# Estimating Emission Benefits of Electronic Open-Road Tolling Conversion Projects

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## ABSTRACT

Intelligent transportation systems using vehicle-to-infrastructure communications are being adopted rapidly. Many state and local transportation agencies are currently evaluating the replacement of highway toll plazas with open-road (or overhead) gantries, often mounted with high-resolution cameras for license plate reading and high-speed sensors for transponder detection. Conversion to electronic open-road tolling (EORT) systems can provide a range of benefits, including smoother traffic flow and lower crash risk, better asset management and lower maintenance costs, and the ability to instantaneously adjust fares for variable or congestion pricing. EORT systems can also potentially reduce emissions and energy consumption; however, the environmental benefits between different electronic tolling configurations have not yet been well-characterized.

The goal of this study was to estimate emission and energy reductions for EORT conversion projects to support development of a new tool in the Federal Highway Administration's (FHWA) Congestion Mitigation and Air Quality Improvement (CMAQ) Emissions Calculator Toolkit. A three-tiered approach was applied, utilizing real-world traffic volume and speed data from two Interstate 90 toll facilities near Boston before and after EORT conversion. First, traffic microsimulations of different tolling configurations were run to generate vehicle operating mode distributions to represent driving behavior through toll facilities. Second, operating mode distributions were used as project-level inputs in the U.S. Environmental Protection Agency's Motor Vehicle Emission Simulator (MOVES). Finally, multivariable linear regressions were developed to estimate emissions and energy for traffic conditions not explicitly modeled.

Findings from this study show that EORT systems allow for higher average speeds during peak commuting hours and traffic to achieve free flow conditions during nonpeak hours. Mainline traffic throughput typically also increases after converting to EORT facilities from full stop or rolling cruise (i.e., 5-15 mph) toll plazas. MOVES modeling consistently demonstrated larger emissions and energy benefits for conversion of full stop toll plazas to EORT compared with conversion of rolling cruise plazas. For passenger vehicles on a per mile basis, full stop conversions were found to reduce fine particulate matter (PM2.5) up to 61% and energy consumption up to 28%, whereas rolling cruise conversions reduced PM2.5 up to 34% and energy consumption up to 10%. These findings help confirm the emission benefits and fuel savings of converting legacy toll plazas to open-road systems.

# INTRODUCTION

The business case for electronic open-road tolling (EORT) usually starts and ends with alleviating congestion and lowering crash risk. However, capital costs of these EORT conversion projects, especially the removal of legacy toll infrastructure, can be sizeable for many transportation agencies. State and local agencies often seek funding to subsidize project costs through federal programs like the Federal Highway Administration (FHWA) Congestion Mitigation and Air Quality Improvement (CMAQ) Program.[1] Agencies are required to demonstrate emission reductions of criteria pollutants to be eligible for CMAQ funding.[2] The Volpe Center has supported FHWA in development of the CMAQ Emissions Calculator Toolkit, which provides agencies with well-documented, repeatable methodologies for emission reduction estimates.[3] Over the past year, FHWA has released a series of tools for intelligent transportation system (ITS) projects utilizing vehicle-to-infrastructure (V2I) communications including EORT facilities.[4] This paper lays out methodology to evaluate potential reductions in emissions and fuel use for EORT conversion projects.

Literature on the environmental impacts of converting to EORT facilities is limited, in particular for modern free-flow EORT systems. An early study in this field from Woo and Hoel (1991) developed baseline level-of-service (LOS) and traffic flow estimates for manual toll collection.[5] When electronic tolls were introduced broadly in the 1990s, their traffic conditions still closely resembled manually operated tolls with modest improvements. Sisson (1995) showed how first-generation electronic tolling systems would lead to air quality benefits by reducing queueing and idling at toll plazas.[6] Building upon earlier work, Saka et al. (2002) demonstrated emission reductions through less heavy braking leading up to a low-speed electronic toll and gentler accelerations to return to highway speeds after the toll.[7]

In the early 2000s, technologies for electronic transponder detection improved such that vehicles could maintain higher average speeds through conventional toll plazas. Examples of this better shortwave transponder detection include Coelho et al. (2005), which went on to validate modeled emission results with field measurements for an electronic tolling system in Lisbon, Portugal that only required drivers to brake to a rolling cruise (i.e. 15-20 mph).[8] Venigalla and Krimmer (2006) estimated emission reductions for heavy-duty vehicles driving through electronic tolls with similar rolling cruise configurations.[9] Further geospatial resolution of emissions was presented in Bartin et al. (2007) for electronic rolling cruise tolls on the New Jersey Turnpike.[10]

Electronic tolling infrastructure went through another major transition in the late 2000s with the introduction of commercial open-road (or overhead) gantry systems that enabled higher speed transponder detection. Most of these new open-road systems operate at free-flow or near free-flow conditions. Lin and Yu (2008) found substantial air quality improvements after legacy toll plazas were removed and open-road systems had been installed near Chicago.[11] Their predictions through roadside air dispersion modeling were based on measured average traffic speeds and volumes but did not represent toll-specific driving behavior. A few other helpful EORT studies exist, although they are less directly relevant to emissions. Yang et al. (2011) focused on EORT safety impacts and Klodzinski et al. (2012) performed a cost-benefit analysis of EORT systems.[9,10] Lin et al. (2020) conducted meticulous air quality monitoring before and after EORT installation. Less stop-and-go driving with open-road tolling systems has clear benefits, reducing near-road concentrations of fine particulate matter (PM2.5) and ultrafine particles (UFP).[14]

In our own study of free-flow EORT facilities, we investigated two highway tolling locations on Interstate 90 (I-90, commonly referred to as the Massachusetts Turnpike) near Boston[15] that have been recently converted to open-road systems: one located on the edge of city limits and another in a suburban setting in the greater Boston area. The Massachusetts Department of Transportation (MassDOT) generously provided critical traffic datasets before and after EORT conversion. These datasets confirmed that vehicles were able to achieve free-flow speeds going through open-road tolls, particularly during off-peak commuting hours, and comparable toll throughput to reference traffic volumes on the rest of the corridor. The following section highlights this I-90 toll analysis and how those findings were generalized through microscopic traffic simulations and emission calculations, much in a similar fashion to prior literature.

