A dynamic framework for the monitoring and assessment of the urban transportation modes performance

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ABSTRACT

Growing interest in the environmental performance of transportation sector within the last years, burgeon the need of incorporating sustainability into transportation planning. Although there are multiple view points for assessing modes of transportation, a long-term sustainability-based comprehensive framework for the assessment of the impacts of any urban transportation mode does not exist. Our research efforts attempt to close this void in the state of the art starting with a framework that has its foundations in the over-arching principle of sustainability.

The proposed sustainability framework acts as a filter that decomposes the elements of a transportation mode to reveal its sustainability dimensions. The sustainability filter is composed of four layers (environment, technology, energy, and economy), and three controllers (users, legal framework, and local restrictions). The fundamental attributes of vehicle and infrastructure: manufacture of vehicles, construction of infrastructure, and energy (fuels and power), operation and maintenance for both vehicles and infrastructure are decomposed through the Sustainability Decomposition Prism into their sustainability categories.

A complete methodology for developing the sustainability categories required, to assess any urban transportation mode, and quantifying energy and emission indicators, is presented. Sample results of emissions and energy requirements for three types of vehicles follow as a case study. The results include well-to-wheel emissions and energy requirements for the manufacture, maintenance, fueling and vehicle operation stages for three different types of vehicles: a conventional gasoline vehicle, a hybrid electric vehicle and a pickup truck. The proposed framework has a dynamic character that is able to assess any urban transportation mode at global, regional and local level and provide a comprehensive understanding of a transportation system.

Keywords: sustainable transport, urban modes, sustainability framework.

INTRODUCTION

Growing interest in the environmental performance of transportation sector within the last years, burgeon the need of incorporating sustainability into transportation planning. Sustainability has a multidisciplinary character, whereas traditional approaches to tackle transportation issues used a single predetermined methodology.

In this approach, traditional transportation mode evaluations are based on demand and supply comparisons, costs, and benefit evaluations, financial risks analysis, and cost-effectiveness analysis. Recent assessments begin to focus on detailed energy requirements and pollution emissions. Other applications attempt to internalize the cost of accidents. In short, there are multiple view points for assessing modes of transportation due to their important and pervasive impacts to society and economy, both positive and negative. However, a long-term sustainability-based comprehensive framework with a dynamic character for the monitoring and the assessment of the impacts of any urban transportation mode does not exist. Our research efforts attempt to close this void in the state of the art starting with a framework that has its foundations in the over-arching principle of sustainability.

Currently, attempts at incorporating sustainability into transportation planning have resulted in research, mainly by universities and institutes, on the development of variables defined as measures, indicators or indices representing elements of sustainability (Nichols et al.2009; Black et al.2006; Litman 2009; Maoh and Karanoglou 2009; Jeon et al. 2008; CTS 2002; Zietsman et al. 2003). Transport sustainability indicators have been developed that measure transportation impacts mostly on mobility, safety and environmental effects; but major components of sustainable transportation are omitted in this approach, such as infrastructure, manufacture and maintenance (Maoh and Karanoglou 2009; Jeon et al. 2008; CTS 2002; Zietsman et al. 2003). In addition, existing studies consider only personal vehicles or all modes present on a section of a corridor using aggregate measures, such as average speed (to measure the ability to overcome long distances, which is a dimension of mobility) (Jeon et al. 2008), total vehicle emissions (to measure air pollution) (Jeon et al. 2008; CTS 2002) and total fatalities (to measure safety) (CTS 2002). Detailed breakdowns by mode are necessary for the proper understanding of performance and impacts which in turn lead to accurate planning, policy and technological solutions.

This paper reviews briefly definitions of sustainable development and transportation and proposes a dynamic sustainability framework that is capable of assessing any urban transportation mode in detail and covering the whole sustainability spectrum of any transportation mode. A complete methodology for developing the sustainability categories required to assess any urban transportation mode and quantifying energy and emission indicators follows. The proposed sustainability framework acts as a filter (in the form of an “optical prism”) that decomposes the elements of a transportation mode to reveal its sustainability dimensions. The sustainability filter is composed of four layers (environment, technology, energy, and economy), and three controllers (users, legal framework, and local restrictions).

Utilization of different methodologies for the quantification of the proposed criteria and indicators is necessary due to the multidisciplinary nature of sustainability. Life cycle assessment methodology is used as a first step to estimate energy requirements and emissions associated with the manufacture-maintenance, fueling and operation activities of three different types of vehicles, a conventional gasoline vehicle (CGV), a hybrid electric vehicle (HEV) and a pickup truck.

The sample results of the three vehicles together with the application of the proposed framework to appraise urban transportation modes are discussed, with additional suggestions for further research and practice.

