# OPTIMIZING FREIGHT ROUTES AND MODES TO MINIMIZE ENVIRONMENTAL IMPACTS: INTEGRATING TRUCK EMISSIONS COST IN TRAFFIC ASSIGNMENT

**Final Report**

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16. Abstract

Adverse impacts of greenhouse gasses (GHG) and the imperative for reducing the production are well established. The transportation sector accounts for 28% of all U.S. GHG production. Heavy-duty vehicles (e.g., large freight trucks) account for nearly 1/5 of the U.S. total and this fraction is growing. Most current efforts emphasize one of four areas: (1) engineering improvements to improve fuel economy or reduce emissions, (2) shifts to other transport modes, (3) improved logistics to reduce the movement of partially full or empty containers, and (4) reduced travel costs for individual trucks. A small fraction of studies have assessed modifications to route choice considerations as a means of improving fuel economy of individual vehicles. These studies suggest the potential gains are very small. In this study, potential gains of emissions-based route choice were assessed by integrating the EPA Motor Vehicle Emissions Simulator (MOVES) with a macroscopic regional traffic demand model. For this integration, route choices included a simplified emission calculation within the repeated model iteration runs of a Frank-Wolfe type algorithm. Analyses suggest reductions of freight truck emissions are possible and show an example where the total systems truck emission was reduced by up to 0.61% (88.8 tons).

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## EXECUTIVE SUMMARY

The adverse impacts of greenhouse gasses (GHG) and the imperative for reducing the existing rate of GHG production are well established. In the U.S., the largest source of greenhouse gas emissions from human activities in the United States is from burning fossil fuels, primarily for the generation of electricity and for transportation. The transportation sector accounts for 28% of all U.S. GHG production, a value that exceeds the total GHG production from all sources by any other country in the world except China (Greene and Plotkin, 2011). Heavy-duty vehicles, such as large freight trucks, account for nearly 1/5 of the U.S. total and this fraction is expected to grow rapidly. Consequently, many efforts are in use to reduce freight trucks total emissions. Most efforts emphasize one of four areas: (1) engineering improvements to improve fuel economy or reduce emissions, (2) shifts to other transport modes, (3) improved logistics to reduce the movement of partially full or empty containers, and (4) reduce travel costs for individual trucks. A small fraction of studies have assessed modifications to route choice considerations as a means of improving fuel economy, a value almost directly related to emissions, of individual vehicles. These studies suggest the potential gains, though valuable, are very small.

In transportation studies, equilibrium models are used to distribute traffic flows over road networks based on a minimization of a measure of path cost usually involving the measurement of congested travel time. A common algorithm used for this traffic assignment step is usually the Frank-Wolfe algorithm. This algorithm will minimize path costs for the entire system iteratively until no new paths can be found to reduce the total systems path cost. Traditionally, travel time is the measure of cost used, but tolls, the value of time, or other measures can be used to determine route preferences. Traffic assignment can also be used to reduce the total atmospheric emissions from the transportation system. Evaluations of the complete system benefit from the use of an iterative traffic assignment algorithm within the emissions calculation.

In this study, the potential gains of emissions-based route choice are assessed by testing a simplified measure of emissions within a regional macroscopic travel demand model. The emissions measure is updated and utilized as part of the path cost in a Frank-Wolfe

algorithm. This measure of emissions is not intended to be a more accurate measure of emissions but a relative measure that can be used to reflect paths of potentially less emissions based on the updated congestion results of the traffic assignment. Results are checked with the U.S. Environmental Protection Agency Motor Vehicle Emissions Simulator (MOVES) as a way to verify potential emissions reduction. Analysis of an example showed reductions of freight truck emissions for an entire region of up to 0.61% (88.8 tons).

This research is an incremental contribution to the ongoing work of reducing transportation system emissions. It provides a method for considerations of total system emissions within the traffic assignment step. In doing so, it considers the total truck volume using the system, representing route choice at regional scale rather than for individual trucks.

## DESCRIPTION OF PROBLEM

Reductions in detrimental atmospheric emissions from the transportation system is a global imperative. Numerous action alternatives have been proposed, most of which emphasize one of four areas: (1) engineering improvements to improve fuel economy or reduce emissions, (2) shifts to other transport modes, (3) improved logistics to reduce the movement of partially full or empty containers, and (4) reduce travel costs for individual trucks. A sampling of these studies is provided here. Dablanc et al. (2013) reviewed 261 international references in an effort to identify the most effective strategies employed in other countries which could be adopted in the U.S. Environmental impact programs focused on reducing truck emissions and energy consumption by improving engine performance, shifting to cleaner burning diesel trucks or alternative fuel trucks, or shifting freight to more energy efficient modes. Though improvements using route choice alone were not evaluated, their results emphasized strategies that address the entire commercial fleet have the most impact, even if the impact is small on a per vehicle basis. Similarly, Bühlera and Jochemb sought to reduce emissions associated with freight transport by shifting from heavy-duty trucks to other modes, such as rail and maritime vessels.