## BACKGROUND AND RESEARCH METHODS

Starting in 2016, Massachusetts constructed overhead gantries equipped with high-resolution cameras for license plate reading and sensors for transponder detection at highways speeds close to but not in identical locations as existing I-90 toll plazas.[16] Once the gantries were in place and equipped with EORT systems, MassDOT activated the new EORT technology and began demolition of toll plazas along the highway's right-of-way. Over the next year, the agency implemented temporary lane closures to systematically demolish legacy Massachusetts Turnpike tolling infrastructure.[17]

### Massachusetts Turnpike Case Study

To verify that these open-road tolling systems could be operated at free-flow or near free-follow traffic conditions, we developed a case study for two recently-converted locations of mainline Massachusetts Turnpike tolls in and around Boston: Allston and Weston. The Allston all-electronic toll (AET 13) is located along the Charles River, about four miles west of downtown Boston but still within city limits. The Weston all-electronic toll (AET 10) is situated roughly 25 miles from Boston and was constructed nearly five miles further west than the legacy toll plaza site, right after the I-95 interchange. Figure 1 shows images and approximate locations of the two EORT overhead gantries in Allston and Weston respectively. Likewise, Figure 2 shows comparable pre- and post-demolition images of the I-90 toll plazas in Allston and Weston.


Figure 1a. A photograph of westbound I-90 traffic passing under the Allston toll gantry from October 2018 (top) and a map of the Allston gantry location circled in red (bottom) (Source: Google Maps)

Figure 1b. A westward-facing photograph of the Weston I-90 toll gantry from October 2018 (top) and a map of the Weston gantry location circled in red and the demolished toll plaza site marked (bottom) (Source: Google Maps)


Figure 2. Images of the Massachusetts Turnpike before and after legacy toll plazas were demolished in (a) before: Allston/July 2011, (b) after: Allston/September 2018, (c) before: Weston/August 2013, and (d) after: Weston/September 2018 (Source: Google Maps)

With data provided from MassDOT, detailed traffic conditions were compared before and after the overhead gantries and the EORT systems were installed. Massachusetts had purchased proprietary speed data (averaged each minute) from INRIX[18] and was able to supply average speeds for the two chosen tolling sites. Figure 3 demonstrates how average speeds for eastbound vehicles traveling into Boston have changed for representative weekdays in Allston and Weston. Peak commuting hours still had significant slowdowns even after EORT conversion, but off-peak hours approached free-flow conditions. In Allston, speed improvements were most pronounced during the morning peak despite heavy congestion, similar though less remarkable speed improvements occurred during the evening commute. The highest speeds in Allston were recorded overnight, equivalent to or greater than the posted speed limit of 55 mph. Off-peak times during the rest of the day hovered around an average speed of 50 mph. In Weston, midday speeds improved dramatically and were close to free-flow conditions after EORT conversion. Overnight speeds met or exceeded the posted speed limit of 65 mph. However, the morning and afternoon commuting peaks did not demonstrate large increases in average speeds.

