ANALYSIS OF MOVES AND CMEM FOR EVALUATING THE EMISSIONS IMPACTS OF AN INTERSECTION CONTROL CHANGE

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ABSTRACT

EPA's Motor Vehicle Emission Simulator (MOVES) provides greater capability than the MOBILE emission models for estimating the impacts of traffic operational changes. EPA has proposed requiring the use of MOVES for conducting "project-level" analysis of PM and CO hot-spots. Local sustainability programs and federal grant program such as CMAQ reinforce the need for a consistent modeling system for estimating emissions from traffic operational changes.

This research compares the emissions estimates from MOVES with those generated by the Comprehensive Modal Emissions Model (CMEM), developed under NCHRP 25-11. CMEM was developed to meet the need for an emissions modeling system responsive to traffic operational changes. CMEM integrates with existing microsimulation software packages that generate second-by-second speed/acceleration vehicle profiles (trajectories).

The research developed a microsimulation test bed of a 3-leg intersection modeled as a pre-timed traffic signal and as a roundabout under 2 traffic volume scenarios. CMEM and MOVES output for CO and NOx (grams/hour) are evaluated. For NOx, results from CMEM are similar to those from MOVES when a detailed Link Drive Schedule is estimated from trajectory data using K-means clustering and LOESS scatter plot curve fitting. For CO, results from CMEM and MOVES are significantly discrepant over all modeling scenarios. Both CMEM and MOVES (utilizing Link Drive Schedules) estimate higher emissions for the roundabout when compared to the traffic signal.

Sources of emissions differences between CMEM and MOVES are discussed and enhancements to facilitate linking MOVES to microsimulation models are proposed.

INTRODUCTION

In May 2010 EPA published draft guidance for performing "project-level" transportation conformity analysis of PM "hot-spots", sub-regional areas where local pollution concentrations might exceed NAAQS standards (*1*). EPA has proposed requiring use of the Motor Vehicle Emission Simulator (MOVES2010) model to quantify PM and carbon monoxide (CO) emissions impacts from hot-spots.

Beyond this significant regulatory requirement, there is a call from other quarters of society for consistent, accurate, and easy-to-use tools for estimating the emissions impacts of traffic operational changes. For example, cities and universities have initiated sustainability programs to measure and reduce transportation-generated air emissions. The carbon reduction toolkit accessible to these non-regional entities includes traffic operational strategies such as travel demand management programs, traffic signal optimization, and investments in alternative modes. In addition, many federal grant programs require documentation of air emissions benefits from a proposed project.

Specific examples of each of these are:

1. The City of Portland, OR has partnered with the Climate Trust to obtain carbon dioxide offsets in return for quantified reductions in CO2 emissions resulting from a multi-year, city-wide traffic signal optimization and coordination project (*2*).
2. Many universities have created Sustainability Departments to quantify the institution's carbon footprint and promote low carbon policies. The University of New Hampshire (UNH) is a university with a climate action plan incorporating transit investment and transportation infrastructure changes (*3*). To support this program UNH has invested in a land use-based traffic microsimulation model to evaluate the air emissions impacts of traffic operational strategies, travel demand management programs, and land use changes they have control over.
3. The Congestion Mitigation Air Quality (CMAQ) program requires an assessment of a proposed project's emissions reduction benefits. Guidance published for CMAQ states: "State and local transportation and air quality agencies conduct CMAQ-project air quality analyses with different approaches, analytical capabilities, and technical expertise.(*4*)" The CMAQ guidance acknowledges the variety of approaches and technical sophistication of the program's applicants.

Recent advances in traffic modeling and air emissions tools yield promise that a consistent emissions-estimating modeling system may be close at hand. Having a reliable, easy-to-use model for evaluating the emissions impacts of these strategies and policies is meaningful to sub-regional entities that are not otherwise required to perform Conformity Analyses.

BACKGROUND

Since the late 1970s EPA's MOBILE models have been used to conduct regional air quality analysis from transportation sources. MOVES is EPA's latest air emissions calculator for mobile sources. MOVES supports regional air quality analysis, but provides more detailed analysis than the previous MOBILE models of emissions from traffic operational changes. Such improvements are termed a "Project-Level Analysis" in MOVES.

MOVES documentation states that the model "allows users to represent intersection traffic activity with a higher degree of sophistication compared to previous models (*5*)", accounting for "speed and temperature variations", linked to emissions factors and processes obtained from extensive in-vehicle data collection. With this improved functionality, MOVES is a candidate tool for conducting air quality assessments of operations-level changes such as intersection improvements. Indeed, as described above, EPA has proposed that MOVES be used to complete PM and CO hot-spot analysis. In addition, MOVES will likely be used to complete NEPA analysis of transportation projects.