SUSTAINABLE DEVELOPMENT AND TRANSPORTATION DEFINITIONS

Sustainability is a term of high interest and has been used widely, especially within the last few years. It can be applied to any system, to describe the maintenance of a balance within the system. Initially, it was used to depict concerns mostly associated with environmental issues, and grew to include energy economy and social issues. The energy aspects are of major interest to the analysis of transportation modes because they require considerable energy to be built (both vehicle and infrastructure) and then to be operated, maintained, refurbished and eventually divested, whereas throughout these procedures the amount of emissions produced is also considerable.

Different points of view and desired objectives and goals pursued by every community (e.g. region, nation, group of states or nations, world) require adjustments in sustainability definitions and approaches. There are literally dozens definitions of sustainability and sustainable development; the most well know definition of sustainable development was given in 1987 by The World Commission on Environment and Development (WCED) and defined sustainable development as (WCED 1987):

"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:

- the concept of needs, in particular the essential needs of the world's poor, to which overriding priority should be given
- the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs."

Sustainability has been used extensively in development and transportation due to the environmental, social and economic impacts that these sectors have on communities. A sample definition of sustainable transportation that includes most of the environmental, social and economic concerns is provided by The European Council of Ministers of Transport (ECMT, 2001). It defines a sustainable transportation system as one that:

- Allows the basic access needs of individuals and societies to be met safely and in a manner consistent with human and ecosystem health, and with equity within and between generations.
- Is affordable, operates efficiently, offers choice of transport mode, and supports a vibrant economy.
- Limits emissions and waste within the planet's ability to absorb them, minimizes consumption of non-renewable resources, limits consumption of renewable resources to the sustainable yield level, reuses and recycles its components, and minimizes the use of land and the production of noise.

Several governmental and regional agencies have applied sustainability to their transportation programs. Jeon and Amekudzi (2005) studied sustainability initiatives in North America, Europe and Oceania and reported that there is not a standard definition of transportation system sustainability, however, the majority of these studies share common transportation system objectives such as the mobility of people and goods, accessibility and safety within environmental limits.

Research has been conducted the last years by universities and institutes on how a transportation system can embrace sustainability and how it can move towards sustainability. The Center for Sustainable Transportation (CTS 2002) used indicators to study whether the transportation sector improves in respect to its adverse impacts on environment and health. In addition, indicators were developed to assess the impact of transportation on environment, economy and society (Maoh and Karanoglou 2009; Zietsman et al. 2003) whereas another study added a fourth sustainability dimension, system effectiveness (Jeon et al. 2008). Attention has focused on urban development and transportation as a result of increased environmental, economic and social problems, which are linked with urban transportation.

An urban transportation system is composed of different modes which are designed to serve travel demand. Each mode has different characteristics which affect the transportation system. These characteristics range from energy required to manufacture, fuel, operate and maintain them and emissions emitted during these stages, to the safety, mobility and accessibility offered to the traveler.

LIFE CYCLE ASSESSMENT IN TRASNPROTATION

Urban transportation mode characteristics that are associated with energy requirements and emissions generation can be studied throughout the mode’s lifetime. A complete energy and emissions analysis for all life stages of a mode will promote complete assessments rather than operation based assessments. To perform such an analysis for different products the Life Cycle Assessment (LCA) methodology has been used by governmental agencies, private companies and so on.

LCA is a methodology first used in 1960s in U.S by Harold Smith to estimate energy requirements for the production of chemical products (Ciabrone 1997). Later LCA was used by Coca Cola Company to compare the environmental effect of different containers. Since then, LCA has been used in many different fields such as agriculture, water technologies, construction, domestic product production, energy production, transportation and so on, mainly to estimate energy requirements and emissions generation of one or more products. As environmental concerns rapidly increase, environmental performance of technology has become an important issue in its development, operation, maintenance and disposal. LCA has defined as a “cradle-to-grave” approach for assessing industrial systems. The term “life cycle” refers to the most energy and emissions intense activities in the product’s lifetime from its manufacture, use, and maintenance, to its final disposal or recycling. “Cradle-to-grave” includes the extraction and collection of raw materials from the earth to create the product and ends when all materials are returned back to the earth (EPA 2006).

Different LCA methods, such as the cradle to grave, cradle to gate, cradle to cradle, well to wheel, life cycle cost analysis (LCCA) and the economic input-output life cycle assessment (EIOLCA), have been developed to enhance product analysis based on the requirements. Typical inputs, outputs and life cycle stages that are considered in the LCA are shown in Figure 1.