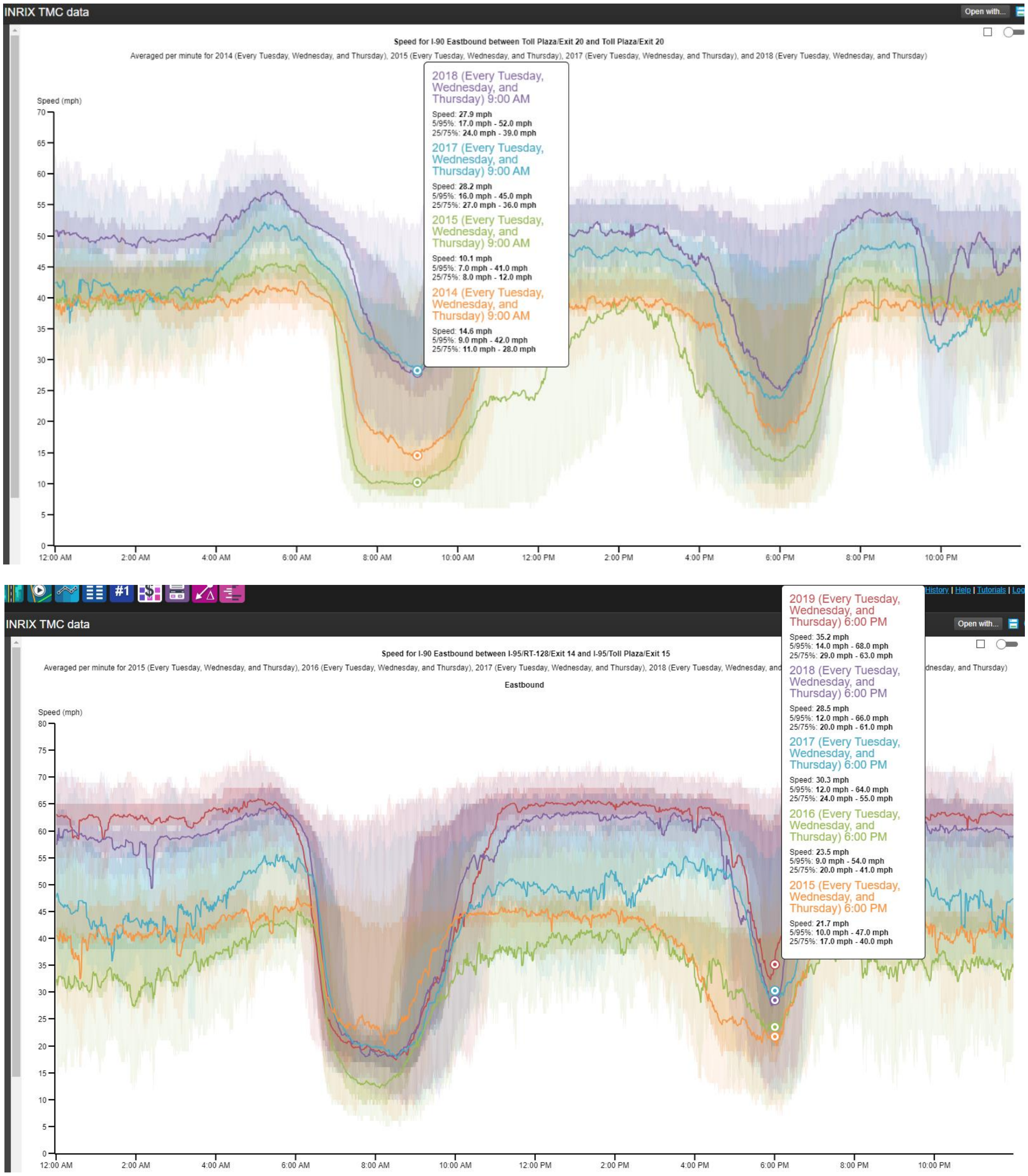


Figure 3. Example weekday speed data (averaged per minute) on the Massachusetts Turnpike before and after conversion to EORT systems in Allston (top) and Weston (bottom) (Source: INRIX/MassDOT)

Traffic volumes for open-road tolls mimicked free-flow conditions. Massachusetts purchased traffic volume data through another third-party vendor, MS2,[19] and made vehicle counts (averaged over 15-minute intervals) for certain roadways publicly available, including on the Massachusetts Turnpike. In Allston, the I-90 diurnal patterns are inverted as commuters travel into Boston each morning and leave the city in the early evening. The effective EORT throughput after conversion in terms of passenger cars per hour per lane (pcphpl) is much greater than the estimated volume ceilings for manually-operated tolls or lower speed electronic tolls.

For example, manned tolls in Woo and Hoel were estimated to have 600-750 pcphpl capacity.[5] In comparison, Saka et al. expected roughly 475 pcphpl for manned tolls or gated electronic tolls and 1350 pcphpl for rolling cruise electronic tolls.[7] Measured vehicle counts on the Massachusetts Turnpike were not able to reach these theoretical upper bounds.

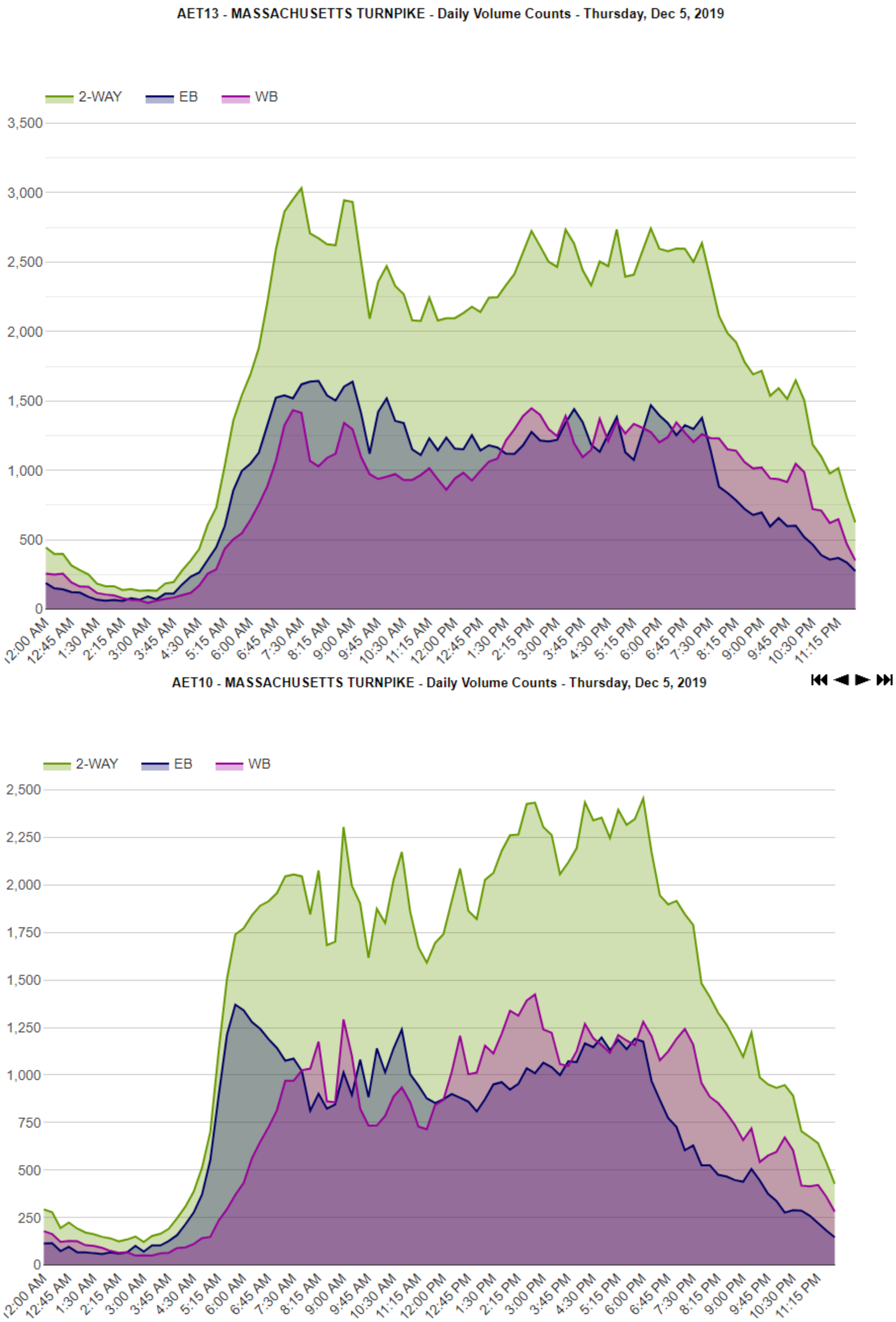


Figure 4. Time series of example I-90 traffic volumes in both directions collected for the Allston all-electronic toll (AET13, top) and for the Weston toll (AET 10, bottom) after EORT conversion (Source: MS2/MassDOT)