An alternative approach to estimating transportation-related emissions impacts is described in NCHRP 25-21, "Predicting the Air Quality Effects of Traffic Flow Improvements", published in 2005 *(6*). This comprehensive study recommended a methodology for predicting the short-and long-term effects of traffic-flow improvement projects on air quality, with a focus on the key question: Will a specific traffic-flow improvement contribute to improved or worsened air quality locally and at the regional level, in the short term and in the long term (*7*)?

The study evaluated the most promising modeling approaches then being used to estimate the air emissions impacts resulting from traffic-flow improvements. The report recommended a hybrid modeling approach uniting the resolution and accuracy of microsimulation models with the system-wide predictive capacity of macroscopic models. The recommended modeling approach specifies a short-term "operations" effect of traffic-flow improvement projects which can create immediate "opening day" travel time savings or travel flow smoothing benefits. Longer term "traveler behavior" effects causing changes in traveler route or mode choice, and ultimately changes in land use patterns, are also described as important to understanding the total air emissions effects of a traffic-flow improvement project.

Interestingly, the authors of NCHRP 25-21state: "It is assumed that the traveler behavior effects cannot completely eliminate the opening-day travel time improvements…" (*8*). This assumption suggests that the short-term operations effects dominate the longer-term effects. It follows that estimation accuracy is most critical at the operations level of analysis.

NCHRP 25-21 goes on to state that the Comprehensive Modal Emissions Model (CMEM, NCHRP 25-11 (*9*))" provides the most detailed and best tested estimates of hot-stabilized vehicle exhaust emissions at different speeds and accelerations." A number of recent studies have used CMEM for evaluating the air emissions impacts of a range of operational changes *(10, 11, 12, 13, 14).*

There are many traffic microsimulation tools that can be used for modeling the operations effects and extensive validation measures have been established for these tools *(15).* These microsimulation tools generate a significant amount of detail on vehicle performance that is critical for determining air quality impacts (*16*). Details such as second-by-second speed/acceleration profiles, vehicle characteristics, and network characteristics produce inputs to equally detailed air emissions models.

MOTIVATION FOR THE RESEARCH

The motivation for this research stems from the foregoing discussion, and can be summarized as follows:

1. There is a need for consistent emissions estimates caused by operational changes. This need comes from recently-established federal requirements for hot-spot analysis, and is reinforced by locally-based sustainability programs and by federal grant programs requiring demonstration of emissions reductions.
2. Longer term systemic adaptations to operational changes – termed "traveler behavior effects" – can reduce the immediate air emissions benefits of operational changes. However, this longer term compensating feedback will not eliminate the emissions benefits generated by operational changes. Fortunately there are abundant tools for developing highly accurate traffic microsimulation models so that the most critical component in the modeling system – accurately modeling the operational change – is now commonly achieved by practicing traffic engineers. Establishing an easy-to-use linkage with an accurate air emissions model is the remaining critical piece.

This paper compares two options transportation engineers have for calculating air emissions related to traffic operational changes: MOVES and CMEM. Both models enable "project-level" or operations-level evaluations of emissions and both models can be linked with traffic microsimulation models. These modeling packages are evaluated for their analytical results. A discussion about ease of use and future improvements is provided.

To conduct this comparison, a test bed microsimulation model of a 3-leg intersection controlled by a pre-timed signal has been constructed (Base Case). Emissions results from the Base Case are compared with emissions results from an Alternative, where the intersection is controlled by a roundabout. Two traffic volume scenarios are modeled for both control types, representing light, off peak hour traffic and heavy, peak hour traffic.

DESCRIPTION OF MODELING TOOLS AND APPROACH

There are three modeling tools used in this research. At the front end of the analysis, a traffic microsimulation model is built using the Paramics software (*17*). The microsimulation model can represent a wide variety of networks, with a great degree of complexity in roadway geometry and traveler behavior. A key attribute of a microsimulation model is its ability to generate vehicle trajectories – second-by-second descriptions of each vehicle’s operating characteristics, including location, speed, and acceleration (Table 1).

