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Life Cycle Assessment Framework of Traffic Systems Based on Microscopic Simulation

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1. Overview

Transportation is an important infrastructure process needed in many steps of the supply chain of any product. Transportation-associated global impacts are therefore important factor influencing the sustainability of any product cycle. Moreover, traffic integrates throughout different product cycles combining transportation of raw materials and products with passenger transport. Traffic improvement is needed to accommodate growing transportation demands of product-cycles while mitigating associated environmental, social and economic impacts. Emissions from by road transportation depend on traffic conditions to greater extent compared to other means of transportation. Emissions from road transportation depend on phased operation of a vehicle mix that is affected by traffic and road conditions.

This report describe integrated modeling framework to assist environmental impacts of traffic systems in by road transportation. The methodology can be optimally used to evaluate impacts of new development and to justify the needs for smart traffic technologies and more resilient transportation infrastructure. The frame work integrates three modeling tools: microscopic traffic simulation software (VISSIM), Motor Vehicle Emission Simulator (MOVES) and a new TRACI-based Traffic Life Cycle Assessment tool (T2LCA). The new T2LCA is based on the EPA-TRACI environmental assessment protocol. TRACI protocol was developed as a Tool for the Reduction and Assessment of Chemical and Other Environmental Impact.

The framework was organized by the National Institute for Advanced Transportation Technology (NIATT) – University of Idaho, Moscow, Idaho. The work was developed in two phases to integrate with MOVES Input-Output. In phase1, NIATT developed the protocol to interface VISSIM with MOVES generating its input from traffic microscopic simulation. In phase 2, NIATT contracted EAST-Environment Automated Sustainable Technologies, Pullman, WA, to develop the T2LCA framework interfacing with MOVES' output to evaluate global LCA impacts of the simulated traffic system. The integrated framework was then tested by a case study simulating the traffic of small-to-mid sized city (Moscow-Idaho). Global impacts of the city optimized traffic were compared with current (base condition) traffic to evaluate the environmental cost savings associated with traffic improvements.

2. PHASE 1: VSSIM-MOVES interfacing

In order to create an accurate MOVES project scale emissions model, the user must provide detailed vehicle operation information in the form of drive schedules or an operating mode distribution table. Representing microscopic vehicle operation and interaction can be the most difficult and time consuming part of constructing a MOVES project-scale model, and can also be a major source of inaccuracy in the model. In response to this, the idea put forward here is to use VISSIM to generate second-by-second vehicle drive schedules, which can then be used to create MOVES user input database tables.

In MOVES, vehicle activity and operating mode assignment are calculated in two different steps. One, the project total activity generator (TAG) calculates the sum total of source (vehicle) hours for each of the three vehicle activity categories: operating, extended idle, and non-operating, as well as the total number of starts. The project TAG also allocates activity to source types, links, and road types. The allocation of vehicle activity to operating modes takes place in the second calculation step, and is controlled by a core model input table containing the “operating mode distribution” (OMD). The OMD table is the basis for assigning emission rates to hours of source activity, and so is a critical input for nearly all exhaust emission calculations. Therefore, realistically representing vehicle operation in the OMD table is essential to creating an accurate MOVES model and is the purpose of using VISSIM vehicle speed profiles for MOVES input.

There is more than one approach that may be taken to represent source activity in the OMD table. The allocation of activity to operating modes can be performed by the MOVES operating mode distribution generator (OMDG), which computes the contents of the OMD table from roadway geometry and user defined or default vehicle drive schedules. This step is automatically initiated if an OMD table is not present in the user input database. If this method is used, individual vehicle speed profiles would likely need to be aggregated into a single profile for each link, with links defined physically according to VISSIM vehicle speed profiles power (VSP) and vehicle trajectory data speed profile. This method could get prohibitively complex as the size of the simulation area grows, because the number of potential vehicle trajectories increases

multiplicatively. In such case, and to maintain statistically significant level, a number of vehicle trajectories in the VISSIM output files can be sampled. It would, however, be fairly simple computationally, and would require no MOVES default or other additional data.

Alternatively, VSP can be calculated for each second for each vehicle, and this information can be used to generate an operating mode distribution table directly outside of the MOVES computational structure. Computing VSP and assigning operating modes would involve several MOVES default tables, but would make it possible to preserve much of the detail from the micro simulation activity data. It should be noted here that MOVES default tables are not adjusted for local conditions such as temperature, humidity, sulfur contents, fuels used, etc. Either of these approaches can be used effectively, although there are benefits and drawbacks associated with each.

2.1. MOVES Project-Scale Emissions Modeling

MOVES can model vehicle emissions at three scales: national, county, and project. Of these, project scale is the highest resolution and so requires the greatest detail in user input information. For example at the national scale, the vehicle operating mode distribution is calculated largely from default drive schedules that are specific to very general roadway parameters and do not differentiate between geographic locations, road length, or most other link-specific roadway characteristics. At the project scale, operating mode information must be provided by the user in the form of link-specific speed profiles, operating mode distributions, or link average speed. The additional information required for project scale modeling must be provided in the form of a special “user Input database”, which is entered under the geographic bounds tab of the MOVES Runspec. When MOVES is executed, the user input database is combined with default and Runspec information to create the execution database, which is where all information is read and written in subsequent calculation steps

2.1.1. Core Model Input Generators

Before emission calculations begin, a series of generators convert user and default data into core model input tables (CMITs), which describe all vehicle activity and environmental conditions in

the correct format for emissions calculations. The CMIT generators used in a typical project-level MOVES run are listed below.

- Operating mode distribution generator (OMDG)
 - o Generates the OpModeDistribution table
 - o Allocates total activity to operating modes with distinct emissions profiles
- Total activity generator (TAG)
 - o Generates the SourceHours, Starts, ExtendedIdleHours, and SHO tables
 - o Calculates total hours for each activity category in each link, road type, and source type
- Source bin distribution generator (SBDG)
 - o Generates the SourceBin and SourceBinDistribution tables
 - o Creates detailed source type population distribution for each source use type
 - o Maps “source use types” used in TAG and OMDG to “source bins” used by the emissions calculators
- Meteorology
 - o Generates two fields in the ZoneMonthHour table
 - o Calculates heat index and specific humidity from user defined temperature and relative humidity

In addition to those listed above, several generators related to evaporative emissions are run at larger model scales. However, MOVES does not currently model evaporative emissions at the project level. In addition, the start OMDG is not used at the project level, because a start operating mode distribution requires user input if an off-network link (e.g. parking lot) is specified.

At the project scale, nearly all of the information used to populate the CMITs is contained in the user input database. The SBDG is an exception to this rule, as it is essentially a mechanism for mapping user defined vehicle types and model years to the source types that are used in emissions calculations. For example, the source use type “light commercial truck” of a certain model year is mapped to a population distribution that contains multiple distinct emission rates, and is calculated from default tables.

The tables produced by the TAG and OMDG provide all vehicle activity information for energy and emission calculations in MOVES. These tables are key to understanding how emissions are calculated in MOVES, and are further explained in the following two subsections.

2.1.2. The Total Activity Generator (TAG)

The project TAG computes and allocates source activity based on user supplied information in the Runspec and the user input database. All data used in the project TAG is supplied by the user. The inputs to the project TAG are the user defined Links, OffNetworkLink, SourceTypeDistribution, and AgeDistribution tables. Source activity is calculated separately for each link and source type, and is allocated to activity categories as follows:

Source Hours Operating (SHO)

SHO is calculated by multiplying the hourly volume of each source type in a link by the average time spent in the link. All operating activity takes place within the link network.

Source Hours Parked (SHP)

SHP is calculated by multiplying the vehicle population in the off-network link by the fraction of vehicles that are parked. It is calculated separately for each vehicle age. All parked vehicle activity takes place in the off network link.

Starts

The number of starts is calculated by multiplying the vehicle population in the off-network link by the hourly fraction of vehicle starts. It is calculated separately for each vehicle age. All starts take place in the off network link.

Extended Idle (ExtIdle)

Extended idle is calculated as the product of the vehicle population and the extended idle fraction. It is calculated separately for each vehicle age. All extended idle activity takes place in the off network link.

Source Hours (SH)

This is calculated in the same way as SHO for roadway links and the same as SHP for off-network links. It is used for evaporative emission processes, and so is not currently used in project-level analysis.

2.1.3. The Operating Mode Distribution

The operating mode distribution table contains a fractional distribution of operating modes for each link and source type. Operating mode bins are differentiated by a number of operational parameters, most notably vehicle specific power (VSP). The information contained in this table is used to allocate the total vehicle activity calculated by the TAG to operating modes for emissions calculations.