Prior to EORT conversion, legacy I-90 toll throughputs provided by MassDOT averaged approximately 250-300 pcphpl in 2014. After EORT conversion, MS2 traffic counts for a representative weekday in 2019 reached a peak of roughly 1700 pcphpl and ranged 750-1250 pcphpl for nonpeak daytime hours, as shown for Allston in Figure 4. On the same representative day, the Weston electronic tolling gantry recorded a slightly lower peak of roughly 1400 pcphpl but had similar daytime ranges of 750-1250 pcphpl as tolls closer to the city. Toll throughput markedly increased upon conversion to open-road systems. Real-world data from the Massachusetts Turnpike confirm that EORT systems have led to notable speed and throughput increases compared to legacy toll plazas. Furthermore, these data suggests that overhead gantries do not impede traffic as previous tolling infrastructure did.

## Electronic Tolling Tool Development

To calculate potential emission reductions of electronic tolling conversion projects for CMAQ eligibility, a new tool was developed using a three-tiered modeling approach: 1) microscopic traffic simulations of varying tolling configurations, 2) modal emissions and energy modeling of the simulated driving behavior through tolls, and 3) multivariable linear regressions to estimate benefits not explicitly simulated. As part of the CMAQ Toolkit, the EORT tool was first publicly released in November 2021 along with accompanying documentation. Tiered modeling methodology has been laid out in the tool's user guide and emissions data document.[20] The following sections summarize the methodology for each of the three modeling tiers.

### *Tolling Microsimulations*

We created three distinct tolling configurations in order to adequately distinguish driving behavior between scenarios, primarily for light-duty vehicles (LDV):

- Full stop (queueing and idling through tolling area),
- Rolling cruise (low speed cruise, usually 10-20 mph, through tolling area), and
- Free flow (open-road tolling systems that do not impede traffic).

Traffic conditions were varied consistently between the three tolling configuration to produce comparable and robust results that could then be used in emissions and energy modeling. Traffic variables included average vehicle speed through the tolling area, average highway speed, toll throughput, and percentage of heavy-duty vehicle (HDV) traffic, as laid out in Table 1.

For performance and ease-of-use in traffic microsimulations, we chose Eclipse Simulation of Urban Mobility (SUMO) because the software is lightweight, efficient, and open-source.[21] The three tolling configurations were applied across several unique scenarios on the same four-lane, nearly 2.5-mile traffic network. The network was coded as three straight-line road segments: one as an approach zone (1.357 miles in length) for vehicle deceleration and braking, another as a zone to travel through the tolling area itself (0.015 mi), and a final one as a departure zone (1.021 mi) for acceleration back to highway speed. The first and second configurations represented conventional toll plazas on the highway mainline with a full stop or a reduced speed respectively and the final configuration represented an EORT system as uninterrupted highway traffic flow. As a simplification, these scenarios assumed minimal lane changes—only to avoid crashes or for heavy-duty vehicles to move into their dedicated toll lane. Most vehicles did not change lanes.

Table 1. Listing of all the traffic conditions tested in the tolling microsimulations

| Traffic Variables | Values |
|---|---|
| Average speed through tolling area | Full stop (LDV idle: 3.8 s, HDV idle: 21.0 s) |
| | Rolling cruise at 15 mph |
| | Free flow (equivalent to average highway speed) |
| Average highway speed | 50 mph |
| | 60 mph |
| | 70 mph |
| Toll throughput | Peak (345 LDV/lane, 115 HDV/lane, 1150 veh/hr total) |
| | Non-peak (216 LDV/lane, 72 HDV/lane, 720 veh/hr total) |
| | Overnight (99 LDV/lane, 33 HDV/lane, 330 veh/hr total) |
| Percentage of heavy-duty traffic | 0% HDV traffic (in dedicated HDV lane with 3 LDV lanes)* |
| | 10% HDV traffic (in dedicated HDV lane with 3 LDV lanes) |

*Note this case was not explicitly simulated in SUMO but instead post-processed through the emissions model.

Microsimulation conditions were further calibrated with in-use tolling data supplied by MassDOT. Varying conditions were then combined into 27 distinct scenarios, each becoming its own SUMO run. Once run, SUMO generated second-by-second vehicle trajectories that could be utilized in project-level emissions modeling. For further reading beyond the CMAQ Toolkit documentation, Eilbert et al. (2018) performed a similar crosswalk between traffic microsimulations and vehicle-specific emission estimates.[22] The next section describes how we characterized driving behavior from SUMO vehicle trajectory data based on their speed and power to estimate emissions and fuel use between these different tolling scenarios.