Table 1: Illustrative Trajectory File Output from Paramics

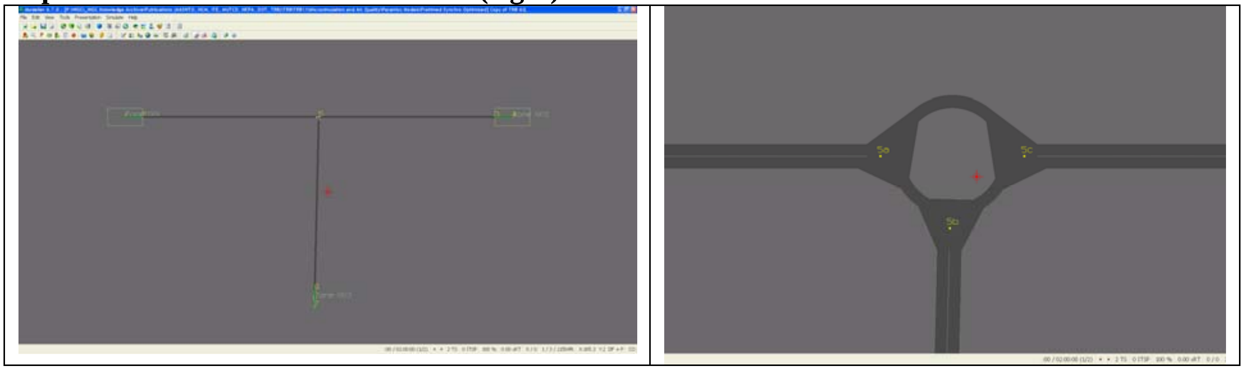
time	ID	type	origin	destination	lane	x	y	z	bearing	length ft	speed mph	acceleration fpss	link	link length ft	link speed mph
3601	444	1	1	2	1	-3432.91	1634	0	-270	13.12	15.43	8.2	1:02	328.08	30
3601	442	1	1	2	1	-1840.56	1634	0	-270	13.12	33.83	0	2:05	3280.84	30
3601	443	1	1	2	1	-2001.22	1634	0	-270	13.12	32.82	0	2:05	3280.84	30
3601	437	1	2	1	1	718.3	1646	0	-90	13.12	32.91	0	3:05	3280.84	30
3601	438	1	2	1	1	789.91	1646	0	-90	13.12	34.47	-0.02	3:05	3280.84	30
3601	441	1	2	1	1	1817.19	1646	0	-90	13.12	30.76	-0.41	3:05	3280.84	30
3601	434	1	2	1	1	-357.39	1646	0	-90	13.12	33.18	0	5:02	3280.84	30
3601	431	1	1	3	1	-77.73	-1366	0	-178	13.12	33.57	3.28	5:06	3220.78	30
3601	435	1	1	3	1	-7.22	1591	0	-178	13.12	27.96	6.56	5:06	3220.78	30
3601	433	1	1	2	1	759.31	1634	0	-270	13.12	32.48	-0.1	5:03	3280.84	30
3601	432	1	3	1	1	5.02	1597	0	-359	13.12	0	0	6:05	3220.78	30

These detailed operational data are then linked to an emissions estimator -- CMEM and MOVES. In the case of CMEM, the linkage is automatic through a Paramics plug-in developed by the CMEM software team (*18*). In the case of MOVES, the linkage requires post processing of the vehicle trajectory file to create a Project-Level input file. A detailed description of each modeling tool and the model test bed follows.

Description of the Microsimulation Model Test Bed

To evaluate CMEM and MOVES for an operational change a simple intersection model was constructed using the Paramics microsimulation software. The Base Case intersection is a 3-leg intersection of urban streets controlled by a pre-timed traffic signal (left in Figure 1). The operational alternative that will be used to evaluate emissions impacts is a single lane roundabout (right in Figure 1).

Figure 1: Simple Simulation Model Showing Base Case Pretimed Traffic Signal (left) and Operations Alternative Roundabout (right)



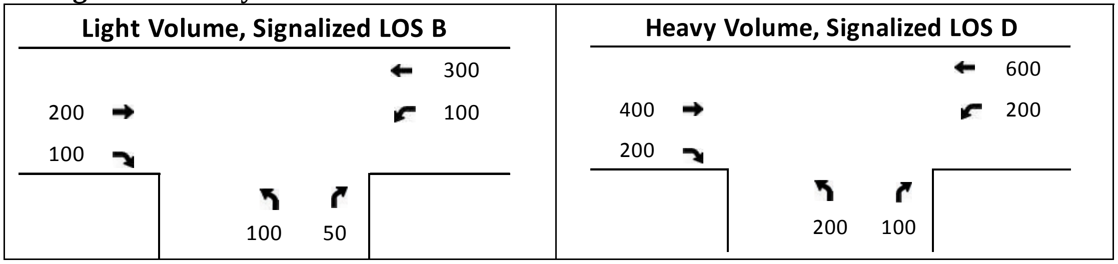
In both networks, three road segments posted at 30-mph lead to the intersection, each 0.60-0.62 miles in length. This length was selected so that all vehicles were at cruise speed when entering the network. In this way, the emissions reflected hot stabilized operating conditions helping to isolate the effects of the intersection control change.