China is the second most populous country in the world and home of one of the fastest growing economies. Yan and Crookes (2009) sought to analyze the future trends of energy demand and GHG emissions in China's road transport sector and to assess the effectiveness of possible reduction measures using detailed models of the historical energy demand trend future demand forecasts. Proposed reduction efforts emphasized potential policy impacts, such as the imposition of fuel taxes and greater support of alternative fuels. Li, Bao, and Bao reported on efforts to reduce future transport related emissions in China's largest city, Shangai, by legislative action. These regulations can be categorized into five policy packages; none of the packages address potential benefits that could be achieved by route choice methods.

Pietz and Gregor (2014) authored a state-wide study in Oregon to develop a long term strategy for emissions reduction and control for all contributing sectors by the year 2050. Their report noted that freight proved the most challenging travel market to reduce overall emissions and modeling projections show it to be the largest emitting segment of the transportation sector in the future. Freight strategies such as increasing operational efficiencies and technological improvements for cleaner fuels were found to help reduce emissions, as did urban consolidation centers and true cost pricing, but substantial reductions were not predicted.

Bhagat et al. evaluated the potential reduction in emissions that could be achieved by shifting the times of freight movements from busier daytime periods to less congested nighttime periods (2014). The PierPASS program was designed to reduce congestion and improve air quality; though voluntary, a fee was imposed on containers moved during regular working hours from Monday to Thursday. Using data from PierPASS, a microscopic transportation simulation of container movements was developed in TransModeler and integrated with MOVES to assess emissions. Researchers found that much freight traffic was successfully shifted to off-hours, PierPASS had little impact on congestion in the study area and likely resulted in only a small overall decrease in the emissions of various air pollutants. Reductions in pollutants during daytime periods were offset by increased emissions from the same pollutants during off-peak hours.

Greene and Plotkin report that technologies already in existence could reduce GHG emissions from freight trucks by 30% to 50%, with even greater reductions achievable over the next several decades (2011). Changes to vehicle operations could also provide improvement, though some might increase costs, making it unlikely that they will be seriously considered. Other operational changes, such as improvements in truck routing, avoiding empty return trips, consolidating shipments, and reducing truck idling might actually improve profitability while reducing emissions. McKinnon conducted an analysis of the United Kingdom's government's "transport key performance indicator (KPI)" program, which benchmarks the efficiency of road freight operations (2009). He found that the emphasis placed on fuel efficiency (essentially directly related to emissions rates for freight trucks) varied widely between different industries and even between companies within a given industry. Key to this variance were requirements for just-in-time product deliveries, product perishability, and delivery environment (urban, highway, etc.). McKinnon also noted that companies could be reluctant to divulge some efficiency best practices for fear of losing a commercial competitive edge. The latter finding supports the need for increased government participation in emissions reductions using operations guidance, including route choice.

Rowell et al. participated in a Washington State Department of Transportation effort to better characterize freight vehicle route choices to improve future decision making. A survey was conducted of approximately 800 shippers, receivers, and carriers of freight in Washington State to identify strategies used in route choice. They found that off-the-shelf routing software automatically assigns routes on the basis of least cost, given an origin-destination pair (determined by customer requirements) though selected paths can be filtered by other constraints. The survey also revealed that only a small minority of companies in Washington use routing software and that route choice decisions were overwhelmingly driven by the desire to minimize costs (Rowell et al., 2012).

Ahn and Rakha showed that ignoring acceleration impacts in emissions-based route choice algorithms could lead to the use of less beneficial arterial roads rather than highways (2008).

## APPROACH AND METHODOLOGY

Traditionally macroscopic models use emissions models in a post processes procedure. Where the travel demand model calculates the vehicular flows over a road network based on a cost (usually travel time). After flows are produced the loaded network is used as an input to the emissions model to process the amount of emissions that would be produced from the travel demand models results. To include a calculation of emissions within the traffic assignment step of the four-step process, the emissions calculation will need to be integrated within the iterative traffic assignment process. With calculation times of emissions models such as MOVES being very large, a full emissions calculation within the traffic assignment is not feasible. Instead a relative emissions calculation is used based on a binning process and an aggregate Vehicle Specific Power (VSP) calculation. This relative emissions calculation is used within the iterative traffic assignment steps. The iterative emission results are used as an updated value of cost between iterations of the traffic assignment.