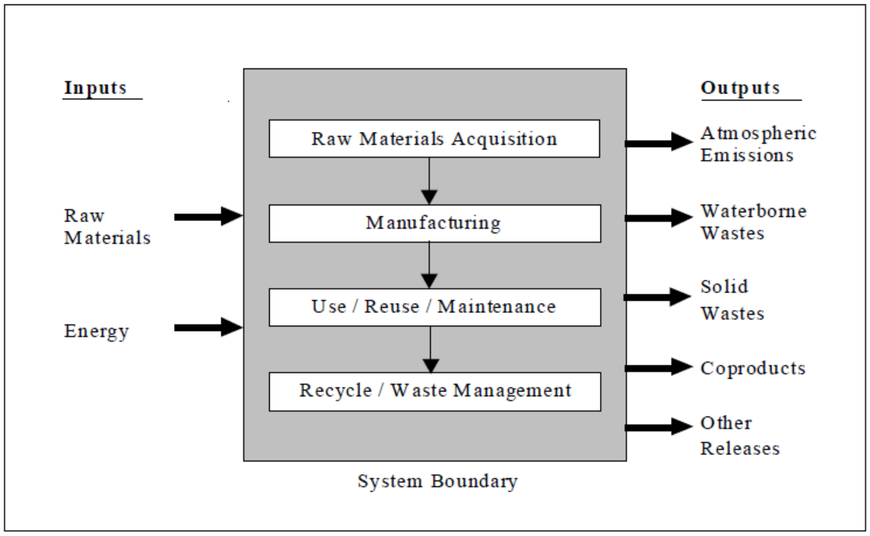

Figure 1.Life Cycle Stages (EPA 1993)

LCA has become a promising tool in the analysis of transportation components due to the detailed energy and emissions inventories that it can generate. It can be implemented in sustainability assessment as it can provide measures to assess partially the environmental dimension of sustainability. In the transportation sector, studies that have used the LCA methodology to analyze the environmental impacts of transportation components include the life cycle assessment for passenger car tires, for lithium-ion batteries, for electric vehicles, for passenger cars, for fuel types and so on (*Continental 1999; Gauch et al. 2009; Volkswagen 2008; Kaniut 1997; Wang et al. 2007).* An extensive assessment of future fuel/propulsion system options used the well-to-wheels methodology to analyze energy use and emissions associated with more than hundred fuel production (well-to-pump) and vehicle operation (pump-to-wheels) activities (Brinkman et al. 2005)

In this paper different tools are used to estimate the well-to-wheel emissions and energy associated activities for the manufacture, fueling, vehicle operation and maintenance, for three different types of vehicles: a conventional gasoline vehicle, a hybrid electric vehicle and a pickup truck.

METHODOLOGY

The goals of the methodology are separated in two stages: theoretical and practical. The theoretical stage aims to set the foundations of the analysis by 1) decomposing a transportation system into its components and attributes and studying their interactions with the defined sustainability categories and 2) developing a complete set of criteria and indicators to assess a set of urban transportation modes. The practical stage uses the definitions of the first stage together with suitable tools to quantify a proposed set of criteria and indicators that compare urban transportation modes in a sustainability context. The three parts of each stage are:

1a. Define the categories (layers and controllers) of a sustainable system
1b. Develop criteria and indicators to assess sustainability of urban transportation modes
1c. Choose urban transportation modes

2a. Utilize suitable tools to quantify the indicators and criteria
2b. Aggregate results and attempt to obtain a sustainability index
2c. Use the sustainability index to compare different urban transportation modes at a global, regional or local level

Sustainability Framework, Criteria and Indicators

In developing a conceptual framework of sustainability for urban transportation modes, the generic structure components of a system and restrictions that may be faced in the implementation were considered. Note that the proposed framework is suitable for the analysis of various systems of urban infrastructure including utilities, with minor modifications for specific applications. These specifications refer to the criteria that must be developed to assess the system. The proposed sustainability framework consists of four fundamental layers and three controllers that manage the deployment of a system.

The four layers are:

- Environment
- Technology
- Energy
- Economy

The three controllers are:

- Users (and other stakeholders)
- Legal framework
- Local restrictions

According to the proposed framework, a prism is used (Figure 2) as a visual representation of the hierarchy of the four layers that structure the system. The three sides of the prism represent the three controllers that restrict the system's creation, implementation and acceptance. These controllers are imposed by the community. The International Council on Systems Engineering (ICSE 2000) defines a system as an integrated set of elements that accomplishes a defined objective. In this context this framework can be used to appraise almost any system such as a wastewater treatment plant, a power plant, a public transit system, proposed HOT lanes and so forth.

The shape of a prism was chosen to depict the dependence that each category exerts on the next one. Energy was taken outside of environment and was made a separate layer due to its importance and complex participation in the development, operation and maintenance of urban systems. The four layers depict the essential components for the development of a system. Interactions within the layer boundaries create a sustainable system.