Several other factors are held constant in this analysis, as follows:

1. Traffic volumes – Two sets of traffic volumes are evaluated for the Base Case (signal) and Alternative (roundabout) (Figure 2).

    a. One set represents lighter traffic illustrative of off peak conditions (850 vehicles per hour) and operating at Level of Service B (11 seconds per vehicle) according to Highway Capacity Manual procedures. A pre-timed signal cycle of 40 seconds is sufficient for maintaining efficient operations under this traffic load.
    b. A second set represents heavier traffic illustrative of peak conditions (1700 vehicles per hour), operating at Level of Service D (35 seconds per vehicle) using HCM procedures. A pre-timed signal cycle of 90 seconds is modeled for this condition.

Figure 2: Light and Heavy Traffic Volumes for Simulation Test Bed



2. Vehicle type – One vehicle type corresponding to a passenger car was modeled in Paramics, CMEM, and MOVES. The corresponding vehicle types used in this analysis are shown in Table 2. 100% of the vehicles in the simulation are passenger cars and are all entered into MOVES as 5 years old, representing a higher mileage vehicle.

Table 2: Corresponding Vehicle Types in MOVES, CMEM, and Paramics

	ID (in modeling software)	Description
MOVES	21	Light Duty General Vehicle, Passenger Car
CMEM	Light Duty Vehicle 4	3-way Catalyst, >50K miles, low power/weight
Paramics	Vehicle Type 1	Passenger Car

3. Emissions process – MOVES estimates emissions from several different processes, including start emissions, running emissions ("hot stabilized"), evaporative emissions, and "hot soak" emissions, referring to evaporative emissions occurring after a hot engine is turned off. To minimize variability in the comparative analysis, emissions representing hot stabilized operation are measured for both CMEM and MOVES. It is assumed that all vehicles are hot stabilized, including emissions that occur during idling while stopped at a traffic signal.
4. The same model runs are used to generate CMEM emissions estimates and the input data for MOVES. As CMEM has been developed with a Paramics plug-in, its emissions estimates are reported at the end of a model run. An output of a Paramics run is a vehicle trajectory file, an illustration of which is shown in Table 1. This trajectory table provides operational data for each vehicle in the network, for each ½ second of operation. Several vehicle attributes are recorded including the instantaneous speed and acceleration of each vehicle. These data are used directly by CMEM in calculating emissions and, as described below, these data can be post-processed for input into MOVES.
5. Pollutants – two pollutants of interest are modeled: carbon monoxide (CO) and oxides of nitrogen (NOx), both of which are NAAQS criteria pollutants. The same methodology can be applied for other near-highway pollutants, such as diesel particulates and CO2. Narrowing the list to CO and NOx simplifies reporting for the purposes of this research. CO is additionally meaningful because EPA will soon require hot-spot analysis of CO using MOVES. NOx, an ozone precursor subject to non-attainment area air quality budgets, is selected as there is now a one-hour NO2 standard which is appropriately-scaled to an intersection-level analysis.
6. Roadway gradient – all links in the model are level (0% gradient).

Description of CMEM

The Comprehensive Modal Emissions Model was developed at the University of California-Riverside Center for Environmental Research and Technology in collaboration with the University of Michigan and Lawrence Berkeley National Laboratory. This extensive data collection and modeling effort was supported under NCHRP 25-11 and is described fully in that project's final report (*19*).

Development of CMEM commenced in 1995 largely in response to the need for an emissions model capable of performing microscale analysis, such as an intersection control change. CMEM developers conducted extensive testing of approximately 340 vehicles in order to develop emissions calculations based on vehicle/technology categories, incorporating considerations of catalytic type, vehicle mileage, and vehicle power/weight ratios. A separate categorization is performed for trucks based largely on truck age and weight (*20*).

For the purposes of this research there are two key features of CMEM that are notable. First is CMEM's fine resolution time scale, which takes information on speed and acceleration for each vehicle, to create a driving cycle power demand. CMEM has established improved emissions prediction accuracy by estimating a temporal component of emissions based on the most recent record (past several seconds) of fuel throttle activity. Validation efforts showed consistency of CMEM predictions when compared to MOBILE (*21).*

A second key feature of CMEM is that it has been built to interact directly with Paramics as a plug-in. A key input of the CMEM plug-in is the categorization of vehicle types. For this research, the Paramics' Vehicle Type 1 (passenger vehicle) was equated with CMEM's Light Duty Vehicle #4, corresponding to a low-power/low-weight vehicle with a 3-way catalyst and >50,000 miles (see Table 2).

For this analysis, 10 model runs for each of the four scenarios (signal, light traffic; signal, heavy traffic; roundabout, light traffic; and, roundabout, heavy traffic) were conducted, and the results averaged for reporting.