MOVES was chosen as the emissions model used. MOVES is commonly used in macroscopic model emissions calculations. It provides calculations of important emissions for diesel long haul trucks and it provides the means for reading in a loaded network and produce emission rates based on the results. MOVES uses a binning strategy to determine emission rates and provides access to its emission database for use in custom calculations for the relative emission calculation that will be utilized in the calculation within the traffic assignment step. Additionally, MOVES is endorsed by the Environmental Protection Agency (EPA) and its directed use is likely to continue.

The transportation model used for travel demand modeling is CITILABS® Cube Voyager. Cube Voyager was chosen because of its common use in the community as well as features that made it applicable to this research. The basic flow of Cube Voyager traffic assignment module “Highway” is shown in Figure 1. Highway provides a means to script functionality in between traffic assignment steps using the adjust phase. It also provides a “converge” phase where some processes could occur after new link travel times had been determined and before the next iteration. Cube Voyager also allows the execution of external applications and network post processing script to customize input files for MOVES, or to provide as data for analysis. A Cube Voyager travel demand time-of-day model for the Hampton Roads area in southeastern Virginia was available and used in the study.

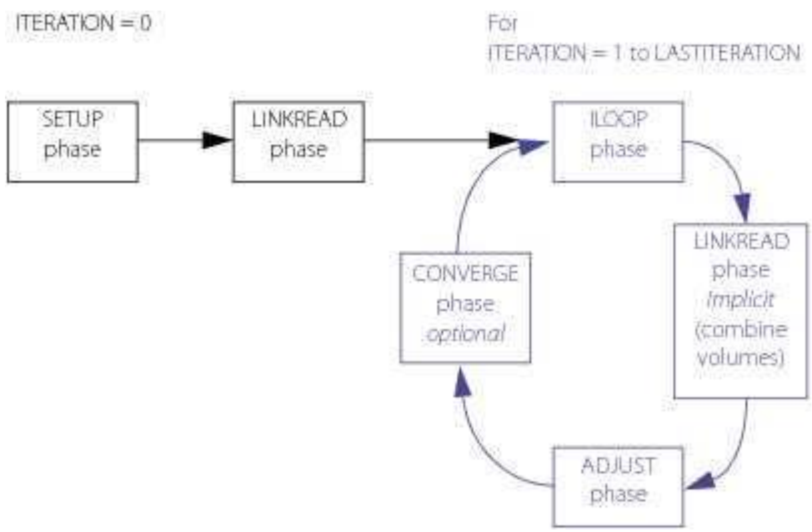


**Figure 1: Flow chart for Cube Voyagers Highway module (Traffic Assignment).**

The Hampton Roads Travel Demand Model (HRTDM) used is a complete four-step model of trip generation, trip distribution, modal split, and traffic assignment. It does this process for two peak periods, AM and PM, and two off-peak periods, midday and night. The model includes trips of single occupancy (SOV), HOV2, HOV3, and trucks for varying levels of time. For this particular model, the midday demand modeled more truck trips than the other times of day. The midday model was used because it had the larger truck demand, its traffic assignment inputs were used as the basis for this research. The midday modeled 37,225 trucks, just over 2% of the model's total volume.

The methodology to apply emissions within the traffic assignment algorithm requires that in between traffic assignment iterations, emissions for each segment be determined and stored for each road segment based on updated values of traffic flow and updated measure of congested travel time. The measure of emissions in the traffic assignment step will be based on the binned rates for $CO_2$ retrieved from the MOVES input database. The binned emission rate for a segment can be determined by providing the segments average speed and Operation Mode (Opmode). Opmode classification within MOVES is determined by the average speed and vehicle specific power (VSP).

Average speed can be derived from the congested travel time calculated within the traffic assignment, but VSP needs to be calculated separately. The calculation of VSP from the MOVES documentation is provided in Equation 1. In this calculation vehicle speed, grade and acceleration can be obtained from the model. The rest of the coefficients must be determined based on the area modeled.

**Equation 1: Vehicle Specific Power**

$$VSP = (A/M) * v + (B/M) * v^2 + (C/M) * v^3 + (a + g * sin\theta) * v$$

where,
$A$, $B$, and $C$ = road load coefficients in units of (kilowatt second)/(meter tonne), (kilowatt second$^2$)/(meter$^2$ tonne), and (kilowatt second$^3$)/(meter$^3$ tonne), respectively.
$M$ = mass of the vehicle in kilograms
$g$ = acceleration due to gravity (9.8 meter/ second$^2$)
$v$ = vehicle speed in meter/second
$a$ = vehicle acceleration in meter/second$^2$
$sin\theta$ = (fractional) road grade.

