Investigating the Effects of Transportation Infrastructure Development on Energy Consumption and Emissions

Darren S. Achtymichuk (darrena@ualberta.ca) and M. David Checkel (dave.checkel@ualberta.ca)
Mechanical Engineering, University of Alberta, Edmonton Canada T6G 2G8
phone (780) 492-7210, fax (780) 492-2200

ABSTRACT

This study outlines a model that allows transportation planners to quantitatively assess the potential fuel consumption and emission impacts that different investments in transportation infrastructure may have. For example, plans for upgrading a transportation corridor may include alternatives such as additional lanes, increased bus service, or a light rail transit line running parallel to the roadway. With this model, the fuel consumption and emissions resulting from each scenario could be determined and compared to the baseline case (the corridor in its current configuration). The potential benefits resulting from each scenario can then be weighed relative to its cost to ensure that available funding is spent on projects that provide the greatest environmental return on investment. Sample results investigating the greenhouse gas emission reduction potential of an accelerated fleet replacement program and of light rail transit investment in a transportation corridor are presented to illustrate potential applications of the tool.

INTRODUCTION

The environmental implications of our society's growing consumption of energy have been well researched and documented in recent years. In Canada, the transportation sector accounts for nearly 30% of total energy consumption (Natural Resources Canada), the majority of which is derived from nonrenewable fossil fuel sources. If emission and energy consumption reduction targets are to be met substantial improvements must be made in this sector. These improvements will be realized not only through technical developments that improve the efficiency and emissions of individual vehicles but by ensuring that transportation systems are designed in a manner that allows trips to be made as efficiently as possible.

Major transportation infrastructure investments can have large impacts on system efficiency. The reduced congestion, more direct travel routes, and increased use of more efficient modes resulting from infrastructure development all help reduce energy consumption and emissions. Furthermore, infrastructure developments can shape land use patterns over time, resulting in denser neighborhoods which require less motorized transportation to maintain a high level of accessibility. In an article outlining the potential for reductions in greenhouse gas emissions from the U.S. transportation sector, Greene and Schafer (2003) identify land-use planning and infrastructure development among the avenues having the greatest potential long-term effects.

To facilitate the development of efficient transportation infrastructure, transportation planners require a technique to model the amounts of fuel consumed and emissions produced in a transportation system. This paper outlines a modeling process that allows transportation planners to quantitatively assess the potential environmental impacts that different investments in transportation infrastructure may have. With this tool, statistics outlining the potential benefits of a project relative to its cost can be rapidly generated to ensure that available funding is spent on projects that provide the greatest environmental return on investment.

MODELING PROCESS

Assessing the impact that different investments in transportation infrastructure can have on fuel consumption and emissions involves two major steps - modeling the traffic flow in the transportation system and then modeling the emissions and fuel consumption based on the traffic characteristics. Many software packages capable of modeling traffic flow in transportation systems are commercially available. The inner workings of these software packages will not be discussed in this study; however the effects that the type of model being used has on the interaction between the traffic model and the emissions model will be addressed.

To determine the fuel consumption and emissions production corresponding to the traffic flows predicted by the traffic model, the software model CALMOB6 (Busawon and Checkel 2006) is utilized. CALMOB6 uses data from the US Environmental Protection Agency's (EPA) MOBILE6 vehicle emissions inventory as its calibration standard. CALMOB6 reads traffic flow characteristics from EMME/2, a macroscopic transport modeling package, and computes the amounts of fuel consumed and emissions produced (both greenhouse gases and pollutants) by each vehicle in the network. Work is currently underway to enable CALMOB6 to interface with VISSIM, a microscopic transport modeling package, which will expand its versatility.

Fleet Characteristics

The first step in the modeling process is to define the vehicle fleet in the region being studied. This involves breaking the fleet up into different classes, specifying the portion of the fleet made up by each class, and specifying the age distribution of the vehicles in the region.