One option in a MOVES project-scale model is for the user to enter an operating mode distribution directly in the user input database. If this is done, the user supplied table is used as-is by the emissions generators and the OMDG is unnecessary. Alternatively, the user may enter a vehicle drive schedule speed profile for every link, and this is used with default vehicle parameters in the OMDG to create an operating mode distribution table. A third option, a simple average speed may be entered for each link. In this case, default drive schedules are used in the place of user supplied drive schedules to compute the OMD.

In the OMDG, link drive schedules are used to calculate VSP, which is a key distinguishing point for operating mode bins. VSP is calculated with an algorithm based on vehicle dynamics, and is a function of acceleration, speed, grade, and vehicle characteristics. The inputs for this calculation are as follows:

- Speed and acceleration from second-to-second vehicle drive schedule
- Link grade from user input link table
- Vehicle mass, rolling term, drag term, and rotating term from default SourceUseType table

VSP is calculated for every second of vehicle activity in the drive schedule, which allows travel time to be divided into VSP-specific operating mode bins. Based on this, a fraction of the total operating hours is then assigned to each operating mode bin to create the operating mode distribution table. It should be noted that some operating mode bins are not differentiated by specific power, including starts, braking, and idling.

2.1.4. Emission Calculations

MOVES models a wide range of running and start emissions, some of which require several computation steps. An overview of some of the key elements is given here. From the following discussion, it is apparent that MOVES emission calculations can be rather complex. Unlike in the VISSIM emission module, MOVES emission rates vary in the method of application, units, and interconnection with other calculated emission quantities.

Emission Rate Tables

All default data including emission rate tables can be found in the MOVES default database. Rates for age dependent and non-age dependent emissions are contained in the EmissionRateByAge and EmissionRate tables respectively. There are two major types of emissions, mass and energy. Mass emissions are those that are typically measured in mass terms, including N₂O, CH₄, and other air pollutants. Energy emissions are used to calculate the quantities of different sources of energy, including total, petroleum, and fossil fuel. Many emission types have two separate sets of rates, one for base emissions and one that reflects the ideal impact of a reference inspection/maintenance program.

Chained Emissions

A number of emission types are “chained” to other emission quantities in MOVES. This means that the associated emission rates are simply multiplicative factors that relate the quantity of one emission to another. For example, atmospheric CO₂ and CO₂ equivalent are functions of the total energy consumed.

Criteria Pollutants

Criteria pollutants are those that are affected by the presence of an inspection/maintenance (IM) program. There are multiple IM program types supported in MOVES, as well as additional adjustments that can be made to better represent the effectiveness of any given program. The user-defined IM program information determines which pollutants and vehicles are affected as well as to what extent emissions are reduced by the program. The calculation process for criteria pollutant emissions has an additional step in which the effects of the inspection/maintenance program are calculated. In this step, an intermediate table of

emission rates is created that weights IM and non-IM emission rates according to the coverage and effectiveness of the IM program.

Air Toxics

There is no direct relationship between air toxics and vehicle activity in MOVES, as all toxics are chained to other emission quantities. This class of emissions are related to either volatile organic compounds or PM 10 emissions. This illustrates the complexity of tracing default emission rates to final computed quantities, because PM 10 emissions are themselves chained to PM 2.5, some of which are in turn chained to total energy consumed. Toxics include Benzene, Ethanol, MTBE, Naphthalene, 1,3-Butadiene, Formaldehyde, Acetaldehyde, and Acrolein, with some additional air toxics added to the MOVES 2010b release. The rates for these emission types are stored separately from the general emission rates, in a series of default tables with prefix ATRatio.

A/C Adjustment Factors

There are several emission types in MOVES that are affected by air conditioner use, either directly or by way of being chained to emissions that are directly affected. This process involves the calculation and application of A/C adjustment factors, and is the same for all relevant emission types. First, MOVES calculates how much time a vehicle's A/C compressor is engaged based on scenario date and time information, in addition to a heat index calculated from user-defined local meteorological information. Next, the overall fraction of A/C compressors in use is calculated based on default data. This step accounts for several A/C-related variables, including the population fraction of inoperable systems. A/C adjustment factors are then calculated from default A/C factors and the previously computed A/C activity fraction. Emission rates are adjusted by multiplying the default rates by the calculated A/C adjustment factors.

Other Adjustment Factors

- Fuel adjustment factors: listed in some emission calculation steps, but no default values are contained in the default database. It is likely that this field is a place holder for future improvements, or possibly a user input calibration point.
- Temperature adjustment: Calculated from user defined current temperature and default factors in the TemperatureAdjustment table.

- Humidity adjustment: NO_x emissions are adjusted for humidity affects.

2.2. VISSIM Emissions/Fuel Module

The VISSIM emissions module uses the vehicle operation information produced by the traffic flow model to compute exhaust emissions, evaporative emissions, and fuel consumption. Twelve emission types are supported by the VISSIM module: Benzene, CO, CO₂, HC, Fuel, NMOG, NMHC, NO_x, Particulate, Soot, SO₂, and Evaporation. Emissions are not dependent on or “chained to” each other, so any combination of pollutants may be modeled in a simulation. However, an “engine map” or emission rate table must be defined for each combination of vehicle and emission type that is to be modeled. Fuel consumption is modeled as an emission, and so for each vehicle type the inputs are the same as other pollutant categories.

2.2.1. Note on VISSIM Information

This subsection explains the calculation methods used in the VISSIM emissions module in limited depth, as detailed documentation of the calculation algorithms has not been made public. This means that some calculation steps are glossed over or not mentioned at all. Available information is limited to underlying technical documents and user manuals made available by PTV America, the developer of VISSIM

2.2.2. Engine Map Files

Before a VISSIM simulation model with emissions calculations can be run, an emissions layer file (*.sch) should be defined and selected in the emissions dialog box. This file contains the vehicle information needed to calculate emissions, including file names for the “engine maps” that relate specific vehicle operation parameters to emissions rates. Each vehicle type must have an engine map for each emission type to be modeled.

There are three different engine map formats for warm running emissions, one each for passenger car, heavy commercial vehicle (HCV), and motorcycle. Warm running emissions are modeled differently for each of these three vehicle categories. A single engine map format is defined for cold emissions processes, in which emissions rates are a function of operating temperature and normalized required power. The format of the engine map file for each vehicle emissions category is described below:

Passenger cars

- Function of velocity and the product of velocity and acceleration
- Matrix format
- Emission rates in units of mg/s

Heavy commercial vehicles

- Function of engine power and normalized rotational speed
- Matrix format
- Emission rates in units of g/hr/kW

Motorcycles

- Function of velocity only
- Two column table format
- Emission rates in units of g/km

Sub-operating temperature

- Function of operating temperature and normalized required power
- Matrix format
- Emissions rates in units of g/hr/kW

2.2.3. Physical Vehicle Characteristics

In addition to engine maps, a number of attributes must be defined for each vehicle type in order for emissions to be calculated. Physical vehicle characteristics are needed to compute engine speed and instantaneous power requirements, and one or both of these quantities are required for multiple emissions calculations. Many attributes are self-explanatory and readily available for any common vehicle make and model. Others, like the two frontal area coefficients, are not as straight forward in derivation or application. For many typical scenarios, default vehicle types will be used or customized somewhat to better represent actual conditions. Otherwise, input from the developer may be needed to generate some of the less transparent parameters for custom vehicle types. A full list of the vehicle description fields in VISSIM layer file is given later in this report.

2.2.4. Dynamic Correction Factors

Dynamic correction factors are entered as a file name in the layer file. Supporting documentation describes the Dynamic adjustment factors as being based on kinematic variables such as the

number of changes from positive to negative acceleration, idling portions, and mean acceleration values. Little information is provided on the derivation or application of these adjustment factors. It seems that factors were developed independently for several vehicle types, each with a unique set of input variables. Next, they were averaged over multiple vehicle types with input based on the most significance for the greatest number of vehicles. This indicates that vehicle-specific adjustment factors may not be necessary, and that default factors may be used effectively. However, the document that describes this process dates from 1999, and changes may have been implemented in the more recent releases of VISSIM. Also, HCV dynamic adjustment factors are specific to individual engine concepts (suction engine, exhaust gas turbocharger, and exhaust gas turbocharger with charging air cooling).

2.2.5. Calculation Steps for Warm Running Emissions

Passenger Cars

The calculation process for passenger car emissions differs significantly from the process used for HCVs. Passenger car emissions are calculated for each second of operation by looking up the emissions rates in the engine map for each pollutant, and summing for all seconds of operation. VISSIM calculates speed and acceleration values at high temporal resolution for every vehicle in the simulation, so identifying the correct emission rate is a simple matter of looking up speed and speed*acceleration on the engine map for each pollutant. Warm running passenger car emission rates are in units of mg/s, so emission quantities for each second are read directly from the engine maps. An averaged dynamic correction factor is applied to the calculated emission quantities to account for the difference between experimental and calculated results.

