulation the emission factors for each of the three vehicle types at the speeds {2.5, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65 mph} are specified. One of the drawbacks of MOBILE6.2 is that the emission factors at speed above 65 mph cannot be obtained. Whereas in reality, speeds can exceed 65 mph on freeways, the same emission factor as 65 mph is used for speeds higher than 65 mph. A similar analysis of vehicular emissions was performed by Ozbay et al. (13) using SPASM. The vehicle emission factors in SPASM are based on MOBILE5.

The analyzed pollutants in this paper are HC, CO, NOX and Particulate Matter of maximum size of 10 microns (PM10).

ANALYSIS OF RESULTS

The results are presented based on the short and long-term effects of ETC deployment. A spatio-temporal comparison of emission levels is also performed to identify location-based changes in air pollution levels throughout the NJTPK network.

Short-Term Analysis

The goal of this analysis is to evaluate the immediate effect of ETC deployment without any demand change. In other words, the analysis investigates a scenario where there is an immediate shift to ETC system in 1999. Therefore, 1999 network is run for 2 scenarios:

(1) Without ETC deployment, and
(2) With ETC deployment.

Although the total demand is the same in both cases, in the second scenario the total demand includes not only cash users, but also ETC users. The recent ETC user percentage is utilized to evaluate this scenario. Both scenarios are run using the morning peak period (7 a.m. – 9 a.m.) demand. The results show that for the first scenario the total emitted CO, HC, NOx and PM10 are 4,299.3 kg, 507.5 kg, 534.85 kg and 5.69 kg, respectively.

The breakdown of the air pollution levels of the first scenario is given in Table 2a. The results are given for the mainline and toll plaza links separately.

Table 2a shows that total air pollution levels at the mainline links are higher than the toll plaza links. This is expected because the total mainline link length is longer than the total toll plaza link length. Total length of the links in the toll plaza system at NJTPK is approximately 25
miles. This length includes not only the tollbooth links\textsuperscript{3}, but also the on-ramps, off-ramps links and the links leading to the tollbooth links. However, the unit emission results (gram/mile/hour) given in Table 2b also show that the unit emission rate for toll plaza is higher than those of mainline links.

Table 2c shows the breakdown of air pollution levels for the second scenario. The results show that CO, HC and NO\textsubscript{x} emissions reduce by 36.3\%, 47.2\% and 28.2\% respectively at the toll plaza system. However, PM10 emission level increases by 6.7\%. In MOBILE 6.2, the emission factors of each pollutant increase almost linearly with increasing vehicle speeds. However, with the deployment of ETC at toll plazas, vehicles spend less time at the toll links. The analysis shows that average toll plaza delay per vehicle reduce from 1.71 minutes to 0.90 minute due to ETC deployment. To that end, the decrease in CO, HC and NO\textsubscript{x} emissions are expected. The increase in PM10 emissions can be attributed to the MOBILE 6.2 emission factors. For vehicle speeds less than 2.5 mph, the emission rate (in grams/seconds) is given as \(4.10^6\) in MOBILE 6.2. Therefore, in the “without ETC deployment scenario”, the simulation outputs does not produce any PM10 emissions from vehicles that have zero speeds in toll queues. Whereas, in the “with ETC deployment scenario”, vehicles have higher speeds at toll links, which result in an increase in PM10 emissions.

\textbf{TABLE 2.} Air Pollution Levels in 1999 Morning Peak Period without ETC (in kg)