Description of MOVES

MOVES is described in detailed documentation available on the EPA website: http://www.epa.gov/otaq/models/moves/index.htm. To conduct a "Project-Level" analysis in MOVES, which is an analysis of emissions from a traffic operational change, such as an intersection control change, MOVES offers 3 options:

1. Using average speeds for each approach and departure link, referred to as the "Average Speed" approach. In developing emissions calculations using this approach, MOVES refers to default driving schedules that are associated with the speed profile and road type. EPA recommends using the Average Speed approach during initial transition from MOBILE to MOVEs, suggesting that more detailed approaches should be utilized if modeling output can support them.
2. Using a "link drive schedule" for each approach and departure link. This is referred to as the "Link Drive Schedule" approach. A link drive schedule is a second-by-second speed profile for a vehicle, which can be a single vehicle or a generic vehicle that is representative of the driving cycle for multiple vehicles.
3. Using an operating mode distribution. Operating modes are determined by several factors, including cruising, accelerating, coasting, braking, idling, and tire wear. Each of these factors is further divided into bins defined by Vehicle Specific Power, vehicle speed, and vehicle acceleration. There are a total of 23 operating modes in MOVES, not including braking and idling.

In this analysis, the first two options are evaluated, utilizing the Average Speed and Link Drive Schedule approaches. To simplify the modeling and hold as many variables constant as possible, we have chosen to model one vehicle type only which makes unnecessary the detail required by the Operating Mode approach to modeling. This approach to Project-Level analysis should be analyzed in future research.

To obtain average speeds for the Average Speed approach, average speeds for each approach and departure link, as well as for the roundabout links in the roundabout models, were obtained directly from Paramics runs. Average speeds are input into MOVES within the "Links" input file submitted to the MOVES Project Data Manager. The Links input file also contains link volume, length, and gradient, as well as identifiers for road type, and geographical location[1].

For the Link Drive Schedule approach, vehicle trajectory data output from Paramics needs to be post-processed in 2 ways:

1. The vehicle trajectory files need to be analyzed for clustering, which creates a characteristic speed-acceleration profile descriptive of multiple vehicles. To produce appropriate clusters for this analysis, we utilized a k-means algorithm which identifies k clusters from n observations. Figure 3 shows the results of k-means clustering for the vehicle trajectory files produced by Paramics for the "Traffic Signal, Heavy Volume" runs. A total of 20 clusters were estimated for each of the 4 model scenarios.

   Clusters 1, 9, 10, and 11 describe relatively undelayed vehicle progression through the network at various speed/acceleration profiles. The other clusters exhibit some amount of delay, with clusters 18 and 19 showing the longest stopped delay. For input into MOVES the number of vehicles within each cluster must be enumerated. Each cluster is input into MOVES as a unique link with a traffic volume and a link drive schedule.

   In conducting this research we initially modeled each individual vehicle as its own

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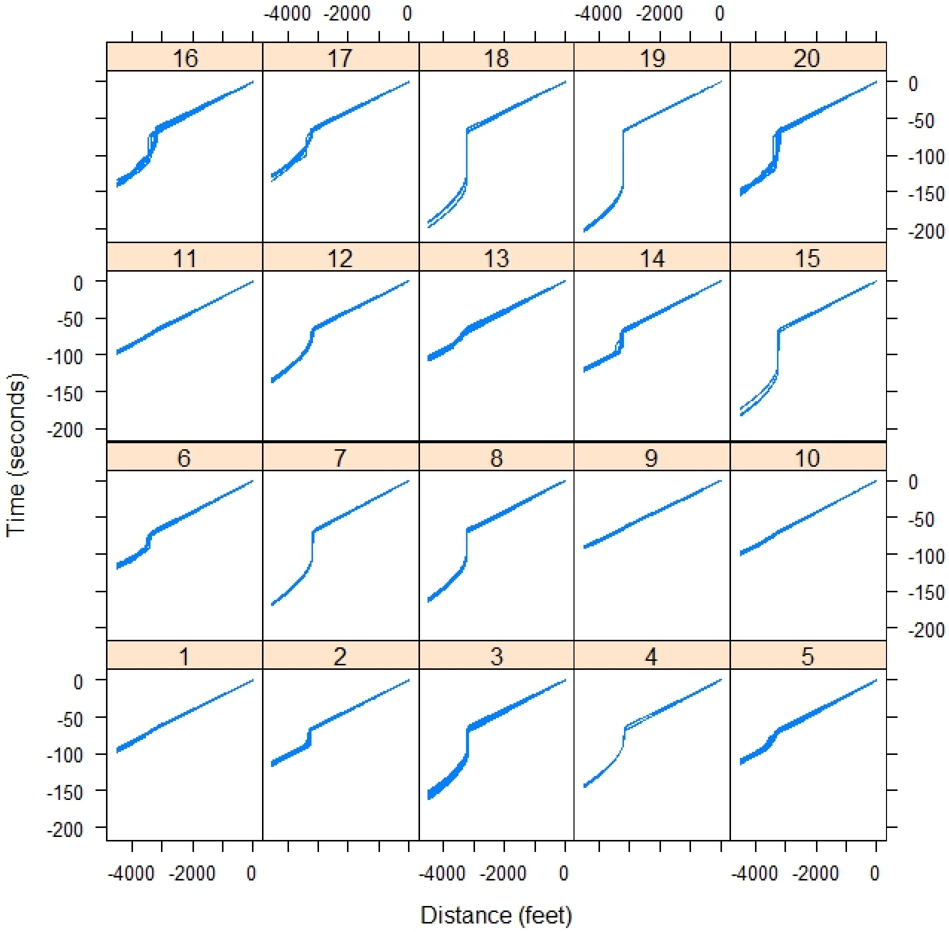
[1] For this research, the area modeled is Strafford County, New Hampshire (county ID 33017); the road type modeled is Urban Unrestricted Access.