Heavy Commercial Vehicles

The calculation process for HCVs includes intermediate steps to calculate vehicle power and normalized engine speed. Engine power for each second in the analysis is calculated from the vehicle speed profile produced by the VISSIM traffic flow model and the vehicle characteristics contained in the layer file. From the original document describing the calculation process, it seems that grade is not considered in power calculations. More recent documents suggest that grade sensitivity has been added in newer versions of the software,

but provide no indication of whether this has been incorporated into instantaneous power calculations. Engine rotational speed is calculated using the vehicle speed profile and the gear ratio information contained in the layer file. Engine speed is normalized by dividing current engine rotational speed by the maximum rotational speed for the vehicle type listed in the layer file. With the second-to-second power and normalized speed calculated, emissions rates can be found in the engine map files. It should be noted that the warm running emissions rates for HCVs are in units of g/hr/kW, which means that the rates must be multiplied by instantaneous engine power to get mass/time. Similar to passenger cars, a dynamic correction factor is applied to HCV emissions to account for the differences between experimental and calculated values.

Motorcycles

The calculation process for motorcycle emissions is not described in any readily available supporting documents. It is clear that emission rates for each pollutant are found by looking up the vehicle speed for each second of operation in the engine maps. It is not clear, however, whether any type of correction factor is applied.

2.2.6. Calculation Steps for Sub-Operating Temperature Emissions

The VISSIM emissions module includes a separate component to account for the additional emissions produced by vehicles operating at warm-up temperatures. This is calculated as an additional emission quantity produced in the time between a vehicle start and when normal operating temperature is reached, during which the engine consumes more fuel and the catalytic converter does not perform to its full potential. This calculation requires a separate engine map for each pollutant and vehicle type, as well as an engine temperature distribution.

As mentioned previously, sub-operating temperature engine maps are in the same format for all vehicle emissions categories. The independent variables needed to look up emission rates are instantaneous vehicle power and engine or catalytic converter temperature. Instantaneous power must be computed for each vehicle using the vehicle characteristics contained in the layer file and the speed profile produced by the VISSIM traffic flow model. Emission rate lookup values for power must be normalized to reach a maximum of 1. Engine coolant and catalytic converter temperature are readily available from the VISSIM vehicle traffic flow simulation. These

temperatures are defined or edited by the user as a distribution in the VISSIM user interface, and can be accessed under Base Data>Distributions>Temperature. Because sub-operating temperature emission rates are in units of g/hr/kW, each must be multiplied by instantaneous vehicle power to get g/hr.

There is no location for sub-operating temperature dynamic adjustment factors in the layer file, and this subject is not discussed in any available supporting documentation. It is possible that no adjustment or calibration factors are used in this calculation, but further research should be conducted on this topic.

2.3. Integrating VISSIM Vehicle Operation Information into MOVES

The following sections describe two different ways in which VISSIM microscopic traffic simulation software may be used to generate vehicle operation information for MOVES input. They represent the most intuitive interface points for the two programs, and both rely on existing user data input points in the MOVES project level Runspec. The average speed method is not discussed here, but most certainly would be the simplest and least detailed way to translate VISSIM output into MOVES input. There are several technical challenges associated with each method of using VISSIM output to generate MOVES project-level input. In addition, there are some issues that will be faced regardless of the method used, including:

- Mapping vehicle types in VISSIM to source use types in MOVES
- Insuring continuity between MOVES RunSpec and VISSIM input

2.3.1. Using VISSIM Data to Create a DriveScheduleSecondLink Table

One of the ways in which vehicle activity is entered in a MOVES project-level model is by creating a second-to-second vehicle speed profile for each link. MOVES uses this speed profile to calculate vehicle specific power (VSP) and generate an operating mode distribution (OMD) for emissions calculations. In a MOVES project-scale Runspec, the speed profile can be entered as a spreadsheet table in the user input database. It would seem intuitive, then, to create a table of speed profiles from VISSIM model output and use it as input for a project-scale MOVES user input database. The problem with this is that VISSIM provides a speed schedule for each vehicle, and MOVES only allows a single drive schedule for each link. This would require either that

each vehicle path be defined as a link (resulting in an unfeasibly large number of links), or that individual vehicle paths are grouped and averaged into a more realistic number of aggregate links.

The desired format for MOVES input is a spreadsheet table with a single, 1-second resolution vehicle speed and grade profile for each link in the analysis. In this case, links will be partially defined by speed profiles produced in the VISSIM simulation, which will require that the physical location of the link correspond to VISSIM vehicle trajectories. This also implies that links should not be defined in the MOVES Runspec until VISSIM output is processed.

VISSIM output should be in the form of 1-second or higher resolution velocity and grade profiles for each vehicle in the analysis. Because MOVES requires 1-second resolution, higher resolution output will have to be sampled at 1-second intervals. The speed profiles must be processed to identify and average similar profile shapes. This step may prove challenging because each speed profile will cover a slightly different time span for the same distance traveled, making a point-by-point averaging of similar profiles impossible. Speed profiles must also be associated with a physical roadway section, so that the correct road geometry and vehicle population are assigned. It should be noted that no acceleration information is required, because the MOVES OMDG uses the discrete changes in velocity to calculate acceleration and the resulting change in VSP.

This technique would require a reliable method for identifying and combining statistically similar velocity profiles. There are likely a number of ways to simplify this process, such as:

- Because each link has a single length value, and because a single grade may be assigned to each entry in a drive schedule, velocity profiles for more than one link can be grouped if the road sections are geometrically similar. For example, west bound left turn and east bound left turn traffic can be combined if the intersection is flat and the source type distribution is the same.
- A single road section may be split into multiple links if different vehicle performance characteristics result in significantly dissimilar speed profiles. For example, a steep road grade may have a separate speed profiles for passenger cars and heavy trucks. This would

require special care to insure that the correct vehicle type distribution is assigned to each link.

- Because of the large number of speed profiles that are output by VISSIM, a software application may be developed to combine and average similar speed profiles. However, this may prove challenging due to the inherent subjectivity in identifying “similar” profiles.

2.3.2. Using VISSIM Data to Create an OpModeDistribution Table.

Vehicle operation information can be input to a MOVES project-scale user input database in the form of a distribution of vehicle operating modes for each link and source type. Note that, in any case, total vehicle activity or operating time is calculated in the MOVES total activity generator, so the operating mode distribution (OMD) table is simply a way of allocating total activity to vehicle operating modes. Nearly all operating mode bins are distinguished by VSP and/or vehicle speed.

Each operating mode bin has a number of pollutant processes associated with it, and is characterized by the operating parameters related to those pollutant processes. For example, most exhaust emissions depend largely on VSP, and the associated Cruise/acceleration bins are differentiated by speed and VSP. Non-running evaporative emissions are dependent strictly on soak time, as are the non-running operating mode bins. In addition, several operating mode bins are simply “catch-all” categories for pollutant processes that do not depend on the operating parameters listed above. These categories include starts, extended idle, and braking.

Because the OMD table is a core model input, it represents the highest level of detail for vehicle operation information that is supported by MOVES. If VISSIM output could be used to generate this table directly instead of going through the MOVES OMD generator, a higher level of detail could be preserved thereby taking maximum advantage of the micro-scale simulation. A software application would likely be required as an interface between the two programs, otherwise each MOVES run would require a great deal of spreadsheet calculations and manual data processing.

The format of the MOVES OMD input table is a list of all possible combinations of link, source type, pollutant process, and operating mode. Each entry in the list is associated with a fraction of the total activity for that combination of source type, link, and operating mode. That is, each combination of source type and link, an operating mode will have a given quantity of running activity calculated by the total activity generator, and the sum of operating modes fractions for each combination of link and source type is 1.

The algorithm used to calculate the OMD can be loosely based on the MOVES project-level OMD generator, but must be executed for each vehicle trajectory. Computationally, this would be similar to executing the MOVES OMD generator with each vehicle path defined as a link. The difference is that the many individual vehicle paths are then pre-aggregated into a realistic number of links to simplify subsequent MOVES calculations. Essentially, the calculation for each vehicle would consist of a) calculating VSP (if applicable) and b) assigning the operating mode for each second to a MOVES operating mode bin. After this is complete for all vehicles, the second-to-second, individual vehicle data can be converted into a fractional distribution.

The biggest challenge of using VISSIM output to generate an OMD table would be in making sure that enough information is available for each step in the calculation process. For example, each VSP calculation requires several pieces of information including time variables (speed, etc.) link geometry, and default vehicle parameters. This would require that several MOVES default tables be available to lookup vehicle parameters and operating mode ID numbers. However, once the OpModeDistribution table is generated and input to the project-level user input database, MOVES would be executed in the typical fashion.