Vehicle Classes - To describe the vehicles in the region being studied, CALMOB6 breaks the fleet up into twenty-one classes, as shown in Table 1. Representative characteristics for each of these vehicle classes, such as mass, frontal area, and coefficients of drag and rolling resistance, are built into the model. To facilitate calibration against MOBILE6 data, each of these classes correspond to MOBILE6 group numbers.

While the emissions modeling process requires that the fleet be broken up into very detailed classifications, traffic forecasting generally makes use of a smaller number of more general classes. EMME/2, for example, classifies traffic using five classes - passenger cars, light-duty trucks, medium-duty vehicles, heavy-duty vehicles, and buses.

To accommodate this, the twenty-one CALMOB6 classes are assigned to the EMME/2 classes as shown below.

Table 1 - Vehicle classification

EMME/2 Classification	CALMOB6 Classification	MOBILE6 Groups	Description
Passenger Cars	Light-Duty Vehicle - Mini	1,14	Passenger car Mini
	Light-Duty Vehicle - Economy	1,14	Passenger car Economy
	Light-Duty Vehicle - Large	1,14	Passenger car Large
Light-Duty Trucks	Light-Duty Truck 1	2,15	0-6000 lbs GVWR; 0-3750 lbs LVW
	Light-Duty Truck 2	3,15	0-6000 lbs GVWR; 3751-5750 LVW
	Light-Duty Truck 3	4,28	6001-8500 lbs GVWR; 0-5750 lbs LVW
	Light-Duty Truck 4	5,28	6001-8500 lbs GVWR; >5751 lbs LVW
Medium-Duty Vehicles	Medium-Duty Vehicle 2b	6,16	8501-10000 lbs GVWR
	Medium-Duty Vehicle 3	7,17	10001-14000 lbs GVWR
	Medium-Duty Vehicle 4	8,18	14001-16000 lbs GVWR
	Medium-Duty Vehicle 5	9,19	16001-19500 lbs GVWR
Heavy-Duty Vehicles	Heavy-Duty Vehicle 6	10,20	19501-26000 lbs GVWR
	Heavy-Duty Vehicle 7	11,21	26001-33000 lbs GVWR
	Heavy-Duty Vehicle 8a	12,22	33001-60000 lbs GVWR
	Heavy-Duty Vehicle 8b	13,23	>60000 lbs GVWR
Buses	Transit Long	25,26	60' articulating transit buses
	Transit New	25,26	40' transit buses
	Transit Old	25,26	Older 2-stroke 40' transit buses
	Transit Short	25,26	Community transit buses
	School Bus Long	25,27	Long school buses
	School Bus Short	25,27	Short school buses

Fleet Age Distribution - As time passes, technical advancements lead to more efficient, less-polluting vehicles. However, the fleet operating in a region is comprised of a mix of new and old vehicles manufactured any number of years ago. To account for the differences in fuel consumption and emissions production between vehicles of different model years, a fleet age distribution is defined in CALMOB6. As shown in Figure 1, the fraction of the fleet made up of vehicles between zero and twenty-three years old is defined.

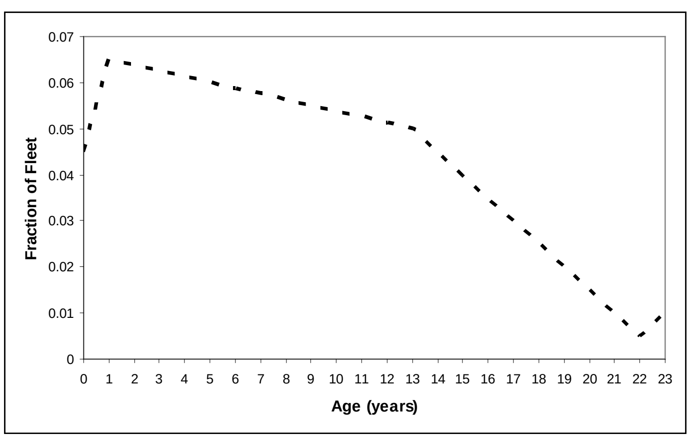


Figure 1 - Sample fleet age distribution

Velocity Profiles

Once the fleet characteristics have been defined, velocity-time profiles for all the vehicles travelling on the network must be established. The manner in which CALMOB6 performs this step is dependent on the type of traffic model being used.