***Emissions and Energy Estimates***

The Motor Vehicle Emission Simulator (MOVES) is the regulatory model from the US Environmental Protection Agency for producing emission inventories for highway vehicles.[23] We developed project-level MOVES inputs using the simulated vehicle trajectories for each scenario run in SUMO. Each scenario had its own unique driving behavior and subsequent MOVES operating mode distribution. Operating modes were assigned for each row of trajectory data and then operating mode distributions were calculated using a matrix of vehicle-specific power and speed, as summarized in Table 2. As defined in Equation 1, vehicle-specific power (VSP) is dependent on instantaneous speed $v_i$ and acceleration $a_i$, such that

Equation 1. Definition of instantaneous vehicle-specific power (VSP) in MOVES

$$VSP(v,a)_i = \frac{Av_i + Bv_i^2 + Cv_i^3 + mv_i a_i}{m},$$

where *A* is the tire rolling resistance coefficient, *B* is the rotational resistance coefficient, *C* is the aerodynamic drag coefficient, and *m* is the vehicle mass. Road load coefficients *A*, *B*, and *C* and vehicle mass were pulled from the MOVES default database for a LDV and HDV.

Table 2. Operating mode assignments based on instantaneous vehicle-specific power, speed, and acceleration

| Operating Mode (opModeID) | Operation Mode Description | Vehicle-Specific Power ($VSP_i$, kW/metric ton) | Vehicle Speed ($v_i$, mph) |
|---|---|---|---|
| **0** | Deceleration/Braking* | | |
| **1** | Idle | | $-1 \leq v_i < 1$ |
| **11** | Coast | $VSP_i < 0$ | $1 \leq v_i < 25$ |
| **12** | Cruise/Acceleration | $0 \leq VSP_i < 3$ | $1 \leq v_i < 25$ |
| **13** | Cruise/Acceleration | $3 \leq VSP_i < 6$ | $1 \leq v_i < 25$ |
| **14** | Cruise/Acceleration | $6 \leq VSP_i < 9$ | $1 \leq v_i < 25$ |
| **15** | Cruise/Acceleration | $9 \leq VSP_i < 12$ | $1 \leq v_i < 25$ |
| **16** | Cruise/Acceleration | $12 \leq VSP_i$ | $1 \leq v_i < 25$ |
| **21** | Coast | $VSP_i < 0$ | $25 \leq v_i < 50$ |
| **22** | Cruise/Acceleration | $0 \leq VSP_i < 3$ | $25 \leq v_i < 50$ |
| **23** | Cruise/Acceleration | $3 \leq VSP_i < 6$ | $25 \leq v_i < 50$ |
| **24** | Cruise/Acceleration | $6 \leq VSP_i < 9$ | $25 \leq v_i < 50$ |
| **25** | Cruise/Acceleration | $9 \leq VSP_i < 12$ | $25 \leq v_i < 50$ |
| **27** | Cruise/Acceleration | $12 \leq VSP_i < 18$ | $25 \leq v_i < 50$ |
| **28** | Cruise/Acceleration | $18 \leq VSP_i < 24$ | $25 \leq v_i < 50$ |
| **29** | Cruise/Acceleration | $24 \leq VSP_i < 30$ | $25 \leq v_i < 50$ |
| **30** | Cruise/Acceleration | $30 \leq VSP_i$ | $25 \leq v_i < 50$ |
| **33** | Cruise/Acceleration | $VSP_i < 6$ | $50 \leq v_i$ |
| **35** | Cruise/Acceleration | $6 \leq VSP_i < 12$ | $50 \leq v_i$ |
| **37** | Cruise/Acceleration | $12 \leq VSP_i < 18$ | $50 \leq v_i$ |
| **38** | Cruise/Acceleration | $18 \leq VSP_i < 24$ | $50 \leq v_i$ |
| **39** | Cruise/Acceleration | $24 \leq VSP_i < 30$ | $50 \leq v_i$ |
| **40** | Cruise/Acceleration | $30 \leq VSP_i$ | $50 \leq v_i$ |

*Braking is defined by a substantial deceleration (negative acceleration values) in the previous second or moderate deceleration over multiple seconds prior.

These operating mode distributions were generated externally to MOVES for quicker processing times and then imported into the model's project level inputs. Further details on MOVES project-level inputs and run specifications can be found in the CMAQ Toolkit documentation.[20] The following section discusses how we expanded and generalized these 27 tolling parameter combinations to allow for a greater range of CMAQ tool inputs.

***Multivariable Linear Regressions***

Given the different tolling configurations and wide range of traffic conditions, we could not come close to modeling all possible conditions. Instead we developed a multivariable linear regression (MLR) for each of the three tolling configurations (full stop, rolling cruise, free flow) and across the seven pollutants included in CMAQ Toolkit reporting, which meant 21 independent regressions in total. Reported criteria pollutants included carbon monoxide (CO), nitrogen oxides (NOx), particulate matter with diameters of 2.5 microns or less (PM2.5), particulate matter with diameters of 10 microns or less (PM10), and volatile organic compounds (VOC) as well as total energy consumption (TEC) and greenhouse gases in carbon dioxide equivalent ($CO_2e$).

Each MLR took the same general form and included the same predictive variables—toll throughput, average speed, proportion of heavy-duty traffic, and evaluation year. As highlighted in Equation 2, we predicted emission inventory estimates $E$ as,

Equation 2. General form of regressions for predicting emissions and energy from different tolling configurations

$$E = k_{q_{scen,pol}} \cdot q + k_{s_{scen,pol}} \cdot s + k_{\alpha_{scen,pol}} \cdot \alpha + k_{y_{scen,pol}} \cdot y + K_{scen,pol}$$

where $q$ is the hourly toll throughput per lane (veh/ln/hr), $s$ is the average speed through tolling facility (mph), $\alpha$ is the percentage of heavy-duty vehicle traffic, and $y$ is the project evaluation year. There is an accompanying coefficient $k$ for each of these regression variables along with an error term $K$ (y-intercept) by scenario and pollutant. The regression coefficients and correlation statistics for the 21 MLRs modeled can be found in the CMAQ documentation. Figure 5 presents boxplots of adjusted $R^2$ values (which adjusts predictive power when increasing the number of explanatory variables) by tolling configuration. Regressions for rolling cruise (0.862-0.987) and free flow (0.860-0.990) had stronger goodness-of-fit than the full stop regressions (0.798-0.903) but a broader range of adjusted $R^2$ values. Even the full stop configuration generated high enough goodness-of-fit values, such that we were comfortable using the MLRs to predict emissions and energy for other user-supplied traffic conditions at tolling facilities.