3. PHASE 2: MOVES-T2LCA interfacing

The T2LCA was implemented to interface with MOVES' output as depicted in Figure 1. An output array of emission is generated by moves for each simulated process of vehicle operations. A transformer model was built to map MOVES emission arrays to more detailed chemical compounds considered in the TRACI protocol. The TRACI matrix consists of factors to scale the emissions to an equivalent compounds quantifying global impacts, e.g. CO₂e for the global warming impact. Each module is described in more detail in the following sections.

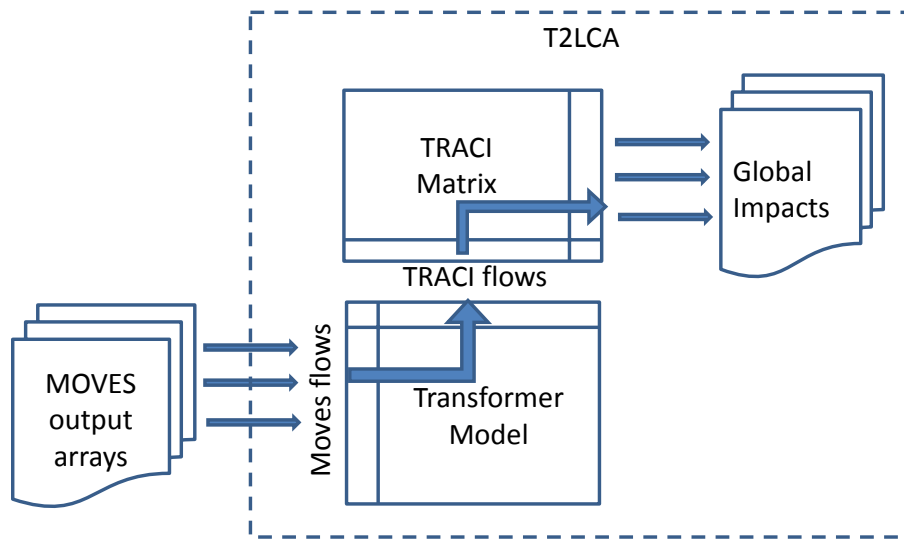


Figure 1 Framework of Traffic LCA (T2LCA)

3.1. MOVES output

Emission output from MOVES version 2010b is organized in a matrix of pollutants and processes as presented in Appendix A. Possible emission outputs marked “X” are specified before running MOVES simulation. The same matrix of all possible emissions is used as input to the T2LCA. It is worth mentioning that as illustrated in section 3.3 the T2LCA algorithm evaluates LCA impacts for any selection of pollutants and processes defined by the user. Thus the T2LCA runs as flexibly as MOVES output would be configured.

Each column in the output matrix refers to a MOVES process for which indicated emissions are simulated. According to MOVES 2010b user guide, engine operation creates Running Emissions Exhaust, Start Emissions Exhaust (the addition to running emissions caused by the engine start), and Extended Idle Emissions Exhaust (i.e., “hotelling” emissions from a combination, long-haul truck). MOVES also distinguishes Crankcase Running Exhaust, Crankcase Start Exhaust, and Crankcase Extended Idle Exhaust to describe the exhaust gases that escape around the piston rings and enter the crankcase during normal operation.

MOVES models evaporative emissions, situations in which unburned fuel escapes the vehicle's fuel system, through the Evap Fuel Vapor Venting, Evap Permeation, and Evap Fuel Leaks processes. In addition, vehicle refueling can cause Refueling Spillage Loss and Refueling

Displacement Vapor Loss. Brakewear and Tirewear describe the non-exhaust particulate emissions that result from brake use and tire wear. It's worthwhile to mention there are Process dependencies on other Processes or other conditions that apply to all pollutants that share the process association. The first three dependencies relate to the Time Spans panel, suggesting that all hours must be selected to run the process for any selected pollutant. For instance, all Evap process require all hours to be selected while configuring MOVES output.

3.2. Transformer model

A transformer model was implemented to map MOVES pollutant output to TRACI flows. Transformation stoichiometry was evaluated to convert MOVES correlated outputs into specific chemical flows considered in the TRACI protocol. LCA protocols consider independent flows of chemical compounds to allow scaling of their global impacts to indicator compounds as illustrated in section 3.3. MOVES calculates lumped emissions defined by vehicle operation standards in addition to specific compounds of ecological concern. Vehicle emissions include criteria pollutants, greenhouse gases and selected air toxics associated with motor vehicle operation in addition to energy consumption. For many pollutants, the emissions calculation is function of another pollutant emission. Thus, MOVES displays an error message if the user selects a dependent pollutant but not the base pollutant. Pollutants and base pollutants are listed in the MOVES user guide.

The implemented MOVES-TRACI transformer considers the direct assignment of specific chemical compounds and elemental heavy metal fractions of particulate matter from tire and break wear as listed in the Appendix B: MOVES-T2LCA Transformer. The transformer would also support fractionations of hydrocarbons that was not implemented in the current T2LCA version since it is subject to current research supported by EPA and planed for next MOVES versions.

3.3. TRACI protocol

TRACI was developed in context of the US EPA development of US specific LCA and sustainability metrics <http://www.epa.gov/nrmrl/std/traci/traci.html>. Based on a nationwide survey of LCA case studies the TRACI methods provide consistent quantification of emergent

global warming and ozone depletion impacts as well as site specific impacts of importance to US such as acidification, eutrophication, photochemical oxidation and human health carcinogenic and non-carcinogenic impacts. The T2LCA implemented characterization factors of these impacts are listed in Appendix C: TRACI Characterization factors. Only compounds in the air and soil compartments were considered as they could be estimated from traffic dependent air emissions and soil depositions. Applying the transformer model and TRACI characterization factors all listed impacts except ozone depletion could be estimated by T2LCA. Chloro-Floro-Carbon (CFC) compounds could be generated from coolant fluids' evaporation that is not currently simulated by MOVES.

Impacts were evaluated at mid-point level in equivalent compound units. Chemicals affecting global warming were scaled to kg CO₂-Eq based on their radiative forcing and lifetime. Acidification impact was quantified as moles H⁺ Eq based on each chemical compound potential to cause wet or dry acid deposition. Similarly, Eutrophication impact was quantified as kg N-q, eco-toxicity was quantified as kg 2,4-D-Eq, respiratory effects as PM_{2.5}-Eq, photochemical oxidation in kg NO_x-Eq and human health carcinogenics in kg benzene-Eq and non-carcinogenics in kg toluene-Eq.

3.4. T2LCA computational framework

MOVES output from each simulated process j of vehicle operation is inputted to T2LCA as an array a_i , i.e. forming the MOVES output matrix $A_{i,j}$. We developed the transformer matrix $T_{i,k}$ and the TRACI scaling matrix $S_{k,l}$ where k is the index of chemical compounds in the TRACI protocol and l is the index of the evaluated impacts. Accordingly the impacts m_l associated with each MOVES simulated vehicle operation is evaluated from the following

$$\forall j: m_l^T = (a_i^T T_{i,k}) S_{k,l} \quad \text{Equation 1}$$

This matrix operation was implemented in excel and repeated for each simulated MOVES process to give the final matrix $M_{l,j}$ of impacts.

4. Case Study

4.1. Generating MOVES Activity Tables from VISSIM Vehicle Data

This subsection describes a case study in which VISSIM vehicle profile information is used to create an operating mode distribution for MOVES input. A hypothetical stop sign controlled intersection with approach road sections is used in the example, although along with all scenario and vehicle operation parameters, the intersection geometry is essentially arbitrary. A 1-hour time span is modeled with results output in 1-second resolution. Because vehicle activity is calculated from the VISSIM data, and because all directional traffic is given the same vehicle type distribution, the intersection is modeled as a single link. The data could be easily disaggregated to allow road sections or lanes to be modeled separately, which would require that link identification be included in the VISSIM output file.

4.1.1. Scenario Description

Vehicle Types and Population

Three default vehicle types with associated operational parameters were used for this example, Passenger car, HCV, and Bus. The only relevant difference between vehicle types is in performance characteristics, as the resistance terms and emission characteristics are sourced from the MOVES default database. In many cases, custom vehicle types correlating to MOVES source types will need to be created in VISSIM. This step is avoided in this case study because only source types that correlate with VISSIM default vehicle types are included in the MOVES model. Detailed vehicle performance data is not defined for MOVES source types, so VISSIM default data is used as an alternative to seeking out and formatting vehicle manufacturer's data. The population fraction for each vehicle type is shown below. Note that the population fractions need not sum to 1, as VISSIM recalculates each one as a fraction of the sum.

- 0.85 Passenger cars (default parameters)
- 0.10 HCV (default parameters)
- 0.10 Busses (default parameters)

Vehicle populations for each direction of travel are given below. The vehicle type distribution given above is assigned to all directions of travel.