Vehicle acceleration is not directly given and must be estimated to provide a more accurate measure of VSP. Flow based macroscopic models provide flow for a static period of time, so an acceleration will only be an estimate. Because the model does not provide dynamic flows, the estimate for acceleration comes from the change in average speeds from an upstream link to a downstream link. Therefore, a links average speed is represented by:

$$Accel = (downstreamSpeed^2 - upstreamSpeed^2)/(2 * \left(\frac{distance}{normalizeValue}\right))$$

Determining the distance becomes very difficult because macroscopic models represent an average speed for the length of a segment connected to the next segment which instantly has an average speed measured for it. Because of this issue a distance value is normalized based on the extreme case where a vehicle accelerated from the lowest speed to the highest speed resulting in the highest Opmode. This allows the measure of acceleration to provide reasonable results so that the methodology can be tested.

Downstream segments speed is preprocessed using network scripts within Cube Voyager where upstream links are provided values of downstream speed based on the average free flow speed of all adjacent downstream segments. The updated values for downstream vehicle speeds cannot be retrieved in the same traffic assignment time step because of the timing when the updated travel time values are available. Because of this limitation, the current segment within the cost calculation utilizes an updated vehicle speed value and then uses the recorded downstream speed from the pre-processing. During the adjust phase shown in Figure 1, the script loops through every link and stores the updated congested travel time. Using the downstream travel times/vehicle speed values for each segment an acceleration value for that link can be calculated.

Using the acceleration value and the updated speed of the road segment, a rough measure of VSP can be obtained and with that and the segments average speed an Opmode value can be determined. The Opmode value is then used to determine a mean base rate value from the input bin table. Using the updated value for volume on the segment at the particular iteration of traffic assignment, the amount of emissions can be determined by multiplying volume by the mean emissions base rate. The resulting value can then be incorporated in the path cost for the next iteration of traffic assignment. The resulting measure of emissions is not intended to provide a better calculation of emissions, but a calculation that can be used in comparisons to find better routes that minimize the total system emissions.

After traffic assignment has run, the loaded network provides the distribution of flows based on the cost value specified and can report the value of total emissions per iteration to demonstrate how well it is converging to a minimum. The final total emissions can be observed to get an idea of how much reduction in emissions occurred based on the calculation above. To test if emissions were reduced, the loaded output network is run through MOVES using its inventory calculation to determine a more accurate measure of total emissions from the model run.

The methodology was tested with truck volumes alone, allowing a better understanding of what the truck volume would do without the influence of car traffic. A traffic assignment is run for two scenarios: one where trucks choose paths based on travel time (TT) and one where trucks choose paths based on travel time plus emissions. The emission results can be compared between the two scenarios and convergence can be observed to ensure that traffic assignment is working to minimize the systems total emissions. After the truck volume alone is tested, traffic assignment is set up to model truck flows and passenger car flows. Truck flows pick paths based on the congested segments TT value plus the truck volumes emission calculation. Passenger cars use TT alone as the path cost. The combined truck and passenger car flow scenarios were run twice, first with truck flows utilizing a path cost of travel time plus emissions and cars using only TT and then with trucks and passenger cars both using only TT. The combined car and truck scenarios emission calculation will have the traffic assignment determine the minimization of emissions based on truck flows but also inherently passenger car flows because the passenger cars will have an effect on the congested speed of the segments used by trucks. It is also important to note that the truck flows could take paths that influence passenger cars to reroute. The final loaded networks are then used as inputs with MOVES to determine the amount of emissions produced by each scenario and if there is any reduction in emissions using the methodology.

## FINDINGS; CONCLUSIONS; RECOMMENDATIONS

Traffic assignment was run for truck volume only with path costs set to congested travel time plus emissions and for TT only. The purpose of the initial tests was to verify that the traffic assignment algorithm converged to a lower emission value and behaved as intended, an incremental minimization of total system cost over the traffic assignment iterations. An extreme drop and then equilibrium was not preferred as this could indicate that the cost is not flexible enough to allow the system to adapt out of a local minimum. Results that showed emissions increase and decrease without an average minimization behavior were not preferred as this shows the system is unable to minimize towards equilibrium. Complete equilibrium was not needed for the first test, so only ten iterations were run and results were observed.

After ten iterations, the desired relative gap value was achieved. Relative gap shows how close the system is to equilibrium by showing the change in system cost between traffic assignment iterations (UMTA, 1977). Because emissions contribute to the total system cost, the reduction in total systems emissions should reflect the same shape as the change in relative gap per traffic assignment iteration. The results of the first run were unfavorable because the emission values were so large in comparison to the travel time value that the traffic assignment algorithm is meant to utilize. To achieve a more appropriate value of emissions cost in the traffic assignment algorithm, a flat factor was divided by the emission value for the cost measurement. The true measure of emissions was recorded for comparative purposes.