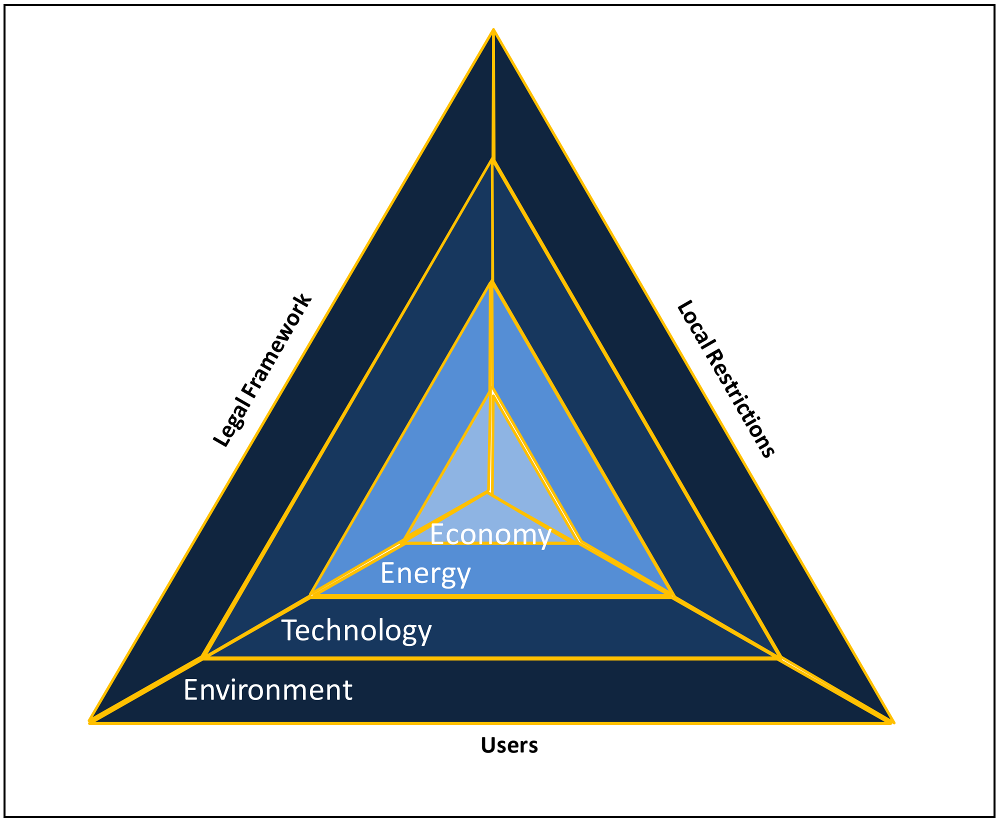

Figure 2. Sustainability Decomposition Prism.

All activities and processes occur within the broad environmental limits and they are part of it. Technology is the human creation of tools and crafts to affect environment. Energy is a part of technology, as all technology components are not related to the creation and distribution of energy. Not all technologies that are related to energy are directly related to the economy, thus sustainable economy should be developed within specific limitations, imposed by the environment, as well as the technology and energy availability. When a system fulfills these prerequisites, it tends to be characterized as sustainable.

The three controllers placed on the sides of the prism, imply that even if a system is created and characterized as sustainable in terms of the first four layers, the controllers (users, legal framework, and local restrictions) may not allow its implementation or, in general, control of deployment (e.g. final alignment and station location of a proposed rail system). Each category of the proposed sustainability framework is described below.

Layer 1: Environment - Forming the base of the prism, environment is the broadest component. All activities occur within the environment's limits and for society and economy to be healthy, the first prerequisite is a healthy environment. The European Commission defines a healthy environment as "one of the cornerstones of sustainable development…the natural and cultural heritage that defines our common identity and thus its preservation for present and future generations" (EC 2009).

Layer 2: Technology - Technology refers to all components of the system made by humans to meet their needs. Infrastructure is a necessary element for every system to operate; it is part of technology. Infrastructure occupies area that offsets other land uses; it promotes or hampers the welfare of a community and it connects or separates communities. These are features that are related to environment, economy and society. Globally, technology is one of the most rapidly developing and resource consuming sectors. Manufacturing, fueling, maintaining and operating technology should minimize the consumption of non renewable energy sources, maximize the reuse and recycling of materials, maintain biodiversity, keep activities within environmental limits, and satisfy the users.

Layer 3: Energy - Energy is a major component that is directly connected with environment and economy. Energy price and consumption has short term and long term impacts on lifestyles. Consumption of non-renewable energy sources generates emissions that are harmful to humans in the short term, whereas in the long term, dependence on non-renewable energy sources set activity limitations to a community, thus human needs cannot be met. Technology satisfies a broad spectrum of human needs, and the generation and distribution of energy are part of these needs. Sustainable communities generate energy by using renewable resources or resources that can be replenished with faster rate than energy is consumed. Over utilizing of non-renewable energy sources, deprives energy sources from future generations.