North bound: 200 vph

South bound: 200 vph

East bound: 300 vph

West bound: 400 vph

Vehicle Behavior

Vehicle routing is highly simplified for this example. The Wiedemann 74 car following model was used to describe vehicle interaction. A summary of vehicle behavior and route choice is given below.

- Four-way stop
- All vehicle types in the simulation are assigned to a desired speed of 50 km/hr, with a maximum and minimum of 58 and 48 km/hr respectively
- All north and south bound traffic turns right
- All east and west bound traffic goes straight
- All links are described as “urban motorized”

Roadway Geometry

The intersection used in this example is approximately 62 meters in each direction, with a single lane for each direction of travel. A 1% grade slopes in the south direction, so that the north and south bound lanes have a -1% and 1% grade respectively.

4.1.2. Generating the OMD Table

VISSIM can produce a report of vehicle operation information as part of the simulation run, and this report is used to generate the OpModeDistribution and SHO tables describing all running vehicle activity. To generate vehicle profile data in a VISSIM simulation model, select the vehicle profile box under Evaluation>Files, then choose configure>select parameters. In this menu box, a number of vehicle operation data points can be selected for inclusion in the output. Select and add the following:

Simulation time

Vehicle type
 Gradient
 Speed (m/s)
 Vehicle number
 Acceleration

A screenshot of the output data headings and data is given below in Figure 1. The file is exported from VISSIM rows with fields delimited by semicolons, and can be opened and converted to the spreadsheet format by selecting the “text to columns” option in the data menu.

8	t	: Simulation Time [s]				
9	Type	: Number of the Vehicle Type				
10	Grad	: Gradient [%] of the current link				
11	vMS	: Speed [m/s] at the end of the simulation step				
12	VehNr	: Number of the Vehicle				
13	a	: Acceleration [m/s ²] during the simulation step				
14						
15	Simulation time	Vehicle type	Grade	Velocity (m/s)	Vehicle number	Acceleration
16	12	100	0	14.84	1	0.29
17	13	100	0	7.56	1	-7.28
18	13	100	0	15.02	2	0.26
19	14	100	0	10.53	1	2.97

Figure 2: VISSIM vehicle data.

The desired OMD table consists of six data columns, four of which are created in the following steps. The remaining two columns are hourDayID and LinkID, and are generated as follows: HourDayID must be selected by the user, and only a single hour/day combination is allowed in MOVES at the project level. Because the intersection in this study is modeled as a single link, the linkID is also selected by the user and is the same for all rows.

Step 1: Calculate VSP for Each Second in the Vehicle Data Output

In this case study, all data processing and calculations are completed using a Microsoft Excel spreadsheet and a number of VBA macros that were coded for this purpose. This could also be accomplished with MySQL, which would save the time required to import/export files into the database software. This would, however, require more advanced programming knowledge.

There is a number of operating mode ID numbers that a vehicle may fall under at a given time, and each one is specific to particular pollutant or group of pollutants. For example, consider a vehicle driving at 50 miles per hour up a hill, for which exhaust emissions are largely a function of how much work the engine is doing to overcome the drag, rolling resistance, and vehicle weight on the grade. This vehicle will have a certain operating mode classification ID for the purpose of exhaust emissions that is based on VSP, and another ID for the purpose of brake wear emissions that depends only on speed.

In this case study, only the braking, idling, and VSP-based operating mode classifications are used because only a limited number of exhaust emissions are being modeled. The first step to generating an operating mode distribution from VISSIM output is to calculate VSP for every second in the data. To do this, the SourceUseType table was imported to the spreadsheet from the MOVES default database. A VBA function was designed to lookup vehicle characteristics in the SourceUseTable and combine them with grade, speed, and acceleration values to compute VSP as shown (Equation 1):

$$VSP = [(speed \times 0.44704) \times ((rollingTermA) + (RollingTermB) + (DragTermC))] / (SourceMass) + (speed * 0.44704) \times ((a_Speed - b_speed) \times 0.44704 + (9.81 \times \sin(\text{atan}(grade/100))))$$

Equation 2

Step 2: Assign an Operating Mode ID Number to Each Second in the Vehicle Data Output

To accomplish this step, the OperatingMode table was imported to the spreadsheet from the MOVES default database. A simple VBA subroutine was designed to lookup instantaneous speed, VSP, and, in the case of braking, acceleration in the OperatingMode table to find an operating mode ID number. For this study, braking was defined as acceleration < -1 m/s².

Step 3: Count Occurrences of all Vehicle Type/Operating Mode ID Combinations.

Even though the VISSIM output is for one hour at 1-second resolution, there are nearly 15,000 data points in the output. This is because there is a point for every vehicle in every second, and a number of vehicles may be in the intersection at a given time. For the purpose of calculating the time each vehicle type spends in each operating mode, the occurrence of a

given vehicle type/operating mode combination in the data file is equivalent to a second of time for that vehicle type in that operating mode. A simple VBA subroutine was devised to lookup the occurrence of every possible vehicle type/operating mode combination and list the results under the following three column headings: OpModeID, SourceTypeID, and count. This is shown in the spreadsheet screen shot in Figure 2.

SourceTypeID	OpModeID	Count
100	0	2237
100	1	1731
100	11	805
100	11	805
100	13	520

Figure 3: Results of Step 3.

Step 4: Calculate Operating Mode Fraction from Count Data

The operating mode fraction is calculated by dividing the count for each operating mode/source type combination (previous step) by the total count for that source type. If more than one link were present, this would be done separately for each link.

Step 5: Assign Pollutant Process IDs to Each Operating Mode ID

To accomplish this step, the OpModePolProcAssoc table was imported to the spreadsheet from the MOVES default database. This table contains a list of all pollutant process ID numbers that are associated with each operating mode ID. The calculation process is simply to lookup all pollutant process ID numbers that are associated with each operating mode, and write a new series of data columns containing SourceTypeID, PolProcessID, OpModeID, and OpModeFraction. In this study, this was accomplished with a VBA subroutine. The results of Step 5 are shown below in Figure 3. Note that HourID and LinkID will be inserted between the SourceTypeID and PolProcessID columns.

SourceTypeID	PolProcessID	OpModeID	OpModeFraction
100	-1	0	0.185
100	101	0	0.185
100	201	0	0.185
100	301	0	0.185
100	3001	0	0.185
100	9101	0	0.185

Figure 4: Results of Step 5.

4.1.3. Generate Source Hours Operating Table

MOVES calculates the source hours operating (SHO) in the project TAG from link average speed and length. This is only possible if the links are defined as physical, homogenous road sections, which is not the case in this study. This step can be skipped altogether if the links are to be defined as physical road sections in MOVES. Fortunately, the SHO table can be easily generated from the VISSIM output data. The total SHO is the total number of vehicle operating hours in the model, which is calculated as the number of data points in the VISSIM output divided by 3600. The total SHO must be allocated to source type and age, and at the project level this must be based on user input data. The source type allocation is done according to the vehicle type distribution used in the VISSIM simulation as follows:

0.85/1.05 Passenger cars

0.10/1.05 Busses

0.10/1.05 HCV

The age distribution for each source type is required user input data at the project level. The calculation for each source type is performed by multiplying the SHO fraction that source type by each age fraction in the SourceTypeAgeDistribution table. The results are then written to AgeID, SourceTypeID, and SHO columns in the SHO table. The remaining yearID, monthID, and hourID columns in the SHO table are user defined and are unchanged for all rows at the project level. A VBA subroutine was used in this example to populate the SHO table.

4.1.4. Create MOVES Project-Level Model

The final step in this case study is to create a project-level model in MOVES and input the tables generated from VISSIM data. The OpModeDistribution table is input through the required user input database, in the form of a CSV file. Note that if the SHO and OpModeDistribution tables are input directly, the link average speed information is not used. An off-network link was not included in this model, but this would be required if start and extended idle processes were to be computed. At the project level, a separate OpModeDistribution table must be entered for the off-network link containing all idle and start activity. VISSIM could be used to generate this table as well, but would require a separate (but similar to the one used in this case study) process to convert VISSIM output to MOVES input.

The SHO table is not input through the user input database, instead it must be entered in the “Manage input data sets” tab in MOVES. To do this, a blank database is created and named in the Selections box under the Manage input data sets tab. Next, the SHO table must be added to this blank database. If the SHO table is created in a spreadsheet program, it must be imported as a database table in MySQL. For this study, HeidiSQL browser software was used to import the spreadsheet file to MySQL. Note that the table must be named SHO so that MOVES identifies and uses the contents instead of running the TAG. In addition, all unused tables in the blank database should be removed to insure that MOVES does not import blank or incorrect tables. Other than the two tables described in this study, the MOVES run is set up and executed as normal. Some care may be required to insure that the date/time and scenario information entered in the Runspec is consistent with the user input tables.