<table>
<thead>
<tr>
<th>(a) Air Pollution Levels in 1999 Morning Peak Period without ETC (in kg)</th>
<th>CO</th>
<th>HC</th>
<th>NO\textsubscript{x}</th>
<th>PM10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mainline Links</td>
<td>3,726.8</td>
<td>421.2</td>
<td>475.2</td>
<td>5.2</td>
</tr>
<tr>
<td>Toll Plaza Links</td>
<td>572.5</td>
<td>86.3</td>
<td>59.65</td>
<td>0.49</td>
</tr>
<tr>
<td>Total</td>
<td>4,299.3</td>
<td>507.5</td>
<td>534.85</td>
<td>5.69</td>
</tr>
<tr>
<td>Vehicle miles traveled (VMT)</td>
<td>1,693,456</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(b) Unit Air Pollution Levels in 1999 Morning Peak Period without ETC (kg/mile/hour)</th>
<th>CO</th>
<th>HC</th>
<th>NO\textsubscript{x}</th>
<th>PM10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mainline Links</td>
<td>4.71</td>
<td>0.54</td>
<td>0.60</td>
<td>0.007</td>
</tr>
<tr>
<td>Toll Plaza Links</td>
<td>7.13</td>
<td>1.17</td>
<td>0.68</td>
<td>0.005</td>
</tr>
<tr>
<td>Total</td>
<td>11.84</td>
<td>1.71</td>
<td>1.28</td>
<td>0.012</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(c) Total Air Pollution Emission Level with 1999 Demand with ETC system</th>
<th>CO</th>
<th>HC</th>
<th>NO\textsubscript{x}</th>
<th>PM10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mainline Links</td>
<td>3,915</td>
<td>445.8</td>
<td>490.2</td>
<td>6.0</td>
</tr>
<tr>
<td>Toll Plaza Links</td>
<td>469.3</td>
<td>66.1</td>
<td>51.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Total</td>
<td>4,384.3</td>
<td>511.9</td>
<td>541.6</td>
<td>6.5</td>
</tr>
<tr>
<td>VMT</td>
<td>1,746,482</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(d) Change in Air Pollution Levels based on Tollbooth Links</th>
<th>CO</th>
<th>HC</th>
<th>NO\textsubscript{x}</th>
<th>PM10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1 (kg)</td>
<td>77.5</td>
<td>15.03</td>
<td>6.0</td>
<td>0.03</td>
</tr>
<tr>
<td>Scenario 2 (kg)</td>
<td>37.3</td>
<td>7.0</td>
<td>3.2</td>
<td>0.02</td>
</tr>
<tr>
<td>Percent Change</td>
<td>-51.9%</td>
<td>-53.4%</td>
<td>-46.7%</td>
<td>-33.3%</td>
</tr>
</tbody>
</table>

However, the system-wide total air pollution level increases for all pollutants despite the improved travel times in the toll plaza system. The increase in the total air pollution level can be attributed to the higher number of vehicles in the system owing to the improved efficiency of the toll plaza system. It is observed that the number of vehicles that completed their trips in the system increase by 3\%. Similarly, total VMT increases by 3\% as shown in Table 2. It is

\textsuperscript{3} Tollbooth link is the link before the booths where vehicles queues are formed.

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interesting to note that although ETC deployment provides smoother flow and less congestion at toll plazas, it does not necessarily lead to lower emission levels in the overall network. The majority of air pollution in the system is due to the mainline traffic. This is because of longer link distances and higher vehicular speeds on the mainline as compared to the toll plaza system. To that end, it can be claimed that the reduction of emissions at the toll plaza system does not compensate the increase at the mainline as a result of increased number of completed trips.

Saka and Agboh (3) reported that the ETC system at 3 toll plazas in Baltimore, Maryland resulted in the reduction of HC and CO emissions by 40% and 63%, and the reduction of NOx emission by 16%. Their results were based on MOBILE 5b estimations. Klodzinski et al (4) reported that the ETC system at the Holland East Toll Plaza in Orlando, Florida results in the reduction of HC and CO emissions by 7.2% and 7.3%, and the increase in NOx emission by 33.7%. Their emission results were estimated by MOBILE 5a.

The main difference between our model and the ones presented in the literature is that the toll plaza emission levels shown in Table 2a through Table 2c reflect not only the tollbooth links, but also the whole toll plaza system. Table 2d presents the air pollution levels for both scenarios, when only the tollbooth links are considered. The results in Table 2d show that when only the tollbooth links are considered, the short-term effects of ETC deployment in air pollution levels are substantial.

**Long-Term Analysis**

NJTPK is a part of a larger transportation network. Traffic demand is expected to divert from other parts of the network onto NJTPK network owing to its increased efficiency as a result of ETC deployment. Therefore, the effect of ETC needs to be analyzed over a longer period.

The long-term analysis is two-fold:

1. **Long-Term analysis with ETC**: The first analysis is the comparison of air pollution levels of 1999 network without ETC deployment and the 2005 network with the ETC deployment. This analysis is a mere comparison of the current air pollution levels obtained from the 2005 network with the air pollution levels obtained from the 1999 network. The results reflect the long-term effect of ETC system under the traffic growth over years.