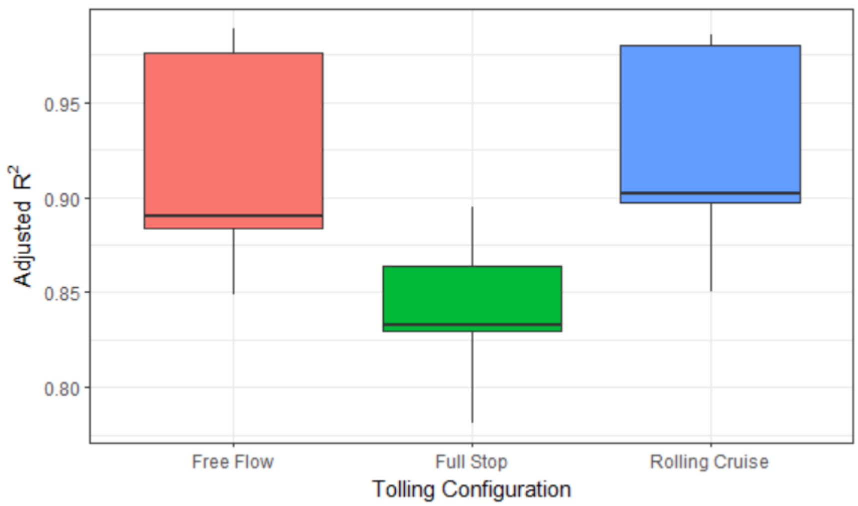


Figure 5. Goodness-of-fit boxplots for adjusted $R^2$ across each of the three tolling configurations

These regressions enable the CMAQ EORT tool to calculate emissions and energy reductions when converting from legacy toll plazas with either a full stop or rolling cruise configuration to free flow associated with open-road tolling systems. The next and final section highlights our modeling results and proposes opportunities for future research.

# RESULTS AND DISCUSSION

To evaluate the representativeness of our traffic microsimulations in SUMO, we conducted some spot-checking of the simulated vehicle trajectories for each of the three tolling configurations: full stop, rolling cruise, and free flow. Comparing across the same small time window and subset of vehicles, trajectories varied by tolling configuration as one would expect. Figure 6 captures snapshots of driving behavior by tolling configuration for five vehicles during nonpeak commuting hours, showcasing similar results to the I-90 tolling conversion in Allston.