4.1.5. Summary of Case Study

This case study described a method that may be used to calculate and input MOVES vehicle activity information from VISSIM output data. The basic steps are given below:

Outline of steps

- 1) Set up VISSIM simulation of case scenario, specify desired vehicle profile data
- 2) Create or select vehicle types corresponding to desired MOVES source use types
- 3) Execute VISSIM traffic simulation

- 4) Calculate VSP for every entry in the output file
- 5) Create operating mode distribution table
- 6) Calculate SHO table from data output file and user defined age distribution
- 7) Input SHO and OpModeDistribution tables to MOVES
- 8) Run MOVES as normal, taking special care to insure continuity between VISSIM and MOVES input

4.2. Evaluating MOVES output using T2LCA

The integrated T2LCA framework was then tested by repeating the above VISSIM-MOVES steps for two scenarios simulating a traffic area in small-to-mid sized city (Moscow-Idaho). Global impacts of the optimized traffic were compared with current (base condition) traffic to evaluate the environmental cost savings associated with traffic improvements. Moves output is presented in Table 1. The MOVES simulations were run for fewer processes and pollutants than the template output to test if T2LCA would still capture the impact difference between the base and the optimized scenarios.

The generated moves output was used as input to the T2LCA and the estimated impacts of each scenario are listed in Table 2. Environmental savings of optimized traffic was 7% for global warming acidification, respiratory effects, eutrophication and photochemical oxidation impacts. Savings in toxicity was 3% for carcinogenic, non-carcinogenic and ecological impacts that were mainly contributed by brake wear. Fractionation of the PM of the brake wear was important to estimate toxicity impacts in addition to the direct impact to the human health respiratory effects.

In general the implemented T2LCA framework captured the environmental savings analyzing few outputs compared to the complete MOVES output template. The results could be further refined utilizing full simulated output from MOVES. Future work should consider more fractionation of hydrocarbons to cope with next MOVES upgrades and quantify their associated toxicity impacts.

Future software implementation would optimally integrate the T2LCA algorithm with VISSIM and MOVES instead of the soft linking through input-output data.

Table 1: MOVES output for case study scenarios

Pollution \ Operation	Running Exhaust	Start Exhaust	Brake wear	Extended Idle Exhaust	Total
<u>Base Condition Scenario</u>					
Volatile Organic Compounds	6.28	12.56		1.30	20.14
Carbon Monoxide (CO)	340.64	164.20		3.06	507.90
Oxides of Nitrogen (NOx)	18.26	3.98		1.57	23.81
Nitrogen Oxide (NO)	56.90	14.09		4.04	75.03
Nitrogen Dioxide (NO2)	13.41	0.95		2.14	16.51
Sulfur Dioxide (SO2)	1.08				1.08
Primary PM10 - Organic Carbon - Total	9.24				9.24
Primary PM10 - Elemental Carbon	0.72				0.72
Primary PM10 - Sulfate Particulate	0.006				0.006
Primary PM10 - Brakewear Particulate			0.72		0.72
Primary PM2.5 - Organic Carbon	9.24				9.24
Primary PM2.5 - Elemental Carbon	0.72				0.72
Primary PM2.5- Sulfate Particulate	0.006				0.006
Primary PM2.5- Brakewear Particulate			0.72		0.72
<u>Optimized Scenario</u>					
Volatile Organic Compounds	6.03	12.56		1.30	18.36
Carbon Monoxide (CO)	316.79	164.20		3.06	470.74
Oxides of Nitrogen (NOx)	17.16	3.98		1.57	22.05
Nitrogen Oxide (NO)	52.92	14.09		4.04	69.67
Nitrogen Dioxide (NO2)	12.60	0.95		2.14	15.42
Sulfur Dioxide (SO2)	1.03				1.03
Primary PM10 - Organic Carbon - Total	8.99				8.99
Primary PM10 - Elemental Carbon	0.70				0.70
Primary PM10 - Sulfate Particulate	0.71				0.71
Primary PM10 - Brakewear Particulate			0.70		0.70
Primary PM2.5 - Organic Carbon	8.99				8.99
Primary PM2.5 - Elemental Carbon	0.70				0.70
Primary PM2.5- Sulfate Particulate	0.71				0.71
Primary PM2.5- Brakewear Particulate			0.70		0.70

Table 2: Case study impacts and environmental savings of optimized traffic

Impacts	Base Condition					Optimized scenario					Environmental savings of optimized traffic
	Running Exhaust	Start Exhaust	Brake wear	Extended Idle Exhaust	Total	Running Exhaust	Start Exhaust	Brake wear	Extended Idle Exhaust	Total	
TRACI human health carcinogenics US kg benzene-Eq			0.78		0.78			0.76		0.76	3%
TRACI environmental impact global warming GLO kg CO2-Eq	534.80	257.80		4.80	797.40	497.37	237.18		4.52	739.06	7%
TRACI environmental impact acidification US moles of H+-Eq	785.81	159.40		62.91	1008.13	739.42	141.87		53.88	935.16	7%
TRACI human health respiratory effects, average US kg PM2.5-Eq	1.10	0.18		0.07	1.35	1.04	0.16		0.06	1.26	7%
TRACI human health non-carcinogenics US kg toluene-Eq			10723.27		10723.27			10425.41		10425.41	3%
TRACI environmental impact eutrophication US kg N	0.81	0.18		0.07	1.05	0.76	0.16		0.06	0.98	7%
TRACI environmental impact photochemical oxidation US kg NOx-Eq	22.37	5.29		1.52	29.19	20.98	4.78		1.30	27.06	7%
TRACI environmental impact ecotoxicity US kg 2,4-D-Eq			847.95		847.95			824.40		824.40	3%

Appendix A: MOVES output and T2LCA input template

Polution x_i	Running Exhaust	Start Exhaust	Brakewear	Tirewear	Evap Permeation	Evap Fuel Vapor Venting	Evap Fuel Leaks	Crankcase Running Exhaust	Crankcase Start Exhaust	Crankcase Extended Idle Exhaust	Refueling Displacement Vapor Loss	Refueling Spillage Loss	Extended Idle Exhaust
Total Gaseous Hydrocarbons	X	X			X	X	X	X	X	X	X	X	X
Non-Methane Hydrocarbons	X	X			X	X	X	X	X	X	X	X	X
Non-Methane Organic Gases	X	X			X	X	X	X	X	X	X	X	X
Total Organic Gases	X	X			X	X	X	X	X	X	X	X	X
Volatile Organic Compounds	X	X			X	X	X	X	X	X	X	X	X
Carbon Monoxide (CO)	X	X						X	X	X			X
Oxides of Nitrogen (NOx)	X	X						X	X	X			X
Ammonia (NH3)	X	X						X	X	X			X
Nitrogen Oxide (NO)	X	X						X	X	X			X
Nitrogen Dioxide (NO2)	X	X						X	X	X			X
Nitrous Acid (HONO)	X	X						X	X	X			X
Sulfur Dioxide (SO2)	X	X						X	X	X			X
Primary Exhaust PM10	X	X						X	X	X			X
Primary PM10 - Organic Carbon - Total	X	X						X	X	X			X
Primary PM10 - Elemental Carbon	X	X						X	X	X			X
Primary PM10 - Sulfate Particulate	X	X						X	X	X			X
Primary PM10 - Brakewear Particulate			X										

Appendix A: MOVES output and T2LCA input template (continued)

Polution x_i	Running Exhaust	Start Exhaust	Brakewear	Tirewear	Evap Permeation	Evap Fuel Vapor Venting	Evap Fuel Leaks	Crankcase Running Exhaust	Crankcase Start Exhaust	Crankcase Extended Idle Exhaust	Refueling Displacement Vapor Loss	Refueling Spillage Loss	Extended Idle Exhaust
Primary PM10 - Tirewear Particulate				X									
Primary Exhaust PM2.5 - Total	X	X						X	X	X			X
Primary PM2.5 - Organic Carbon	X	X						X	X	X			X
Primary PM2.5 - Elemental Carbon	X	X						X	X	X			X
Primary PM2.5- Sulfate Particulate	X	X						X	X	X			X
Primary PM2.5- Brakewear Particulate			X										
Primary PM2.5 - Tirewear Particulate				X									
Total Energy Consumption	X	X											X
Petroleum Energy Consumption	X	X											X
Fossil Fuel Energy Consumption	X	X											X
Brake Specific Fuel Consumption (BSFC)	X												
Methane (CH4)	X	X						X	X	X	X	X	X
Nitrous Oxide (N2O)	X	X						X	X				
Atmospheric CO2	X	X											X
CO2 Equivalent	X	X											X
Benzene	X	X			X	X	X	X	X	X	X	X	X
Ethanol	X	X			X	X	X	X	X		X	X	

Appendix A: MOVES output and T2LCA input template (continued)