2. **Long-Term analysis without ETC**: The second analysis is the comparison of air pollution levels of 1999 network without ETC deployment and the 2005 network without ETC deployment. This analysis estimates the air pollution levels, had there been no ETC system. It is implicitly assumed in this analysis that the traffic demand would have grown at the same rate without ETC deployment as it is observed between 1999 and 2005.

**Long-Term Analysis with ETC**

The simulation analysis of 2005 network with ETC system shows that during morning peak period (7 a.m. – 9 a.m.) in 2005 the total emitted CO, HC, NOx and PM10 are 5,437.6 kg, 645.1 kg, 976.2 kg and 17.1 kg respectively. The breakdown of the air pollution levels for the mainline and toll plaza links are given in Table 3a. Similar to the results shown in Table 2a, total air pollution levels at the mainline links are higher than toll plaza links. The unit emission results (gram/mile/hour) given in Table 3b also show that the difference between unit emission rates for toll plaza and mainline links are less than the differences observed in Table 2a.
TABLE 3. Air Pollution Levels in 2005 Morning Peak Period with ETC (in kg)

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>HC</th>
<th>NO\textsubscript{x}</th>
<th>PM10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mainline Links</td>
<td>4,933.0</td>
<td>575.9</td>
<td>905.1</td>
<td>16.2</td>
</tr>
<tr>
<td>Toll Plaza Links</td>
<td>504.6</td>
<td>69.2</td>
<td>71.1</td>
<td>0.959</td>
</tr>
<tr>
<td>Total</td>
<td>5,437.6</td>
<td>645.1</td>
<td>976.2</td>
<td>17.1</td>
</tr>
<tr>
<td>VMT</td>
<td>2,161,766.18</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(b) Unit Air Pollution Levels in 2005 Morning Peak Period with ETC (kg/mile/hour)

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>HC</th>
<th>NO\textsubscript{x}</th>
<th>PM10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mainline Links</td>
<td>6.04</td>
<td>0.71</td>
<td>1.07</td>
<td>0.020</td>
</tr>
<tr>
<td>Toll Plaza Links</td>
<td>6.03</td>
<td>0.89</td>
<td>0.77</td>
<td>0.009</td>
</tr>
<tr>
<td>Total</td>
<td>12.7</td>
<td>1.60</td>
<td>1.84</td>
<td>0.029</td>
</tr>
</tbody>
</table>

The comparison of Table 2a and Table 3a show that between 1999 and 2005 the air pollution levels are substantially increased for the mainline links. This result can be attributed to the annual demand increase over six years. Based on the OD demand data, morning peak traffic demand increased by 14.9%. The breakdown of this growth for vehicle types is: passenger cars (13.6%), trucks (1.47%) and buses (116.8%).

At the toll plaza links CO and HC levels have decreased by 12% and 20%, respectively. However, NO\textsubscript{x} and PM10 levels have increased by 20% and 96% at the toll plaza links. It is clear that the short-term impacts of ETC deployment in toll plaza emission levels as shown in Table 2 diminish in the long-term where traffic demand is higher.

Similar to the short-term analysis, the air pollution levels at tollbooth links are estimated. The results show that the total emission levels for CO, HC, NO\textsubscript{x}, and PM10 are 39.8 kg, 7.03 kg, 4.3 kg and 0.04 kg, respectively, at the tollbooth links. The comparison of these values with the 1999 tollbooth link emission levels show that CO, HC and NO\textsubscript{x} emission have reduced by 48.6%, 53.2% and 28.1%, respectively. However, PM10 level increases by 29.2%. As mentioned in the short-term analysis results, the reason can be attributed to the PM10 emission rate of 4*10\textsuperscript{-6} grams per second for vehicle speeds under 2.5 mph. Hence, PM10 emissions increase as a result of increased speeds at the toll plaza due to ETC deployment.

**Discussion:** Between 1999 and 2005, the traffic demand at NJTPK in the morning peak hours has increased by 14.9%. This additional demand is approximately 20,000 vehicles. Although ETC deployment has reduced congestion at toll plazas, the overall air pollution level has still increased in the long-term due to this additional demand. By simple calculations, it can be shown that the decrease in air pollution level at toll plazas does not compensate the increased air pollution levels on the mainline due to this additional demand. To that end, it is sufficient to show that the lower bound estimate of additional emission on the mainline is higher than the upper bound estimate of emission at the toll plaza system.