Macroscopic traffic models, such as EMME/2, produce general performance measures, such as average travel speed, for each class of vehicle traveling on each link in the network. By comparing the average travel speeds to the expected link free cruise speeds, the level of congestion can be estimated. From this, CALMOB6 generates a representative driving profile for each vehicle on the network.

On the other hand, microscopic traffic models, such as VISSIM, simulate the second by second motion of all vehicles in the network. As a result, rather than inferring a velocity-time profile for each vehicle, CALMOB6 simply uses the profiles generated by the traffic model.

Both of the aforementioned techniques have been shown to be valid methods for modeling fuel consumption and emissions. In an investigation into the ability of various fuel consumption and emissions models to capture the effects of traffic congestion, Smit et al (2009) classified the models studied into three categories - Type A models which use driving profiles from traffic micro simulation (such as CALMOB6 interfacing with VISSIM), Type B models which generate representative driving profiles based on macroscopic traffic simulation (such as CALMOB6 interfacing with EMME/2), and distance-based Type C models which simply multiply the vehicle kilometers travelled by constant factors. In comparing the three types of models, it was found that Type A and B models were both capable of capturing the effects of traffic congestion and were suitable for measuring fuel consumption and emissions at a local level. Type C models were found to be useful for measuring the aggregate fuel consumption and emissions in large regions but did not perform adequately at a localized level.

Tractive Power

Once a velocity profile has been established for each vehicle travelling on the network, tractive power traces must be computed. Using equation 1, CALMOB6 computes the second-by-second power requirements for all the vehicles travelling on the network. The vehicle mass, *m*, frontal area, *A*, coefficient of rolling resistance, C_R, and coefficient of drag, C_D, for each vehicle are known based on the vehicle's classification while the slope of the road, β, is given by the traffic model. The vehicle velocity, $\dot{x}$, and acceleration, $\ddot{x}$, are taken from the velocity profile for the instant in time for which the tractive power, *u*, is being computed.

$$u = m\ddot{x} + \rho C_D A \frac{\dot{x}^2}{2} + mC_R g + mg\sin(\beta) \qquad (1)$$

Emission and Fuel Consumption Functions

Using the tractive power traces, CALMOB6 next determines the second-by-second fuel consumption and emissions production for the vehicles on the network. This is done using functions that relate the rate of consumption or production to the instantaneous tractive power, as seen in Figure 2. CALMOB6 incorporates functions relating tractive power to fuel consumption and production of carbon monoxide (CO), oxides of nitrogen (NO_x), non-methane hydrocarbons (NMHC), and particulate matter (PM). These functions, which have been developed for each class of vehicle, are based on laboratory dynamometer testing. Carbon dioxide (CO_2) emissions are determined from the fuel consumption using stoichiometry.