Using the reduction method for the emission cost value, the truck volume scenario was again run for ten iterations. Figure 2 shows that as relative gap is reduced (right chart), the system total emissions also reduced (left chart). It is important to note that relative gap is a measure of the difference between two iterations therefore the first iteration does not contain a relative gap, and the first iteration of traffic assignment is an all or nothing assignment meaning that unrealistic flows are distributed on the system based on free flow speed resulting in a very large relative gap value (and emission value) therefore the first measure is disregarded so that the details of the chart can be seen.

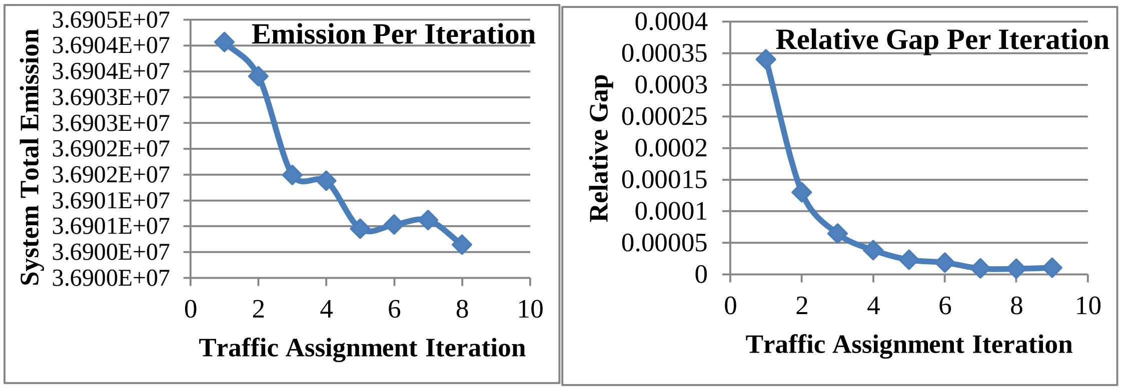


**Figure 2: Emission reduction and relative gap reduction per traffic assignment iteration using a smaller measure of emissions for the path cost.**

The results for the truck only scenarios confirmed that the methodology was working in that traffic assignment converged to a minimum system cost with emissions applied to the path cost. The next test was a comparison of the same scenarios with passenger car traffic along with truck traffic. A test run was completed with twenty iterations and showed the system was still converging with a high relative gap value remaining at the end. This indicated that more traffic assignment iterations should be run to get the system closer to a state of equilibrium. Figure 3 shows the total emission results per traffic assignment iteration from both scenarios of trucks and passenger cars together. The emission path series shows the total emissions per iteration where trucks utilized a path cost including both a weighted TT and emissions considerations and passenger cars used TT as their path cost. The TT path series shows the total emissions per iteration where trucks and passenger cars utilized a path cost of TT only.