The simulation result shows that the overall average speed in the network is 52.6 mph. To estimate a lower bound estimate of additional emission on the mainline, let us assume that 20,000 additional vehicles travel 1 mile in the network with an average speed of 52.6. This results 68.5 seconds of travel time per vehicle and 380 hours of total travel time on the mainline. The emission factors of MOBILE 6.2 for HC, CO, NO\textsubscript{x}, and PM10 are respectively 0.01251, 0.19143, 0.01407 and 0.00008 per second for the vehicle speed range of 50-55 mph. Multiplying these emissions factors by the additional travel time spent on the mainline, the total emissions of HC, CO, NO\textsubscript{x} and PM10 can be calculated as 17.1 kg, 262.0 kg, 19.3 kg and 0.10 kg, respectively. Note that these estimates are the lower bound estimate of the additional emission on the mainline. Let us know calculate the upper bound estimate of emission at the toll plaza system. Suppose that as a result of the ETC system the average time spent at the toll plazas reduces by 2 minutes per
vehicle. Let us also assume that the average speed of these vehicles the toll plazas are 20 mph. MOBILE 6.2’s emission factors for HC, CO, NO\textsubscript{x} and PM10 are respectively 0.00584, 0.05739, 0.00491, 0.00003. Therefore, the emission levels for HC, CO, NO\textsubscript{x} and PM10 at the toll plaza system can be calculated as 14.0 kg, 137.7 kg, 11.8 kg and 0.076 kg, respectively.

Although the ETC deployment results in lower congestion levels at toll plazas, the additional emission on the mainline is 134.9 kg more than that of the toll plaza system. This result is based on simple estimations, yet it can show that even with high benefits of ETC, the overall air pollution level in the network increases in the long-term due to annual traffic growth. The differences between the emission results shown in Table 2a and Table 3 support this fact. The observed difference in total emissions between 1999 and 2005 is estimated as 32.3%.

The deployment of ETC system in 1999 has considerably reduced delays at toll plazas. This in turn helped NJPTK sustain the traffic growth of 14.9% over the 6 years. The next analysis shows the change in air pollution levels over six years had the ETC system not been deployed.

**Long-Term analysis without ETC**

This analysis estimates the air pollution levels, if the ETC system was not deployed in NJTPK. The simulation analysis of 2005 network without ETC system shows that during morning peak period (7 a.m. – 9 a.m.) in 2005 the total emitted CO, HC, NO\textsubscript{x} and PM10 are 4,734.0 kg, 564.4 kg, 553.2 kg and 6.4 kg respectively. The breakdown of the air pollution levels for the mainline and toll plaza links are given in Table 4.

| TABLE 4. Air Pollution Levels in 2005 Morning Peak Period without ETC (in kg) |
|-----------------|-----------------|-----------------|-----------------|
| CO | HC | NO\textsubscript{x} | PM10 |
| **Mainline** | 4,107.9 | 465.9 | 492.4 | 5.9 |
| **Toll Plaza** | 626.2 | 98.5 | 60.8 | 0.5 |
| **Total** | 4,734.0 | 564.4 | 553.2 | 6.4 |
| **VMT** | 1,872,667.81 |

The observed difference in total emissions between 1999 and 2005 as shown in Table 2a reflect the changes in air pollution levels over six years had there been no ETC deployment. These analysis results show that the estimated percentage increase in total emissions of CO, HC, NO\textsubscript{x} and PM10 are 10.1%, 11.2%, 3.4% and 13.0%, respectively.

However, it should be noted that the actual impact of the absence of ETC system on emission levels is expected to be more severe than the results suggest here. It is observed in the simulation that the 2005 simulation network without ETC deployment could not handle the current traffic demand. The simulation results showed that 8% of the 2005 traffic demand could not be processed in the system when compared with the 2005 network with ETC deployment. In other words, within the 2 hours of simulation, approximately 7,000 vehicles could not complete their trips due to increased travel times at the toll plazas. This fact is also clear in the reduction of VMT from 2.1 million, as shown in Table 3, to 1.87 million in the absence of ETC system in 2005.

**Spatio-Temporal Comparison of Vehicle Emission Levels**

The total air pollution rate obtained from simulation (gram/mile/hour) is shown in Figure 2. Each dot in the figure indicates the amount of emissions per hour per mile on each link in the simulation network.