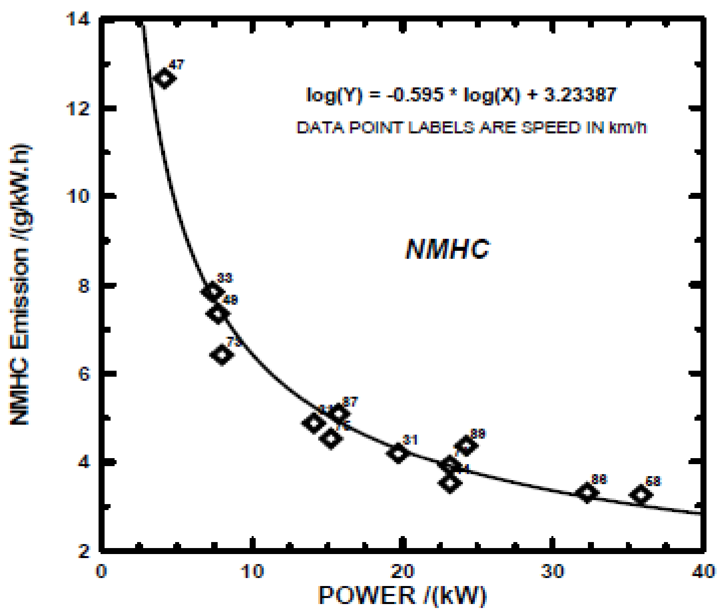


Figure 2 - Sample NMHC function for light-duty gasoline powered vehicles

The amount of fuel consumed and emissions produced by each vehicle while traveling through the network is determined by integrating its corresponding fuel consumption and emissions traces. The aggregate fuel consumption and emissions production is then determined by summing the results from all the vehicles on the network.

Calibration Process

As mentioned above, CALMOB6 uses the US EPA's MOBILE6 vehicle emissions inventory as its calibration standard. The calibration process is performed by running a vehicle from each class through a standard FTP driving cycle and determining the fuel consumption and emissions using CALMOB6's tractive power-based functions. The results obtained are compared to the fuel consumption and emissions MOBILE6 predicts over the same FTP driving cycle and appropriate scaling factors determined. Using MOBILE6 as a calibration standard ensures that the results obtained from CALMOB6 can be compared to the results from other models in the proper context.

APPLICATIONS

While the ability to quantify the total fuel consumption and emissions production in current transportation systems can be of some use, the real value of an emissions model like CALMOB6 is its ability to determine the environmental effects of different scenarios being considered for future development. Having quantitative estimates of the effects that transportation projects will have on energy use and emissions enables planners to consider the environmental implications of potential projects and direct funding towards the most suitable options.

CALMOB6's modeling capabilities are limited only by the robustness of the traffic model being used to predict future traffic flow. If planners feel they can accurately predict the long-term land-use and growth effects of infrastructure projects, such as high density development occurring around major transit hubs, and the resulting traffic patterns, then the impact of the development on energy use and emissions can be studied. To illustrate CALMOB6's emission modeling capabilities, two applications of the model are discussed below.

Fleet Replacement

One potential application of CALMOB6 is investigating the effects of changes to the vehicle fleet operating in a region. Government policies such as rebates on fuel efficient vehicles, cash for clunkers programs, and funding for accelerated transit vehicle replacement all have an effect on the composition of the vehicle fleet in a region. Using CALMOB6, the benefits of such programs could be investigated before implementation and weighed against their costs. The potential return on investment could then be compared to other projects to ensure that funding is allocated in the most efficient manner.

To illustrate this, the cost effectiveness of cash for clunkers programs at reducing greenhouse gas emissions has been investigated. While the rules and regulations governing these programs were different in each region in which they were implemented, a rebate of around $3000 for replacing a vehicle that was ten or more years old was typically offered. Using CALMOB6, the annual greenhouse gas emissions were evaluated in Edmonton, Alberta, Canada with the current vehicle fleet and with a vehicle fleet in which older vehicles had been replaced under the program.

Complete replacement of eligible vehicles was found to result in an annual reduction in greenhouse gas emissions in the City of Edmonton of 74,000 tons. Weighing this value against the total number of vehicles operating in the region, the potential annual reduction in greenhouse gas emissions comes out to 0.094 tons per vehicle per year, as shown in Figure 3. By assuming that the vehicles replaced under the program would have on average remained in operation for 3.4 additional years before being replaced it is found that the program reduces greenhouse gas emissions at a cost of $1,750 per ton. By comparing this value with the $15/ton regulated value of carbon credits in the Province of Alberta, it can be concluded that cash for clunkers programs are not economical solely as greenhouse gas reduction programs; however, the additional benefits they provide, such as reducing criteria pollutants (NO_x, CO, PM, etc.) and stimulating automotive sales in poor economic times, likely led to their implementation.