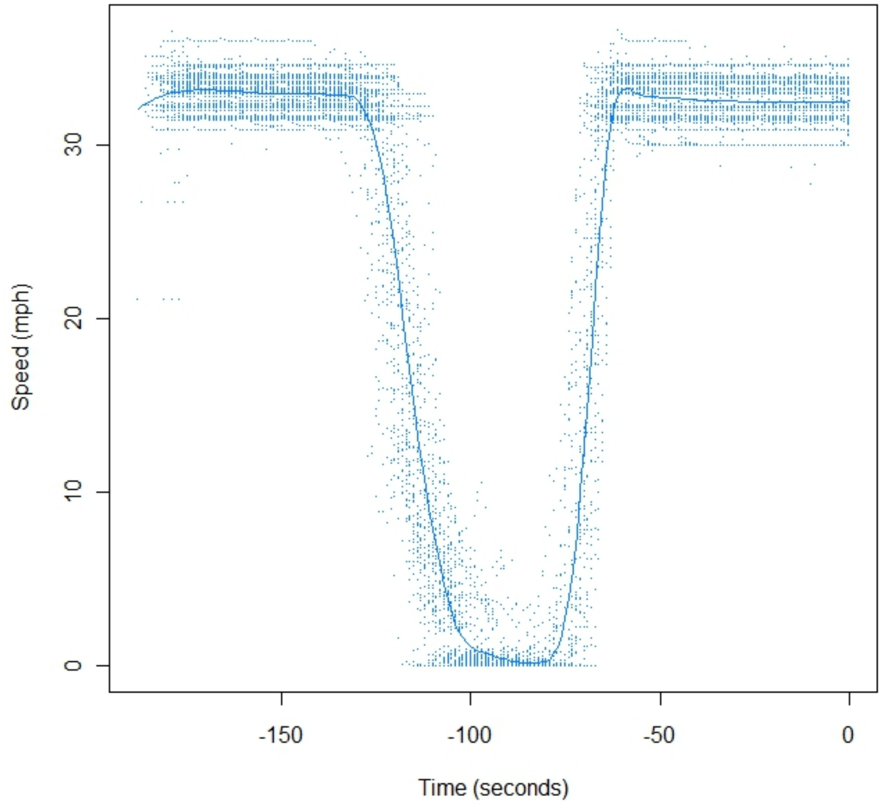
link in MOVES, which would have preserved the unique speed/acceleration profile of each vehicle. For the light volume scenarios, this approach generated nearly 60,000 rows of second-by-second data (850 vehicles X 70 seconds per vehicle (average time on the link)). This number of links exceeded MOVES input capability.

Figure 3: Twenty Distance-Time Clusters for the Traffic Signal, Heavy Volume Scenario



2. The second post processing required for transferring the trajectory files into MOVES is to estimate a characteristic Link Drive Schedule for each of the 20 clusters. To accomplish this we utilized a LOESS (locally weighted scatter plot smoothing) routine. Figure 4 shows a LOESS curve fitted to a scatter plot from dozens of vehicle trajectories. LOESS curve fitting yields a characteristic Link Drive Schedule for each of the 20 clusters for each modeled scenario.

Figure 4: Sample of LOESS Curve Fitting for a Binned Set of Vehicle Trajectories



Both the K-means and LOESS algorithms were implemented in the “R” software for statistical computing.

ANALYSIS OF RESULTS

Figure 5 and Figure **6** show the results for CO and NOx from the CMEM Paramics plug-in. In each case, the results of four modeling scenarios are shown: Signalized, Light Volume; Signalized, Heavy Volume; Roundabout, Light Volume; Roundabout, Heavy Volume. For the Signalized, Light Volume case, CMEM estimates the production of approximately 9500 grams of CO in the hour. When converted to a roundabout, CMEM predicts a 7% increase in CO emissions (10,100 grams). Doubling the traffic volume results in scaling CO emission up by a factor of 1.97 for the traffic signal and 2.05 for the roundabout.