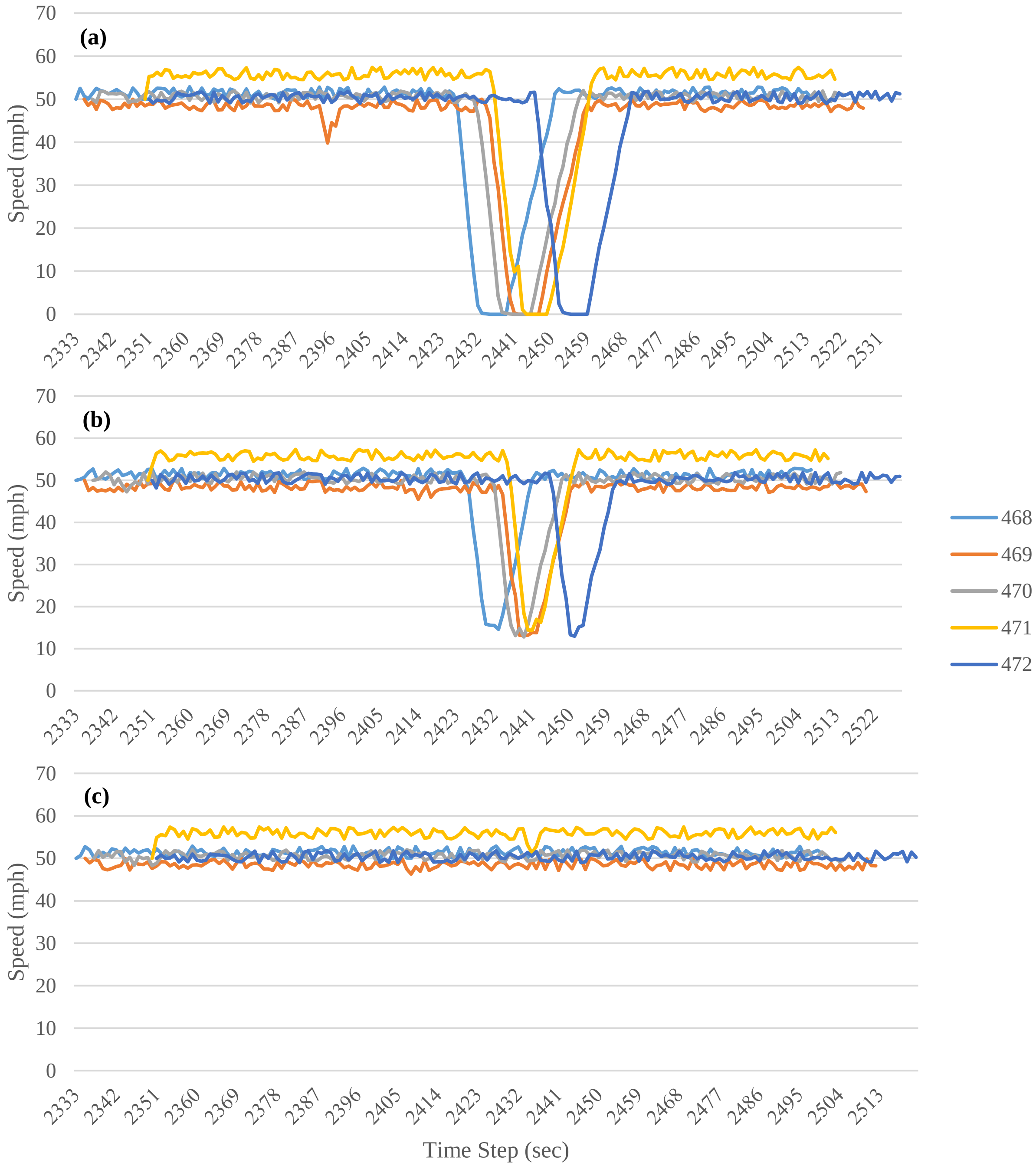


Figure 6. Sample second-by-second LDV speed trajectories for (a) full stop, (b) rolling cruise, and (c) free flow tolling configuration during nonpeak hours across the simulated time window for five vehicles

Based on vehicles movements in the SUMO simulation viewer, the full stop scenarios demonstrated short durations of queueing and idling. The rolling cruise scenarios had vehicles brake substantially when approaching, drive through the toll area at close to a steady-state cruise of 15 mph, and then accelerated back to highway speeds. Finally, the free flow scenarios were shown to operate without any delay due to the open-road tolling infrastructure. Note the slightly differing durations between scenarios, where free flow vehicles traverse the tolling network the most quickly, followed by rolling cruise, and then full stop, as shown in Figure 6.

Next, we verified that the operating mode distributions calculated for the project-level MOVES runs adequately summarized the differences in driving behavior between scenarios. Figure 7 shows an example comparison of LDV operating mode distributions by tolling configuration but otherwise had consistent traffic conditions. It is akin to what was seen at the Allston tolling facilities on the Massachusetts Turnpike. To differentiate the various scenarios modeled, we created a shorthand labeling convention that represented each of traffic parameters chosen: tolling configuration (i.e., F: free flow, R: rolling cruise, S: full stop), highway speed (i.e. 50, 60, or 70 mph), level of congestion (i.e. peak, nonpeak, and overnight traffic volumes), and truck traffic (i.e., percent of HDVs). For instance, F_50_P_10 is shorthand for a free flow scenario with a 50-mph average speed during peak commuting hours and with 10% HDV traffic.

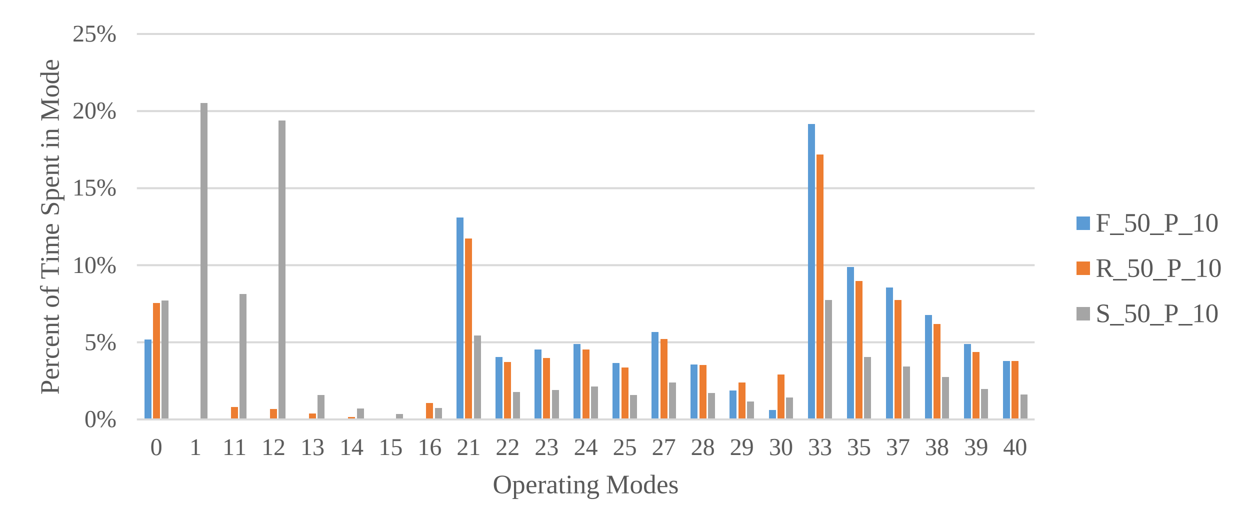


Figure 7. Example plot comparing LDV operating mode distributions between scenarios (F: free flow, R: rolling cruise, S: full stop) at 50 mph during peak hours and with 10% HDV traffic

Intuitively, we find that the example full stop scenario in Figure 7 had more braking (op mode 0) and significantly more idling (op mode 1) than either of the other two configurations. While most of the differences for the full stop scenario came from braking and idling as well as during low power and low speed operation (op modes 11 through 14), that was not also true for the rolling cruise scenario. It demonstrated more braking than the free flow scenario but did not spend any time in idle as anticipated. These rolling cruise scenario differences were derived primarily from operation under high power and low speed (op mode 16) and moderate speed (op modes 29 and 30) to quickly accelerate back to highway speed. Since the full stop scenario has greater braking and idling than the other scenarios and also takes noticeably longer for vehicles to accelerate and pass through the tolling network, less time was spent in the higher operating mode distributions. These scenario dynamics ended up informing the subsequent emission and energy results.

In comparing tolling facilities with matching traffic conditions, we calculated emission reductions and energy savings for the 21 combinations explicitly modeled. Results per vehicle are shown separately in Table 3 for LDVs and HDVs because their operating mode distributions were entered independently into MOVES. However, MOVES has options to report emission and energy consumption inventories either by vehicle class as we have done here or by mixed traffic as the CMAQ tool does. For mixed traffic inventories, contributions for each vehicle class depend on the pollutant and other conditions modeled.