Polution x_i	Running Exhaust	Start Exhaust	Brakewear	Tirewear	Evap Permeation	Evap Fuel Vapor Venting	Evap Fuel Leaks	Crankcase Running Exhaust	Crankcase Start Exhaust	Crankcase Extended Idle Exhaust	Refueling Displacement Vapor Loss	Refueling Spillage Loss	Extended Idle Exhaust
MTBE	X	X			X	X	X	X	X		X	X	
Naphthalene particle	X	X						X	X	X			X
1,3-Butadiene	X	X						X	X	X			X
Formaldehyde	X	X						X	X	X			X
Acetaldehyde	X	X						X	X	X			X
Acrolein	X	X						X	X	X			X
Naphthalene gas	X	X			X	X	X	X	X	X	X	X	X

Appendix B: MOVES-T2LCA Transformer

MOVES Output	TRACI	Acenaphthene	Acetaldehyde	Acrolein	Aluminium	Ammonia	Antimony	Arsenic	Barium	Benzene	Benzo(a)pyrene	Beryllium	Butadiene	Cadmium	Carbon dioxide, fossil	Carbon monoxide, fossil	Chromium
Non-Methane Organic Gases																	
Volatile Organic Compounds																	
Carbon Monoxide (CO)																1	
Oxides of Nitrogen (NOx)																	
Ammonia (NH3)						1											
Sulfur Dioxide (SO2)																	
Primary PM10 - Brakewear Particulate																	
Primary PM10 - Tirewear Particulate																	
Primary Exhaust PM2.5 - Total																	
Primary PM2.5- Brakewear Particulate					0.0021			7E-05	0.0385					2.24E-05			0.0023
Primary PM2.5 - Tirewear Particulate					0.0003		2E-06	4E-06	0.0001					4.7E-06			2E-05
Methane (CH4)																	
Nitrous Oxide (N2O)																	
Atmospheric CO2															1		
Benzene										1							
Ethanol																	
MTBE																	
Naphthalene particle	1																
1,3-Butadiene													1				
Formaldehyde																	
Acetaldehyde			1														
Acrolein				1													
Naphthalene gas											1						

Appendix B: MOVES-T2LCA Transformer (continued)

MOVES Output	TRACI	Chromium VI	Cobalt	Copper	Dinitrogen monoxid	Ethane	Ethanol	Formaldehyde	Lead	Manganese	Methane, fossil	Methyl ethyl ketone	Molybdenum	Nickel	Nitrogen oxides	Particulates, < 2.5 u	Selenium
Non-Methane Organic Gases						1											
Volatile Organic Compounds						-1											
Carbon Monoxide (CO)																	
Oxides of Nitrogen (NOx)															1		
Ammonia (NH3)																	
Sulfur Dioxide (SO2)																	
Primary PM10 - Brakewear Particulate																	
Primary PM10 - Tirewear Particulate																	
Primary Exhaust PM2.5 - Total																1	
Primary PM2.5- Brakewear Particulate	5E-06	6E-06	0.0511						0.0061	0.0025				0.0003			
Primary PM2.5 - Tirewear Particulate	5E-08	1E-05	0.0002						0.0002	5E-05			3E-06	3E-05			2E-05
Methane (CH4)											1						
Nitrous Oxide (N2O)					1												
Atmospheric CO2																	
Benzene																	
Ethanol							1										
MTBE												1					
Naphthalene particle																	
1,3-Butadiene																	
Formaldehyde								1									
Acetaldehyde																	
Acrolein																	
Naphthalene gas																	

Appendix B: MOVES-T2LCA Transformer (continued)

MOVES Output	TRACI	Silver	Sulfur dioxide	Thallium	Tin	Vanadium	Zinc	Arsenic	Cadmium	Chromium	Chromium VI	Lead	Nickel	Zinc	Vanadium
Non-Methane Organic Gases															
Volatile Organic Compounds															
Carbon Monoxide (CO)															
Oxides of Nitrogen (NOx)															
Ammonia (NH3)															
Sulfur Dioxide (SO2)			1												
Primary PM10 - Brakewear Particulate								7E-05	2E-05	0.0023	5E-06	0.0061	0.0003	0.0087	
Primary PM10 - Tirewear Particulate								4E-06	5E-06	2E-05	5E-08	0.0002	3E-05	0.0074	1E-06
Primary Exhaust PM2.5 - Total															
Primary PM2.5- Brakewear Particulate							0.0087	-7E-05	-2E-05	-0.002	-5E-06	-0.006	-3E-04	-0.009	
Primary PM2.5 - Tirewear Particulate		1E-07		4E-04	0.007	1E-06	0.0074	-4E-06	-5E-06	-2E-05	-5E-08	-2E-04	-3E-05	-0.007	-1E-06
Methane (CH4)															
Nitrous Oxide (N2O)															
Atmospheric CO2															
Benzene															
Ethanol															
MTBE															
Naphthalene particle															
1,3-Butadiene															
Formaldehyde															
Acetaldehyde															
Acrolein															
Naphthalene gas															

Appendix B: MOVES-T2LCA Transformer (continued)

MOVES Output	TRACI	Tin	Thallium	Silver	Selenium	Molybdenum	Manganese	Copper	Cobalt	Barium	Antimony	Aluminium
Non-Methane Organic Gases												
Volatile Organic Compounds												
Carbon Monoxide (CO)												
Oxides of Nitrogen (NOx)												
Ammonia (NH3)												
Sulfur Dioxide (SO2)												
Primary PM10 - Brakewear Particulate							0.0025	0.0511	6E-06	0.0385		0.0021
Primary PM10 - Tirewear Particulate	0.007	0.0004	1E-07	2E-05	3E-06	5E-05	0.0002	1E-05	0.0001	2E-06	0.0003	
Primary Exhaust PM2.5 - Total												
Primary PM2.5- Brakewear Particulate							-0.0025	-0.0511	-6E-06	-0.0385		-0.0021
Primary PM2.5 - Tirewear Particulate	-0.007	-4E-04	-1E-07	-2E-05	-3E-06	-5E-05	-0.0002	-1E-05	-0.0001	-2E-06	-0.0003	
Methane (CH4)												
Nitrous Oxide (N2O)												
Atmospheric CO2												
Benzene												
Ethanol												
MTBE												
Naphthalene particle												
1,3-Butadiene												
Formaldehyde												
Acetaldehyde												
Acrolein												
Naphthalene gas												

Appendix C: TRACI Characterization factors

Pollutant	Unit	human health carcinogenics	global warming	acidification	respiratory effects	non-carcinogenics	eutrophication	photochemical oxidation	ecotoxicity
		kg benzene-Eq	kg CO ₂ -Eq	moles H ⁺ -Eq	kg PM _{2.5} -Eq	kg toluene-Eq	kg N	kg NO _x -Eq	kg 2,4-D-Eq
1-Pentanol	kg							0.6796	
1-Pentene	kg							1.6226	
2-Methyl pentane	kg							0.46306	
2-Methyl-1-propanol	kg					0.34752		0.49137	
2-Methyl-2-butene	kg							3.3992	
2-Propanol	kg					0.012034		0.16121	
4-Methyl-2-pentanone	kg					0.7926		0.93065	
Acenaphthene	kg					0.17559			0.10248
Acetaldehyde	kg	0.0043726				4.2491		1.4444	0.00344
Acetic acid	kg							0.13347	
Acetone	kg					0.086045		0.095806	0.013217
Acetonitrile	kg					50.54			
Acrolein	kg					2366		1.6073	7.1214
Acrylic acid	kg					31.372			
Aluminium	kg					11174			7029.6
Ammonia	kg			95.485		3.2061	0.1186		0.073798
Aniline	kg	0.0029101				37.6			
Antimony	kg					2801500			
Arsenic	kg	8496.7				469380			208.59
Barium	kg					18046			
Benzaldehyde	kg								
Benzene	kg	1				14.6		0.19863	0.006342
Benzene, dichloro	kg					12.375			0.15335
Benzene, ethyl-	kg							0.59032	0.003377
Benzene, hexachloro-	kg	82.712				1035.2			273.23
Benzene, pentachloro-	kg					1346.3			78.458
Benzo(a)pyrene	kg	914.27							0.068765
Beryllium	kg	11.642				167540			

Appendix C: TRACI Characterization factors (continued)