Layer 4: Economy – The economy has its foundations on the three layers beneath it. Economic development that does not fall within environmental limits used to be a practice for eons and continues to be applied in several regions. However, global restrictions such as the Kyoto protocol have begun to externalize the costs of polluting and energy consumption. The creation of a sustainable economy requires partial utilization of energy and technology and development within environmental limits. An unsustainable economy results in destruction of environment, affects poor social groups disproportionally and leads to social instability and unsustainable communities.

Controller 1: Users -Users is a representation of a large set of stakeholders including individuals (e.g., residents or travelers), groups of individuals (e.g. schoolchildren), private companies (e.g. taxis, private fleet operators, etc.) and public agencies (e.g. regulatory, operation-and-maintenance agencies, etc.) Depending on the application, users can represent specific social groups. For example, the entire community is the user of electricity from its power plant, but only riders are the users of its bus system. The system's output is the attribute that controls the users' personal choice, as to when, how and at what level (amount) they choose to use this output. Each user perceives the system's output differently, hence the choices often vary. Population displacement for the installation of new or expanded systems is also a form of user costs.

Controller 2: Legal framework – Legal framework relates to existing legislation (international, national, federal, state, local) of a community which controls the construction and operation of a system. For example, particular locations of a community are protected by historical preservation, environmental, coast line management and other laws.

Controller 3: Local restrictions - Feasibility constraints, cultural heritage and archeological sites may not be represented as explicit restrictions in the legal framework. Local conditions form a set of restrictions for the deployment, upgrade or expansion of a system. This is an area in which large changes may occur over time as technology makes feasibility constraints obsolete (e.g. underwater tunneling), or changes in cultural sensitivity (e.g. some archaeological sites or areas of areas of worship, may be wholly removed and restored elsewhere).

These four fundamental layers and three controllers form the sustainability prism which is the key element in decomposing systems with respect to sustainability as illustrated in the comprehensive framework depicted in Figure 2. An urban transportation mode is a system that is composed of components and attributes; with the components being the vehicle and the infrastructure. The system operator controls the supplying capacity of each mode and the traveler decides which mode to use based on the performance of each mode, in conjunction with the trip's characteristics. The attributes of vehicles and infrastructure are: manufacture, fuel, operation, and maintenance for the first, and construction, fuel, operation, and maintenance for the latter. Consideration of such attributes becomes more important when different technologies and fuel types are used. Based on the majority of sustainable transportation definitions, an urban transportation mode may be defined as sustainable when the operator offers mobility, accessibility, safety and minimizes or eliminates non-renewable energy demand and environmental impacts. In this approach, the attributes of the mode are omitted and a very significant portion of impacts on a community are not appraised.

The sustainability prism is used to decompose the subject system or transportation mode (Figure 3). To understand the concept of the prism, each component-attribute is represented by a beam that passes through the Sustainability Decomposition Prism where it is refracted. Each component-attribute beam exits the prism separated into its spectrum of sustainability categories (e.g. vehicle-operation-environment, vehicle-operation-technology, etc.). In order to appraise a transportation mode, criteria are developed for each combination of sustainability category and attribute for vehicle infrastructure. Each table is separated into seven sub-tables that represent the seven sustainability categories (four layers and three controllers). Each of the seven sub-tables is separated into four columns that represent the four attributes of each component (vehicle and infrastructure). For example for the vehicle(component) a sample of developed criteria for the environment-manufacture combination are emissions, noise, percentage of reused and recycled materials. For the users-operation combination a sample criteria are mobility, demand, vehicle breakdown, safety and equity of access. Eventually, each criterion is disaggregated into indicators to capture the complexity and importance of sustainability. For example the indicators that are selected to reflect emissions concerns are CO_2, CH_4, N_20, GHGs, VOC, CO, NO_x, PM_{10}, $PM_{2.5}$ and $SO_{x.}$ A full list of the defined criteria and sample indicators are included in a previous publication (Mitropoulos et al. 2010).

Urban Transportation Modes

The analysis focuses on an on-road set of urban transportation modes (passenger car, pickup truck,) as these modes account for approximately of 80% of population's daily trips (BTS 2002). The sustainability framework is used to compare different transportation systems such as high occupancy toll (HOT) lanes, car-share and bus rapid transit system (BRT). Different vehicle technologies, different fuel production pathways and final fuel types are considered to reveal pros and cons when substitution of vehicle fleets or combined changes in vehicle fleets and traffic conditions occur (e.g. increase the percentage of electric vehicles and introduce HOT lanes). The proposed sets of urban transportation modes are:

Initial set

- Conventional gasoline(CG) passenger car (PC)
- Grid independent hybrid CG,PC
- Pick-up truck
- Electric PC
- Car-sharing
- Diesel Bus
- Bus Rapid Transit System
- High Occupancy Toll lanes