Table 3. Ranges of potential per-vehicle emission reductions for criteria pollutants and energy savings from tolling conversions from either full stop or rolling cruise configurations to EORT systems

| Vehicle | Conversion | CO | NOx | VOC | PM2.5 | Energy |
|---|---|---|---|---|---|---|
| ***LDV*** | Full Stop to Open Road | 27-36% | 14-16% | 17-36% | 24-61% | 10-28% |
| | Rolling Cruise to Open Road | 26-30% | 12-14% | 14-20% | 22-34% | 7-10% |
| ***HDV*** | Full Stop to Open Road | 8-56% | 13-61% | 1-57% | 20-62% | 9-50% |
| | Rolling Cruise to Open Road | 10-20% | 14-25% | 3-16% | 21-31% | 12-16% |

Generally speaking, we found that full stop conversions would yield larger emission and energy benefits and wider benefit ranges than rolling cruise conversions. This can be attributed to rolling cruise scenarios operating closer to free flow than full stop scenarios. For light-duty, PM2.5, CO, and VOC were reduced the most on a per vehicle basis. Similarly for heavy-duty, PM2.5, NOx, and VOC were reduced the most per vehicle. While PM2.5 reductions were quite comparable for LDVs and HDVs in either type of tolling conversion project, NOx and energy reductions were greatest for HDVs in full stop conversions. Interestingly for CO and VOC, LDVs demonstrated greater benefits than HDVs in rolling cruise conversions while HDVs usually showed a lower benefits, especially for full stop conversions.

These are promising results for transportation agencies and ITS project developers. While CMAQ funding eligibility is determined simply by demonstrating emission benefits, many state and local agencies also consider cost-effectiveness when choosing projects. For planning purposes, FHWA regularly assesses and publishes CMAQ project cost-effectiveness.[24] As EORT conversions and other ITS projects come online and apply for CMAQ funding, these cost-effectiveness calculations will be critical for garnering support. In relative terms, other CMAQ-eligible projects such as highway high-occupancy vehicle (HOV) lanes may generate larger emission reductions than EORT conversions, but electronic tolling projects might still have higher cost-effectiveness. Most EORT projects would convert multiple tolling facilities, like on the Massachusetts Turnpike, so the benefits from the CMAQ tool could be multiplied by the number of new toll gantries being installed. This would also raise the project's capital costs. We recommend further analysis of cost-effectiveness as CMAQ applications for EORT conversions are submitted.

Additionally, this electronic tolling analysis was aimed to be applicable over a broad range of projects. The traffic microsimulation and emissions model inputs could be further tailored to a particular project. Further customization of the traffic network, vehicle mixes, speeds, and volumes could generate more project-specific results. Traffic patterns and congestion have changed since the start of the COVID-19 pandemic and will continue to change as workers return to their offices and begin to commute again. These traffic changes will likely affect the relative benefits of open-road tolling.

Lastly, going forward, there is an opportunity for field measurements. Future studies could equip vehicles with portable emissions monitoring equipment or set up near-road air quality monitors like in Lin et al.[14] to confirm these modeled emission benefits of EORT systems.

## SUMMARY

Highway tolling infrastructure has evolved substantially over the past few decades. Toll plazas with human operators have given way to electronic systems with shortwave transponders. At first these electronic tolls had drivers greatly reduce their speeds or even stop, but newer open-road systems deploy overhead gantries equipped with high-speed sensors to detect transponders and/or cameras to pay tolls by license plate number. Electronic open-road tolling (EORT) systems allow drivers to maintain highway speeds and enable free flow traffic conditions. The Massachusetts Turnpike (Interstate 90) transitioned to all-electronic tolling in 2016 and this transition has provided an excellent case study of EORT implementation.

While there are many reasons for state and local transportation agencies to construct EORT systems, including alleviating congestion, reducing personnel and maintenance costs, and implementing dynamic pricing options, emission and air quality benefits should also be considered. Agencies that can demonstrate emission reductions from proposed EORT systems are eligible for funding through FHWA's Congestion Mitigation and Air Quality Improvement (CMAQ) Program. This study estimates the potential emission reductions and energy savings of converting legacy toll plazas to open-road tolling facilities. Emissions and energy estimates of tolling conversion projects are made using a three-tiered modeling approach, including traffic microsimulations, modal emissions modeling, and multivariable linear regressions. This EORT conversion methodology has been integrated into the CMAQ Emissions Calculator Toolkit to assist agencies in quantifying benefits when applying for CMAQ funding.

Our findings provide further evidence that open-road gantries would not impede traffic like previous tolling infrastructure. Converting from a full stop or reduced speed (rolling cruise) toll plaza to an EORT system has demonstrated reductions in criteria pollutants and fuel use. For passenger vehicles, we estimated that carbon monoxide (CO) and volatile organic compounds (VOC) could be reduced by about one-third, energy consumption could be reduced by slightly more than a quarter, and fine particulate matter (PM2.5) would be reduced by more than half on a per-vehicle basis when converting to an EORT system from a full stop toll. A rolling cruise toll conversion would yield somewhat lower, less dramatic reductions for passenger vehicles. Likewise for heavy-duty trucks, a full stop-to-EORT conversion could reduce nitrogen oxides (NOx) and PM2.5 by almost two-thirds per vehicle. These modeled results are encouraging and should be verified through instrumented vehicle testing and near-road air quality monitoring.

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## KEYWORDS

Electronic open-road tolling, EORT, overhead gantries, Massachusetts Turnpike, Interstate 90, I-90, Congestion Mitigation and Air Quality Improvement Program, CMAQ Toolkit, intelligent transportation systems, ITS, emission reductions, energy savings, US DOT Volpe Center.