Figure 5: CMEM Carbon Monoxide Estimates for Four Intersection Scenarios (grams/hour)

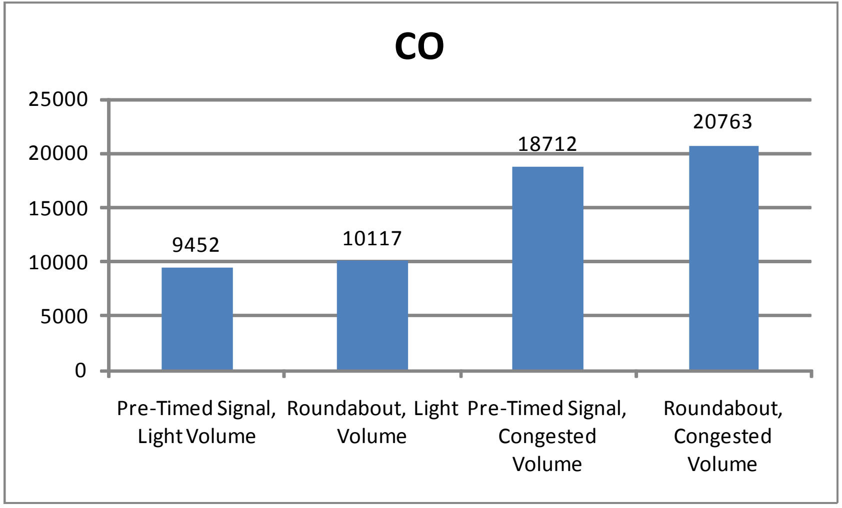
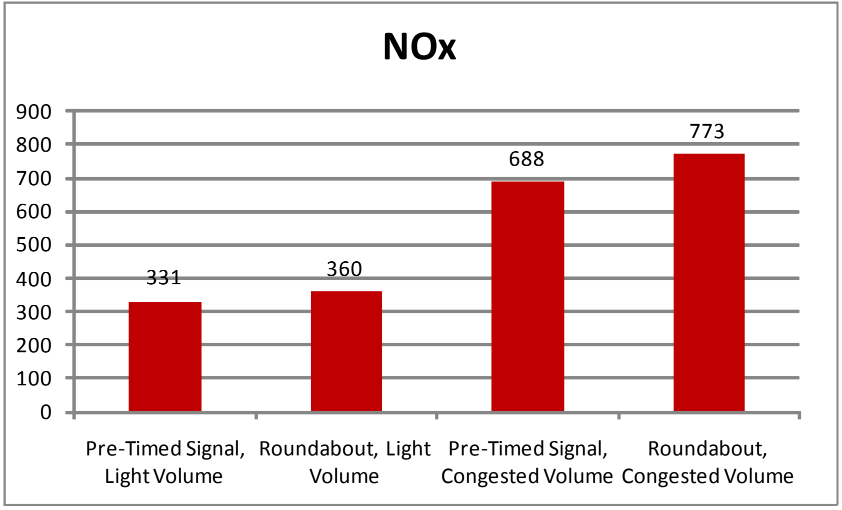


Figure 6: CMEM NOx Estimates for Four Intersection Scenarios (grams/hour)



The pattern of emissions for NOx is similar to that of CO. In the case of NOx, the roundabout scenario is estimated to generate nearly 9% more than the traffic signal in the Light Volume scenario (360 grams to 331 grams) and over 12% more in the Heavy Volume scenario (773 grams to 688 grams).

This particular finding – the roundabouts may generate higher emissions than a traffic signal – has been found in other studies as well. Ahn, et al (*22*) conducted a literature review of the environmental impacts of roundabouts and determined that “the literature presents mixed results on the environmental impacts of roundabouts.” Their particular research, which was also conducted with linked microsimulation models (VISSIM and INTEGRATION) and air quality models (CMEM and VT-Micro) found that a roundabout at a higher speed intersection (>70 km/hr) would generate higher emissions and fuel consumption than a traffic signal and attributed this to the roundabout’s design which causes a deceleration maneuver followed by an acceleration maneuver for every vehicle that traverses it.

Utilizing CMEM the Ahn study estimated a CO emissions rate of 5-11 gram/vehicle, which compares to 11-12 grams per vehicle in this study.

Table 3 shows the CMEM CO output compared with the MOVES output for both pollutants utilizing the Average Speed and Link Drive Schedule approaches.