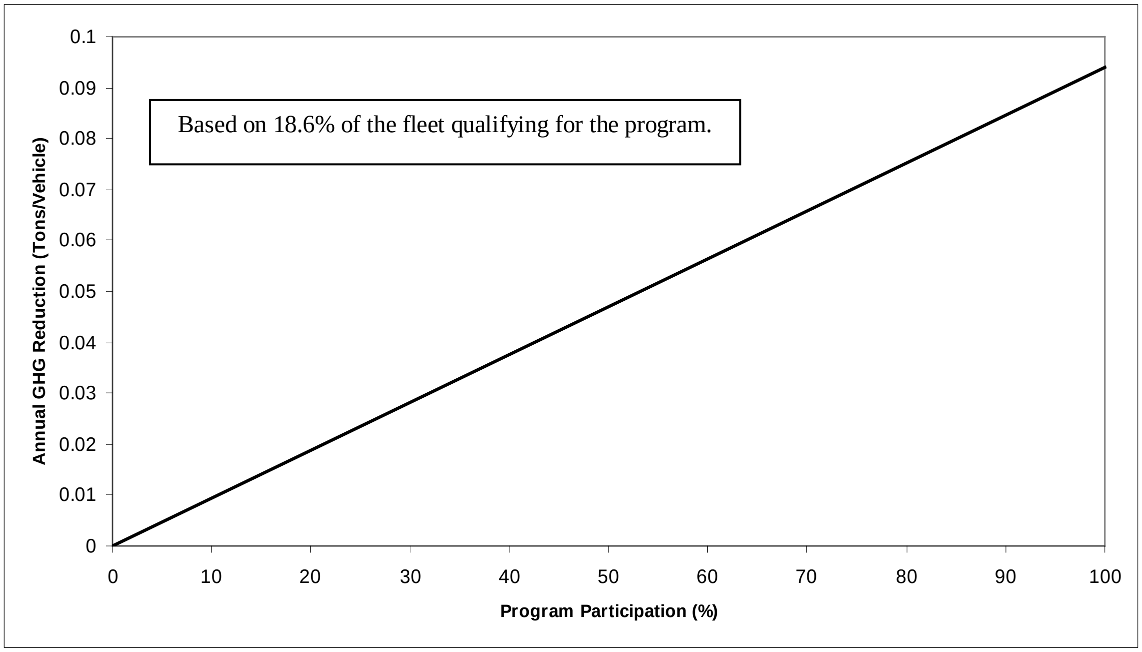


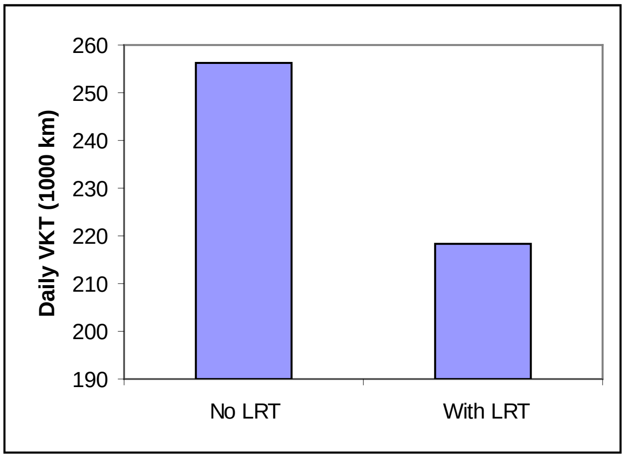
Figure 3 - Annual cash for clunkers greenhouse gas (GHG) emissions reduction relative to the total number of vehicles in the network

Corridor Upgrade

A second potential application for emissions modeling would be in comparing different alternatives being considered for infrastructure development in a congested transportation corridor. Numerous potential upgrades, such as additional lanes, increased bus service, or construction of a light rail transit (LRT) line parallel to the roadway, would be expected to reduce fuel consumption and emissions by reducing congestion and allowing vehicles to operate more efficiently.

Using CALMOB6, the energy use and emissions effects of each of the alternatives being considered could be evaluated and compared to the baseline case (the corridor in its current configuration). The total environmental benefits derived from each development scenario could be determined by summing the reductions in emissions and fuel consumption over the lifespan of the infrastructure. These benefits could then be weighed against the capital and operating costs of the development to provide a measure of return on investment.