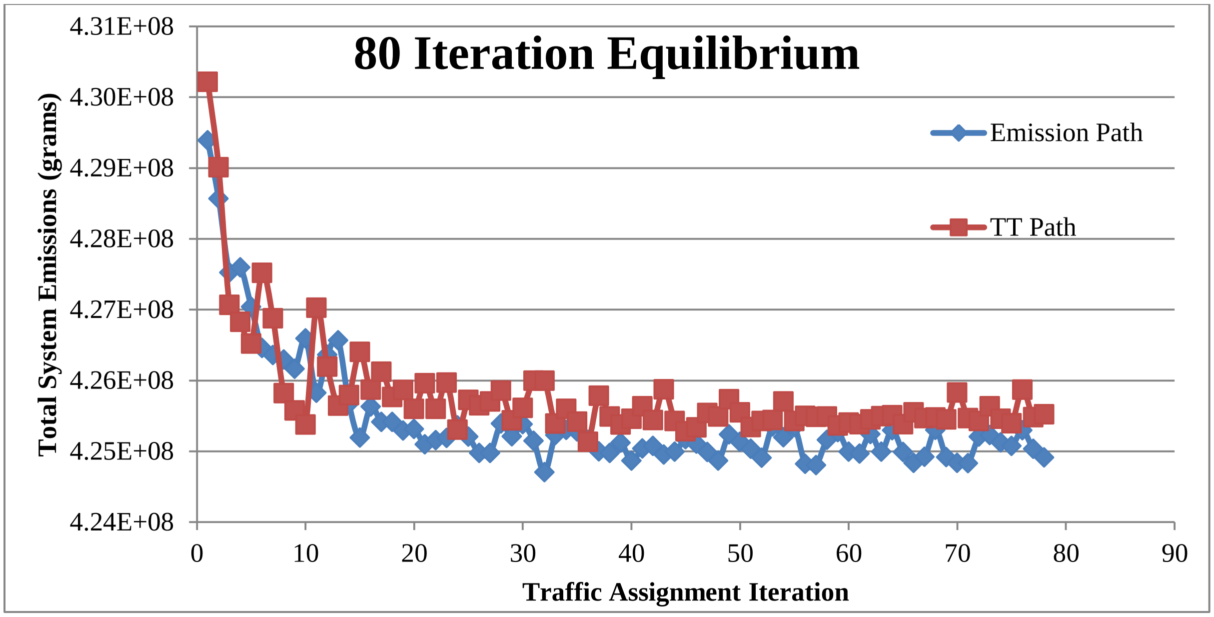


**Figure 3: Comparison of Total System Emissions per traffic assignment iteration for the scenario where trucks use emission in path cost and cars use travel time and the scenario where trucks and cars use travel time only for path costs.**

The results displayed in Figure 3 show that truck emissions reduce as the systems total TT is reduced. This indicates that total emissions could be reduced if emissions are considered in the path cost equation. The results also show that equilibrium was probably reached after approximately sixty iterations as the change in values greatly reduced at that point. The actual amount of emissions that the system produced is predicted using the simplified calculation described in the methodology but a better measure of the emissions will come from a true emissions model such as MOVES. The output loaded networks are post processed so that they can be used as inputs to the MOVES model. MOVES calculates the total emissions for the system and the results for the MOVES runs and the traffic assignment runs are presented in Table 1.

**Table 1: Total System Emissions Compared between Scenarios**

| Scenario and Total System Values | TT Paths CO2 Emissions (grams) | EMISS Paths CO2 Emissions (grams) | percent Improve |
|---|---|---|---|
| MOVES_Car_and_Truck | 14,455,903,587 | 14,367,090,051 | 0.61% (88.8 tons) |
| Cube_Car_and_Truck | 425,522,530 | 424,913,285 | 0.14% |
| Cube_Just_Truck | 36,903,799 | 36,886,838 | 0.05% |

These results report emission values for the total system. The results from MOVES produced values of emissions much higher than the simplified binned version that was used in traffic assignment. The purpose of the simplified calculation used in traffic assignment is not intended to produce accurate emissions results, but to provide comparative results for emissions to allow the system to reduce total emissions. The three scenarios described are shown in the table, the traffic assignment of just truck volume, the traffic assignment of truck volume and passenger cars, and the MOVES results using the results from the traffic assignment of trucks and passenger cars. Results show that the simplified emission calculation provides a more relative and more conservative measure of emissions shown in the difference of the two scenarios of TT Paths and EMISS Paths. The traffic assignment showed 0.14% improvement of emissions and MOVES assessed a 0.61% (88.8 tons) improvement across the entire system. The improvements are small, but are represented for the entire system and represent a large amount of emissions. With a small change in emissions, the results indicate that routes that reduce congested travel time do a pretty good job at reducing emissions. If favorable emissions routes existed in the road network truck volume would be more likely to occupy those routes versus routes that favor travel time.

The two scenarios produced different measures of emissions. Further investigation was completed to understand the rate trucks re-route in order to make these improvements. Consequences to TT are observed in order to accomplish this reduction in emissions. Table 2 shows the total system vehicle distance, vehicle time, and average speed for all demand modeled (truck and passenger car) a total of 1,753,942 vehicles. In order to reduce the total systems emissions, the average speed of all vehicles in the system was reduced by only 0.02 miles per hour. The total vehicle miles traveled had to increase to 8,596.67 and the total vehicle hours traveled needed to increase 32.69 hours.

**Table 2: Total System Travel Changes between Scenarios for Trucks and Passenger Vehicles**

| Scenario | Vehicle Distance (miles) | Vehicle Time (hours) | Average Speed (mph) | Total Vehicles |
|---|---|---|---|---|
| TT Paths | 14,008,913.55 | 358,153.53 | 39.11 | 1,753,942 |
| Emission Paths | 14,000,316.88 | 358,186.22 | 39.09 | 1,753,942 |

Additional investigation sought a better understanding of the types of routes chosen for the two scenarios to learn what in the model prompted reduced emissions. Understanding the route changes used path analysis with observations of the demand on the modeled network with the path file for the two scenarios and identifying any major changes. Two types of truck travel were observed to see what kind of route changes occurred: regional external origin to external destination travel and local internal origin to internal origin.