Additional set

- Personal Rapid Transit
- Fuel Cell PC
- Trucks
- Rail

As a case study, a set of sample results for a sedan conventional gasoline vehicle (CGV), a sedan hybrid electric vehicle (HEV) and a pickup truck are summarized. The two criteria that are used herein, the generated emissions and the required energy, fall under the sustainability categories of environment and energy respectively and they are present for all four attributes; manufacture, fuel, operation and maintenance of a vehicle. U.S car sales (Auto channel 2009) provided the three top selling models that were used herein: Toyota Camry, Toyota Prius and Ford F-150. The average fuel efficiency for Camry, Prius and F-150, is 26, 46.5 and 17.5 miles per gallon (mpg), respectively, and these have been calculated based on 45% highway driving and 55% city driving (DOE 2009). The average vehicle miles traveled are 11,100 for all three vehicle types. The average lifetime in years for the CGV, the HEV and the pickup truck are 16.9, 16.9 and 15.5 respectively (Davis 2006, 2009). A summary of vehicle parameters is shown in Table 1 (Toyota, Ford 2009).

Table 1. Vehicle parameters summary

		Conventional Car	**Hybrid car**	**Pickup**
		Toyota Camry	**Toyota Prius III**	**Ford F-150**
Average lifetime	years	16.9	16.9	15.5
Curb weight	lbs	3256	2884.2	5319
City consumption	mpg	21	21	15
Highway consumption	mpg	31	31	20
Average consumption	mpg	26	26	17.5
Average Annual miles	per household vehicle	11,100	11,100	11,100
Total Lifetime miles	miles	187,590	187,590	172,050

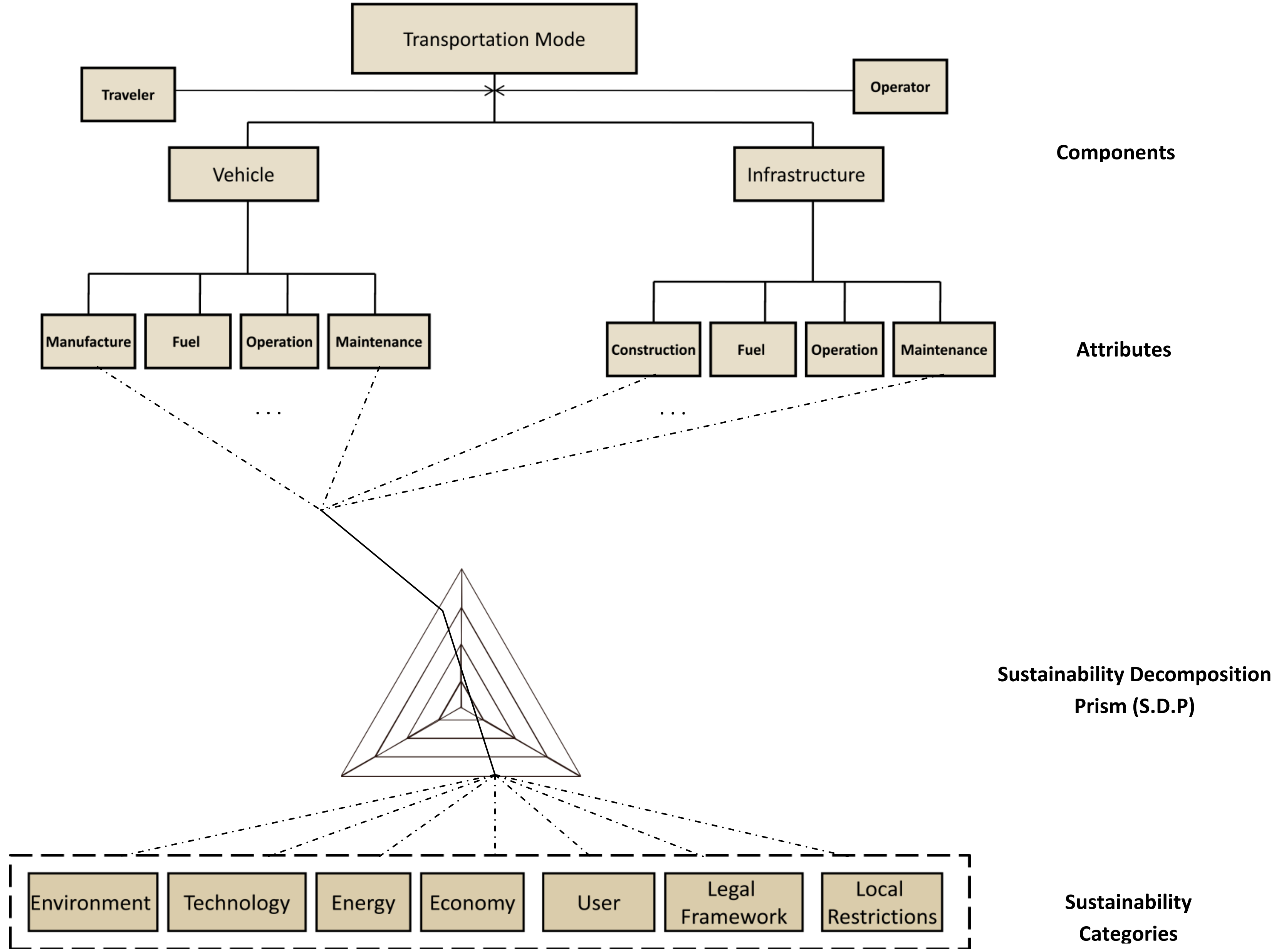

Figure 3. Transportation mode components, attributes, and decomposition into sustainability categories.