Figure 3 shows the spatial pattern of emissions obtained through simulation over various parts of the network. This figure shows an increase in toll plaza emissions at the toll plazas at
interchange 13 and the mainline section between 13 and 13A from 1999 (shown in inset of Figure 3a) to 2005 (shown in inset of Figure 3b). This can be seen as a shift in the color spectrum from blue towards red. The toll plaza emission level increase is due to the increase in demand at interchange 13 by 54% from 1999 to 2005. The mainline emissions increased near interchanges 10 and 11.
FIGURE 2. Air pollution levels at NJTPK during morning peak in 2005 (The units are in grams/mile/hour)
FIGURE 3. Distribution of Emissions (grams/hr/m) between 1999 (a) and 2005 (b) between Interchange 9 and Interchange 14 – Inset shows the section from interchange 13 to 13A
CONCLUSIONS

This paper describes the impact of ETC on air pollution levels in a large-scale highway transportation network, namely the New Jersey Turnpike. The microscopic simulation network model was created and validated using PARAMICS simulation software by (13, 14). A brief description of this process is presented in this paper.

The novelty of this simulation model is two fold:

1. The NJTPK network has 26 operational interchanges with separate toll plaza system. The operational efficiency of the system is highly affected by the toll plaza operations. Therefore, a valid toll plaza model is crucial in the simulation network development. Ozbay et al. (13) developed and integrated a toll plaza lane-decision model using application-programming interface of PARAMICS. The end result is large-scale network with a credible toll plaza system.

2. The traffic volume data were obtained using the available vehicle-by-vehicle transaction data. Highly accurate OD matrices by vehicle type were extracted for before (1999) and after ETC deployment (2005). The detailed description of the dataset is presented in the paper.

Unlike the previous studies in the literature, the analysis presented in this paper does not focus on an individual toll plaza, but the entire network, which consists of a separate mainline and a series of toll plazas.

The disaggregate effect of ETC on air pollution levels is investigated. The developed simulation tool can identify location-based air pollution levels as shown in Figure 2 and Figure 3, which can help policy makers and analysts to understand the problematic locations within the network instead of relying on the total air pollution levels.

MOBILE 6.2 mobile source emission factors (is it the model or output or functions???) developed by the USEPA (1) is utilized and integrated in PARAMICS. At each time step of the simulation, air pollution levels, namely CO, HC, NOx and PM10 emissions are calculated for every individually simulated vehicle based on their vehicle type and speed.

Initially, to analyze the short-term impact of ETC, the simulation is performed for the 1999 demand with and without the deployment of ETC. At the toll plazas, CO, HC and NOx levels reduced by 36.3%, 47.2% and 28.2% respectively. However, PM10 emission levels increased by 6.7% as shown in Table 2a and Table 2b. This analysis also showed that the air pollution emission levels at the tollbooth links were reduced for all pollutants. CO, HC, NOx and PM10 emission levels decreased by 52%, 53.3%, 47% and 33.3% respectively (shown in Table 2d). However, the network-wide air pollution level increased. This increase can be attributed to the higher number of vehicles processed in the system as a result of increased efficiency due to ETC system.

Traffic demand increases due to natural growth and also possibly due to induced demand caused by the deployment of ETC over years. Hence a long-term analysis involving two scenarios is carried out. The first scenario is the analysis of 1999 network without ETC deployment and 2005 network with ETC deployment. The results show that, under this scenario, total network-wide air pollution increased by 32.3% during the morning peak period. At the 26 toll plazas, CO and HC levels reduced by 12% and 20%. However, NOx and PM10 levels increased by 20% and 96% as shown in Table 3a and Table 3b. These results suggest that the positive impact of ETC deployment on toll plaza emission levels also diminished due to the cumulative annual increase in demand in the long run.

The second long-term scenario involves the 1999 network without ETC deployment and 2005 network also without ETC deployment. The results, as shown in Table 4, indicate that the estimated percentage change in total emissions of CO, HC, NOx and PM10 are 10.1%, 11.2%, 3.4% and 13.0%, respectively over the network. However, the clear impact of ETC system cannot be estimated because without the ETC system the network cannot completely process the 2005 demand without major delays.
The spatio-temporal comparison of emission levels over smaller parts of the network is also shown in Figure 2 and Figure 3.

Although short-term benefits of ETC deployment are clearly seen in the analysis, the benefits are not very apparent over a longer period. The primary reason is due to the increase in both natural and induced demand. It should be noted here that induced demand is usually inevitable with improved efficiency of a transportation system. Hence, it is important to analyze long-term impact of any ITS technology to better understand its long-term benefits.

REFERENCES