Figure 4 and Figure 5 show views of regional truck traffic where Figure 4 is showing the results for TT Path and Figure 5 the results for the Emission Path scenario. A noticeable difference in routes can be seen by use of the central bridge tunnel in the TT Path scenario (Monitor Merrimack Bridge Tunnel) and the left bridge by the Emission Path scenario (James River Bridge). Out of the trucks that used the Monitor Merrimack crossing, 25% of them rerouted to the James River Bridge in order to reduce the total systems emissions.

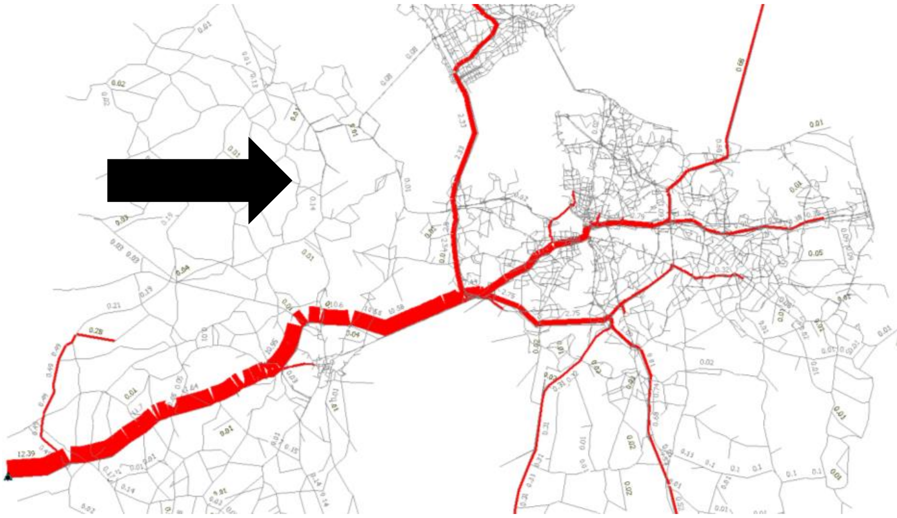

**Figure 4: Regional Truck Travel for the TT Path scenario with noticeable use of the central bridge tunnel (Monitor Merrimack bridge tunnel).**

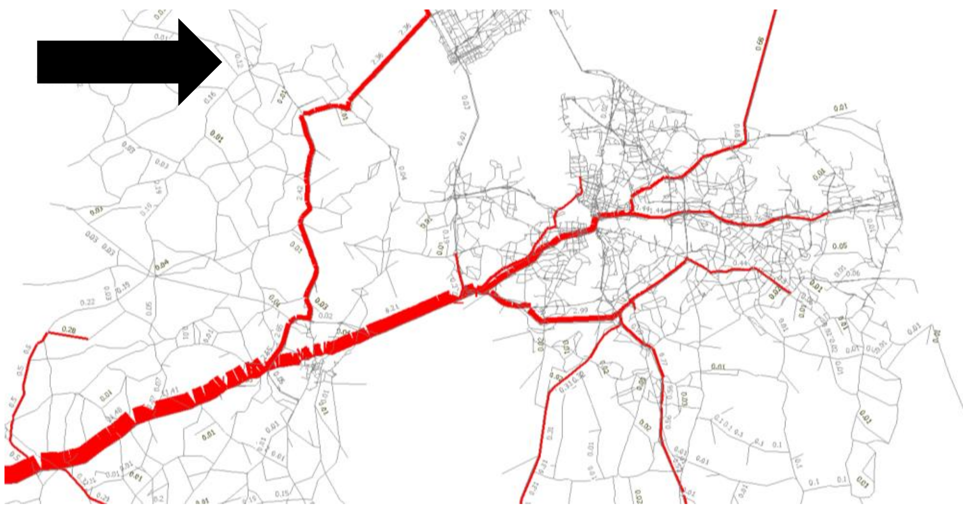

**Figure 5: Regional Truck Travel for the Emission Path scenario with noticeable use of the left bridge (James River Bridge).**

Figure 6 and Figure 7 show views of local truck traffic where Figure 6 is showing the results for TT Path and Figure 7 the results for the Emission Path scenario. A noticeable difference in routes can be seen by the use of the bridge to the right in the TT Path scenario (Berkley Bridge) and the left tunnel by the Emission Path scenario (Midtown Tunnel). Out of the trucks that used the Berkley Bridge crossing, 71% of them rerouted to the Midtown Tunnel in order to reduce the total systems emissions.