Pollutant	unit	human health carcinogenics	global warming	acidification	respiratory effects	non-carcinogenics	eutrophication	photochemical oxidation	ecotoxicity
		kg benzene-Eq	kg CO ₂ -Eq	moles H ⁺ Eq	kg PM _{2.5} -Eq	kg toluene-Eq	kg N	kg NO _x -Eq	kg 2,4-D-Eq
Butadiene	kg	0.4143				1.3289		2.6008	
Butane	kg							0.28573	
Butanol	kg					0.91055		0.70056	
Butene	kg							1.7524	
Cadmium	kg	24.983				387350			6.2632
Carbon dioxide, fossil	kg		1						
Carbon disulfide	kg					188.08			
Carbon monoxide, biogenic	kg							0.013387	
Carbon monoxide, fossil	kg		1.57					0.013387	
Chloroacetic acid	kg					3886.8			
Chloroform	kg	0.81288	30			12.457			0.039801
Chromium	kg	69.887				57677			1048.8
Chromium VI	kg	69.887				57677			1048.8
Cobalt	kg					29043			
Copper	kg					13215			21664
Cumene	kg					0.33011		0.49331	
Cyanide	kg					1374.2			
Cyclohexane	kg					0.030424		0.39032	
Diethyl ether	kg					0.18186		0.8371	
Diethylene glycol	kg							0.89677	
Dimethylamine	kg					19.086		2.4315	
Dinitrogen monoxide	kg		300						
Dioxins, measured as 2,3,7,8-	kg	312960000				3.46E+11			8052.5
Epichlorohydrin	kg	1.2032				1292.2			
Ethane	kg							0.0705	
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	kg		1410						
Ethane, 1,1,1-trichloro-, HCFC-140	kg		144			0.40742			0.006382
Ethane, 1,1,1-trifluoro-, HFC-143a	kg		4400						

Appendix C: TRACI Characterization factors (continued)

Pollutant	unit	human health carcinogenics	global warming	acidification	respiratory effects	non-carcinogenics	eutrophication	photochemical oxidation	ecotoxicity
		kg benzene-Eq	kg CO ₂ -Eq	moles H ⁺ Eq	kg PM2.5-Eq	kg toluene-Eq	kg N	kg NOx-Eq	kg 2,4-D-Eq
Ethane, 1,1,2-trichloro-	kg	1.8321				203.92			0.15067
Ethane, 1,1-difluoro-, HFC-152a	kg		122						
Ethane, 1,2-dichloro-	kg	2.2929				7.1686			0.045979
Ethane, 1-chloro-1,1-difluoro-, HCFC-142b	kg		2270			0.08452			0.000112
Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-	kg		76						
Ethane, chloropentafluoro-, CFC	kg		7250						
Ethane, hexafluoro-, HFC-116	kg		12010						
Ethane, pentafluoro-, HFC-125	kg		3450						
Ethanol	kg							0.38121	
Ethene	kg							1.9815	
Ethene, chloro-	kg	1.6263				105.13			0.00107
Ethene, tetrachloro-	kg	0.71816				74.864		0.023056	0.019362
Ethene, trichloro-	kg	0.06389				0.92998		0.0002048	0.001073
Ethyl acetate	kg					0.12179		0.15895	0.002569
Ethylamine	kg							2.5298	
Ethylene glycol monoethyl ether	kg					0.30377		0.82016	
Ethylene oxide	kg	11.024				618.52		0.017274	
Ethyne	kg							0.24492	
Formaldehyde	kg	0.0036507				5.0661		1.8121	0.050496
Formic acid	kg					0.0668		0.035927	
Furan	kg					36.349		2.8516	
Heptane	kg							0.28492	
Hexane	kg					0.63611		0.3354	1.31E-06
Hydrogen chloride	kg			44.695		0.2102			3.1853
Hydrogen fluoride	kg			81.264					
Hydrogen sulfide	kg					0.048283			
Isoprene	kg							2.2806	
Lead	kg	58.235				2173700			1.4359

Appendix C: TRACI Characterization factors (continued)

Pollutant	unit	human health carcinogenics	global warming	acidification	respiratory effects	non-carcinogenics	eutrophication	photochemical oxidation	ecotoxicity
		kg benzene-Eq	kg CO ₂ -Eq	moles H ⁺ Eq	kg PM _{2.5} -Eq	kg toluene-Eq	kg N	kg NO _x -Eq	kg 2,4-D-Eq
Manganese	kg					6092.7			
Mercury	kg					99912			16.311
Methane, biogenic	kg		23					0.0029637	
Methane, bromo-, Halon 1001	kg		5			1169.5		0.004804	0.83491
Methane, bromochlorodifluoro-,	kg		1860						
Methane, bromotrifluoro-, Halon	kg		7030						
Methane, chlorodifluoro-, HCFC-	kg		1780			0.22364			3.18E-05
Methane, chloro-fluoro-, HCFC-31	kg								
Methane, chlorotrifluoro-, CFC-13	kg		14190						
Methane, dichloro-, HCC-30	kg	0.14229	10			1.1268		0.019169	0.013865
Methane, dichlorodifluoro-, CFC-	kg		10720			3.8023			0.001513
Methane, dichlorofluoro-, HCFC-	kg		148						
Methane, difluoro-, HFC-32	kg		670						
Methane, fossil	kg		23					0.0029637	
Methane, monochloro-, R-40	kg	0.29324	16			39.416			0.005126
Methane, tetrachloro-, R-10	kg	7.4292	1380			1766.8			0.011798
Methane, tetrafluoro-, R-14	kg		5820						
Methane, trichlorofluoro-, CFC-11	kg		4680			0.21755			0.006552
Methane, trifluoro-, HFC-23	kg		14310						
Methanol	kg					0.073602		0.19726	0.019196
Methyl acetate	kg					0.1092		0.023371	
Methyl acrylate	kg					0.35723			
Methyl ethyl ketone	kg					0.9396			0.009567
Methyl formate	kg							0.027524	
Methyl lactate	kg							0.55919	
Molybdenum	kg					36550			
Monochloroethane	kg					0.14806			
m-Xylene	kg					0.18083		2.1976	0.000999

Appendix C: TRACI Characterization factors (continued)

Pollutant	unit	human health carcinogenics	global warming	acidification	respiratory effects	non-carcinogenics	eutrophication	photochemical oxidation	ecotoxicity
		kg benzene-Eq	kg CO ₂ -Eq	moles H ⁺ Eq	kg PM _{2.5} -Eq	kg toluene-Eq	kg N	kg NO _x -Eq	kg 2,4-D-Eq
Nickel	kg	1.5113				71919			7835.6
Nitrobenzene	kg					230.71		0.029202	
Nitrogen fluoride	kg		10970						
Nitrogen oxides	kg			40.04	0.045849		0.04429	1	
o-Nitrotoluene	kg					3.61			
o-Xylene	kg					0.30427		1.5565	0.001764
Particulates, < 2.5 um	kg				1				
Pentane	kg							0.34661	
Phenol	kg					0.049853		0.73782	0.054392
Phenol, 2,4-dichloro	kg					24.208			
Phenol, pentachloro-	kg	4.7399				218.45			2.5177
Phosphorus	kg						1.12		
Propane	kg							0.12806	
Propanol	kg							0.59089	
Propene	kg					0.007731		2.4734	2.93E-06
Propionic acid	kg							0.27282	
Propylene oxide	kg	0.31637				0.6255		0.083871	
Selenium	kg					71282			1527.7
Silver	kg					39323			8487.4
Styrene	kg					0.031349		0.49984	0.001579
Sulfur dioxide	kg			50.79	0.24111				
Sulfur hexafluoride	kg		22450						
t-Butyl methyl ether	kg					0.092467		0.26645	0.002936
Thallium	kg					1920700			499.69
Tin	kg					208.44			
Toluene	kg					1		0.83226	0.002502
Trimethylamine	kg							2.9048	
Vanadium	kg					136860			

Appendix C: TRACI Characterization factors (continued)

Pollutant	unit	human health carcinogenics	global warming	acidification	respiratory effects	non-carcinogenics	eutrophication	photochemical oxidation	ecotoxicity
		kg benzene-Eq	kg CO ₂ -Eq	moles H ⁺ Eq	kg PM _{2.5} -Eq	kg toluene-Eq	kg N	kg NO _x -Eq	kg 2,4-D-Eq
Xylene	kg					0.024636			0.001606
Zinc	kg					10247			5878.8
Arsenic	kg	8885.2				496830			39.085
Beryllium	kg	0.025079				180870			
Cadmium	kg	0.093607				308520			0.78792
Chromium	kg	0.19166				61761			255.81
Chromium VI	kg	0.19166				61761			255.81
Lead	kg	45.874				1731300			0.18063
Nickel	kg	0.0010251				78372			2322.3
Zinc	kg					11123			1736
Vanadium	kg					149020			
Tin	kg					217.8			
Thallium	kg					2026900			90.824
Silver	kg					42043			1912.2
Selenium	kg					76223			380.56
Molybdenum	kg					38883			
Mercury	kg					123560			5.6267
Manganese	kg					6673.5			
Copper	kg					13958			5881
Cobalt	kg					29.296			
Barium	kg					19672			
Antimony	kg					3052900			
Aluminium	kg					8574.2			2155.1