Table 3: Comparison of CMEM CO and NOx Emissions with MOVES CO and NOx Emissions Using the Average Speed and Link Drive Schedule Approaches (grams/hour)

Pre-Timed Signal, Light Volume

	CMEM	MOVES-Average Speed	MOVES-Link Drive Schedule
CO (g/hr)	9452	2379	1670
NOx(g/hr)	331	565	323

Pre-Timed Signal, Heavy Volume

	CMEM	MOVES-Average Speed	MOVES-Link Drive Schedule
CO (g/hr)	18712	4809	3077
NOx(g/hr)	688	1143	589

Roundabout, Light Volume

	CMEM	MOVES-Average Speed	MOVES-Link Drive Schedule
CO (g/hr)	10117	2346	1719
NOx(g/hr)	360	553	337

Roundabout, Heavy Volume

	CMEM	MOVES-Average Speed	MOVES-Link Drive Schedule
CO (g/hr)	20763	4786	3332
NOx(g/hr)	773	1132	646

Key observations from the data in Table 3 are:

- CO estimates from CMEM are 4-6 times higher than those from MOVES. This discrepancy increases with the more detailed modeling method used in MOVES incorporating the Link Drive Schedule, where CO emissions decline when compared to those produced with the Average Speed approach.
- NOx estimates in CMEM are considerably lower than those generated by the MOVES Average Speed approach, but are in line with the estimates produced by the MOVES Link Drive Schedule approach.
- CMEM and MOVES-Link Drive Schedule estimate higher emissions with the roundabout when compared to the signal for either volume scenario. The MOVES Average Speed method shows slightly lower emissions for the roundabout. The relative differences between the Base Case signal and the Alternative roundabout are shown in Table 4.

Table 4: Percentage Change in CO and NOx Emissions When Converting from a Traffic Signal to a Roundabout Under Light and Heavy Traffic Conditions

	Light Volume			Heavy Volume		
	CMEM	MOVES-Average Speed	MOVES-Link Drive Schedule	CMEM	MOVES-Average Speed	MOVES-Link Drive Schedule
CO	7%	-1%	3%	11%	-0.5%	8%
NOx(g/hr)	9%	-2%	4%	12%	-1.0%	10%

DISCUSSION AND FUTURE RESEARCH

This research has successfully developed methods for integrating MOVES with a traffic microsimulation model. Utilization of k-means clustering and LOESS curve fitting are examples of methods that can convert microsimulation model output into usable input files for MOVES.

The research shows that MOVES and CMEM are comparable in NOx estimates, but widely discrepant in their estimates of CO. While this research has sought to hold constant many of the variables that are involved in this analysis – traffic volumes, roadway geometry, driving cycles, etc. – there remain several important sources of differences that may account for the discrepancies in estimates:

1. Meteorology – MOVES explicitly accounts for the prevailing weather conditions for the county which the modeling seeks to represent. CMEM does not incorporate this factor into it emissions estimates
2. Fuel type – MOVES requires the user to select a fuel formulation that is representative of the fuel in the project area. CMEM does not incorporate this detail as a user input in the Paramics plug-in.
3. Pollutant process – both CMEM and MOVES model idling emission, hot stabilized emissions, and crankcase emissions. MOVES extends this list to other processes. The research reported herein analyzed hot stabilized emissions only.
4. Emission rates source data– Emissions rates developed for MOVES rely on a dynamometer data set of 62,500 tests collected in Phoenix, AZ for the 1995-1999 and 2002-2004 time periods (*23*). Much of this information was collected from on-road vehicles using portable emission measurement equipment. CMEM's emission rates were developed from 343 recruited vehicles tested using chassis dynamometers in the 1996-1999 time frame. The MOVES data incorporates the data from CMEM.
5. Pollution modeling—CMEM uses analytical modeling of the physical processes involved in combustion. The MOVES model uses statistical modeling of emissions from vehicles grouped by vehicle specific power and speed (*24*).

The research suggests that emissions associated with a roundabout can be greater than a simple pre-timed signal. Existing research on this topic shows mixed results.

This research has tested a very simple network and raises the question of how MOVES can be adapted to a more realistic network. There are limits to the number of Link Drive Schedules that can be input into MOVES. A complicated network with dozens of intersections may challenge the processing capability of the software while also requiring substantial sophistication from the modeler. Future research into the application of MOVES for microsimulation applications should address the following questions:

1. What is the limit for network complexity when utilizing MOVES' more sophisticated processes (e.g. Link Drive Schedules or Operating Mode Distributions)?
2. What are the best methods for automating the connection between microsimulation model outputs and MOVES Link Drive Schedule and Operating Mode Distribution inputs?
3. How will emissions estimates vary when modeling an identical operations change using the

Link Drive Schedule and Operating Mode Distribution approaches? How do these approaches compare for accuracy, consistency, and ease of use?

4. In utilizing k-means clustering for characterizing similar vehicle trajectories, what is the optimal number of clusters for a given set?
5. Can MOVES support a hybrid modeling approach for more complex networks where Average Speeds could be used for the non-changing elements of a network, but more detailed data can be applied to the portions of the network where infrastructure changes are being contemplated?

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