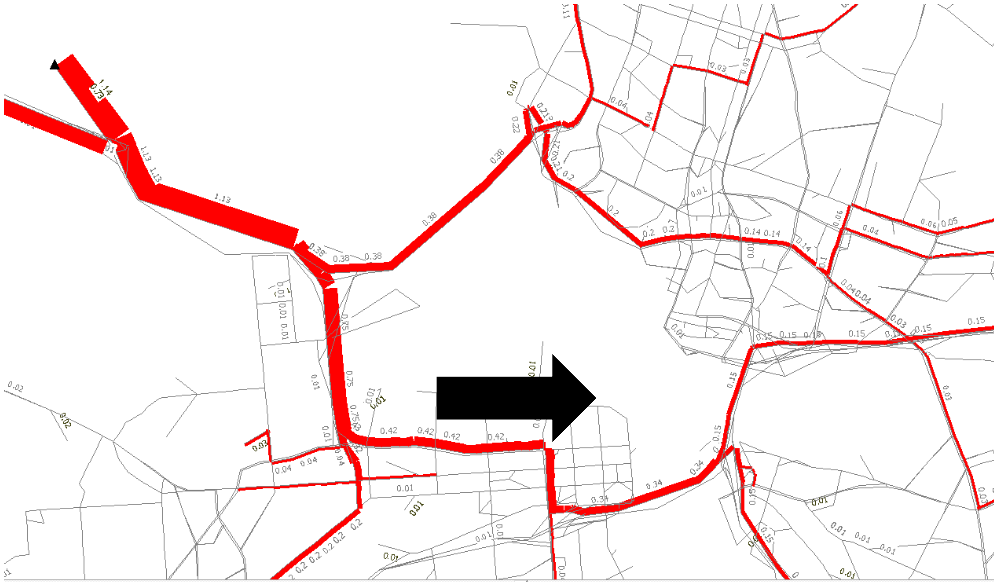

**Figure 6: Local Truck travel with noticeable use of the bridge to the right (Berkley Bridge).**

**Figure 7: Local Truck travel with noticeable lack of use of the bridge to the right (Berkley Bridge).**

Car paths changed very slightly in various parts of the road network, on freeways, arterials, and local roads. Large reroutes were not identified and only small ones occurred for the passenger cars throughout the system.

A simplified emissions calculation was used based on a binning method using the information from the input tables in MOVES and an aggregate measure of VSP. This calculation was executed between the traffic assignment Frank-Wolfe iterations, providing an up to date value of emissions per segment. With an updated emission value per segment the path cost equation was amended to include emissions as an added cost to congested travel time. Using the emissions plus travel time path cost, the model was run and tested with truck volume to see if it would converge. Results showed that emissions values were too large to allow good convergence, but reducing the size of emissions by dividing the emission values by a flat static value could be used to model with results that converged. The total truck emissions as calculated in the traffic assignment were recorded for a scenario where trucks used a path cost of emission plus travel time and passenger cars used path costs of travel time only. They were also recorded for a scenario where trucks and passenger cars used a path cost of travel time only. Results from both scenarios were run with the MOVES emissions model and compared. The methodology described was able to reduce total system truck emissions by a small percentage (0.61%, 88.8 tons) but showed that the methodology is capable of minimizing emissions. The results showed that reducing emissions came at essentially negligible cost to the total system travel time and trucks changing routes did not impact passenger car travel. The area modeled showed that emissions produced by truck equilibrium where travel time is reduced is very close to the equilibrium where emissions are reduced.

Studies such as this and ones that utilize this methodology for truck traffic can help answer several questions: What regional emissions reductions can be achieved based on route choice? How will this operational decision effect travel time? How do these decisions impact the routes and congestion of passenger cars? Although truck emission reduction was not large in this scenario, the results are greatly dependent on the type of network used, such as number of routes that can be used for rerouting, and percentage of trucks compared to cars.

Results could differ in other areas that utilize the same methodology. The possibility of other areas implementing this same methodology is great and results such as these can help planners better understand the potential improvements that can be achieved in the regional transportation system. Results from studies such as this can be beneficial to decision makers who intend to improve emissions for a region through changes in routing.

To extend this research, future work will require improving the VSP calculation. Additional influences, including road grade, rolling resistance, and wind resistance values, should be considered. Implementing these values -- especially grade changes -- may have a great effect on what routes are chosen to reduce emissions. The acceleration value is an aggregate value and would be more accurate when measured from a microscopic model. Regional microscopic models are becoming more viable and the work done in this paper compliments the future of transportation modeling. Large microscopic models will need to utilize dynamic traffic assignment algorithms to determine the distribution of flows and the same methodology can be applied to those models but with a better measure of VSP.

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## APPENDIX

Presentations resulting from this project:

Foytik, P. and Robinson, R.M. "Integrating Truck Emissions Cost in Traffic Assignment," To be presented at the *94th Annual meeting of the TRB*, Washington, D.C., January 11-15, 2015, paper # 15-4936.