To illustrate this, a corridor in the City of Edmonton currently being considered for LRT investment has been investigated. The corridor, which stretches 14 km from a suburban community in the west end to the downtown core (City of Edmonton, 2009), is a major commuting route for individuals who are employed centrally and post-secondary students. Using traffic models developed by the City's transportation department, the greenhouse gas emissions along the corridor have been evaluated both with and without the LRT line. Using CALMOB6, it was found that the inclusion of the LRT line in the corridor results in an annual reduction in greenhouse gas emissions of 2,700 tons (14%). This decrease is a result of the 15% reduction in vehicle kilometers travelled along the corridor in the case where the LRT line has been built. This simple analysis does not include the additional emissions resulting from the electricity consumed by the light rail vehicles or the impact that the LRT line has on vehicle traffic on adjacent corridors but has been included to illustrate the types of scenarios that CALMOB6 can be used to evaluate.



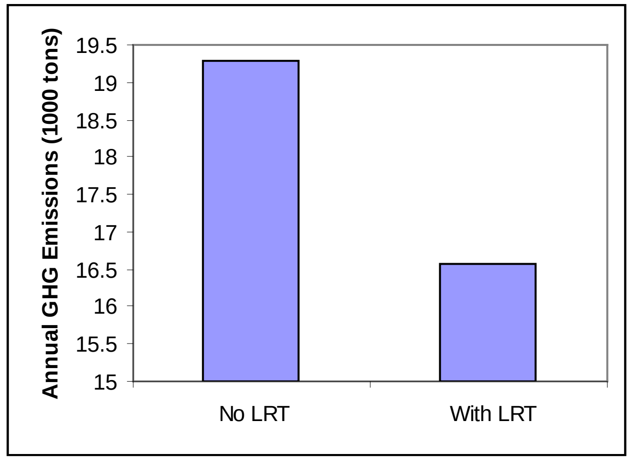


Figure 4 - Daily vehicle kilometers travelled (VKT) and annual greenhouse gas (GHG) emissions with and without LRT

CONCLUSIONS

This study outlines a technique for investigating the environmental effects of potential transportation infrastructure developments. The emissions and fuel consumption associated with the projects being considered are quantified using the software model CALMOB6. By comparing these results to the baseline scenario, the potential benefits of each project can be determined and weighed against their associated costs. Doing so allows planners to ensure that funding is allocated to the projects providing the best environmental return on investment.

Examples investigating the greenhouse gas emission reduction potential of a fleet replacement program and of LRT development in a transportation corridor have been presented. While limited in scope, the examples illustrate the types of development scenarios that can be investigated using CALMOB6. Future work on this project will involve using this technique to perform more robust analyses on various transportation infrastructure development scenarios. In doing so, the process will be further refined and best practices recommended.

REFERENCES

Busawon, R., and M. David Checkel. 2006. CALMOB6: A Fuel Economy and Emissions Tool for Transportation Planners. Paper presented at the 2006 Annual Conference of the Transportation Association of Canada, September 17-20, in Charlottetown, P.E.I., Canada.

City of Edmonton. 2009. West LRT to Lewis Estates. *City of Edmonton.* http://www.edmonton.ca/transportation/ets/west-lrt.aspx

Greene, D., and Andreas Schafer. 2003. Reducing Greenhouse Gas Emissions from U.S. Transportation. Prepared for the Pew Center on Global Climate Change.

Natural Resources Canada. 2009. Canada's Secondary Energy Use by Sector, End-Use and Sub-Sector. *Natural Resources Canada.* http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/tableshandbook2/aaa_ca_2_e_3.cfm?attr=0

Smit, R., A.L. Brown, and Y.C. Chan. 2009. Do air pollution emissions and fuel consumption models for roadways include the effects of congestion in the roadway traffic flow? *Environmental Modelling & Software* 23: 1262-1270.

US Environmental Protection Agency. 2009. MOBILE6 Vehicle Emissions Modeling Software. *US Environmental Protection Agency*. http://www.epa.gov/OMS/m6.htm