Models

For the analysis and quantification of the energy and emissions related indicators the Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) 1.7 and 2.7 models developed by the Argonne National Laboratory and the MOBILE6.2 model developed by the U.S Environmental Protection Agency (EPA) were used. GREET 1.7 and 2.7 were used to obtain the emission inventory for the attribute of manufacture, fueling and maintenance and the energy requirements for vehicle operation (CTR 2005, 2006). MOBILE6.2 was used to simulate the operation performance and provide estimates for vehicle emissions (EPA 2003). The following section provides a summary of the input and output data as well the assumptions that were used in the simulation of the vehicles' manufacture, maintenance, fuel and operation.

Manufacture and Maintenance

GRET 2.7 model was used to obtain the emission and energy inventory for the three different vehicle types. GREET 2.7 calculates the used energy use and generated emissions from vehicle materials, batteries, fluids, vehicle assembly, disposal and recycling (ADR). In detail:

The vehicle material cycle includes:
- The raw material recovery
- The raw material transportation and processing
- Material production, fabrication and processing

The battery cycle includes:
- Material production
- Fabrication for the start up
- Storage batteries

The fluid cycle includes:
- Production
- Disposal of coolants
- Engine oil
- Windshield fluid
- Steering fluid
- Brake fluid
- Transmission fluid

The ADR cycle includes:
- Vehicle assembly
- Painting
- Disposal
- Recycling

Table 2 shows the number of vehicle components that change per lifetime, as these have set in the present simulation for the three different types of vehicles. Due to lack of space, the emission and energy results that will follow will be aggregated under the manufacture and maintenance tag.

Table 2. Components changed per lifetime by vehicle type

		Conventional Car Toyota Camry	Hybrid car Toyota Prius III	Pickup Ford F-150
Components changed per lifetime				
Engine Oil	During lifetime	40	40	40
Brake Fluid	During lifetime	3	3	3
Transmission Fluid	During lifetime	1	1	1
Powertrain Coolant	During lifetime	3	3	3
Windshield Fluid	During lifetime	20	20	20
Adhesives	During lifetime	0	0	0
Battery replacement	During lifetime	2	1	2
Tire Replacements	During lifetime	3	3	3

Fueling

GREET 1.7 model was used for the fueling cycle; it is able to simulate different fuel production pathways and vehicle/fuel systems. According to the input data which may include:

- Fuel production options for fuel types
- Different fuel contents and market share percentages
- Different vehicle technologies
- Different electricity production pathways

The model estimates the energy use and emissions associated with the production and distribution of different fuels, known as well-to-pump activities. For this analysis two fuel production pathways were used:

1. For fuel, conventional crude oil to conventional gasoline (CG) is used
2. For the generation of electricity which is required for the production of transportation fuels (well-to-pump stage), the US mix option is used as shown in Table 3.

Table 3. Electricity Generation mix

Average Generation Mix	
Residual Oil (%):	1.1
Natural Gas (%):	18.3
Coal (%):	50.4
Nuclear Power (%):	20
Biomass Electricity (%):	0.7
Others (%):*	9.5

*Others include renewable sources as hydropower, solar, wind and geothermal.

Operation

For the operation stage, MOBILE6.2 and GREET 1.7 were used to obtain results for all three types of vehicles. GREET 1.7 output data includes estimations on energy and emissions associated with the vehicle operation, known as the pump-to-wheels activities. GREET 1.7 does not account for speed changes along a corridor, hence emissions and energy inventory remain stable for different traffic conditions. In contrary, in MOBILE6.2 the road type and vehicle speed can be simulated for different vehicle types and most of the output data is sensitive to such changes. Unlike most other MOBILE6.2 emission estimates, CO_2 emission estimates are not adjusted for speed, temperature, fuel content, or the effects of vehicle inspection maintenance programs. MOBILE 6.2 input data includes, average speed, vehicle starts per weekday or weekend, fuel efficiency in miles per gallon, min/max temperature, altitude, humidity and other data related to ambient conditions. The road type and average speed used in this simulation were arterial and 20 miles per hour respectively to represent traffic conditions closer to peak hour (TTI 2009). As MOBILE6.2 does not generate estimates for energy, green house gases (GHG) and N_2O, GREET's 1.7 energy estimates, the GHG equation and N_2O estimates are used instead. The GHGs in GREET1.7 are estimated from equation 1:

$$GHG = \text{Global warming potential of GHG relative to } \mathrm{CO}_2 \times (CH_4 + N_2O + CO_2) \qquad (eq.1)$$

The global warming potential of GHG relative to CO_2 for CH_4, N_2O and CO_2 is 25, 298 and 1 respectively, based on Intergovernmental Panel on Climate Change (IPCC 2001). In Greet 1.7 the emission rates of N_2O are derived with data available from the U.S. Environmental Protection Agency (EPA). The emission estimates for HEV were obtained mainly from MOBILE6.2 by changing the fuel efficiency. However, in cases where MOBILE6.2 was not providing plausible results, GREET1.7 operation assumptions (Table 4) were used to obtain emission estimates.

Table 4. Operation Assumptions

	Fuel Consumption (mpg)	VOC* (Exhaust)	VOC (Evap.)	CO	NOx	PM10 (Exhaust)	PM10 (TBW)	PM2.5 (Exhaust)	PM2.5 (TBW)	CH4	N2O
CGV	26	0.122	0.058	3.745	0.141	0.0081	0.0205	0.0075	0.0073	0.015	0.012
HEV in relation to CGV	179%	54%	100%	100%	84%	100%	100%	100%	100%	47%	100%
Pick-up Truck	17.5	0.144	0.069	3.916	0.229	0.012	0.021	0.0112	0.0073	0.016	0.012

*Emissions in g/mile

WELL-TO-WHELL RESULTS

The estimated energy requirements and the emissions inventory per vehicle type as aggregated (totals) for the vehicle cycle, the fuel cycle and the vehicle operation are shown in Table 5. The emissions from the manufacture- maintenance stage converted from kg/vehicle to grams/mile by using the lifetime vehicle miles traveled to provide a comparable result with the emissions output from the fuel and operation attributes. The energy requirements per mile for total, fossil fuels, coal, natural gas and petroleum are lower for the CGV and the HEV compared with the pickup truck. The total energy requirements decrease for the HEV and increase for the pickup truck by 39.7% and 47.2% respectively when they are compared with the CGV. Comparing the HEV and the pickup truck with the CGV, the fossil fuels, coal and petroleum requirements follow the same pattern with total energy, and coal having the highest percentage of improvement of approximately 52% when shifting from a CGV to a pickup truck. Looking at the HEV per mile total energy, fossil fuel and petroleum use, there is a decrease of 145%, 149% and 161.8% respectively when it is compared with the pickup truck. The inventory in Table 5, presents the generated emissions (CO_2, CH_4, N_20, GHGs, VOC, CO, NO_x, PM_{10}, $PM_{2.5}$ and SO_x) in grams/mile for the vehicle cycle, fuel cycle and vehicle operation. There is an obvious emission decrease for the HEV and an increase for the pickup truck when compared with the CGV. The highest improvement in total emissions between the CGV and the HEV appear to be for CO_2, CH_4 and eventually for GHG in favor of the HEV. The only pollutant that presents marginal decrease for the HEV vehicle when compared with the CGV is the CO emissions, with 0.6%, whereas SO_x found to be greater for the HEV compared with the CGV.

Table 5. Aggregated emissions and energy

		Conventional Car Toyota Camry	**Hybrid car Toyota Prius III**	**Pickup Ford F-series**
Emissions				
CO2 (w/ C in VOC & CO)	grams/mile	**456.8**	**275.2**	**680.0**
CH4	grams/mile	**0.6**	**0.4**	**0.881**
N2O	grams/mile	**0.018**	**0.015**	**0.020**
GHGs	grams/mile	**476.8**	**288.7**	**708.0**
VOC: Total	grams/mile	**1.18**	**0.97**	**1.863**
CO: Total	grams/mile	**7.806**	**7.758**	**11.990**
NOx: Total	grams/mile	**0.926**	**0.730**	**1.497**
PM10: Total	grams/mile	**0.145**	**0.122**	**0.211**
PM2.5: Total	grams/mile	**0.059**	**0.049**	**0.085**
SOx: Total	grams/mile	**0.224**	**0.254**	**0.328**
Energy	BTU/mile	**6,127.8**	**3,696.4**	**9,055.7**
Fossil fuels	grams/mile	**5,853.9**	**3,500.7**	**8,718.1**
Coal	grams/mile	**378.3**	**307.3**	**575.4**
Natural gas	grams/mile	**624.8**	**442.0**	**939.3**
Petroleum	grams/mile	**4,850.7**	**2,751.4**	**7,203.4**

Figures 4 to 9 show CO_2, GHGs, VOC, CO, SO_x and PM_{10} and emissions respectively for each of the three vehicle attributes (combined manufacture and maintenance). CO_2 emissions during vehicle operation account for more than 50% of the CO_2 life emissions for each vehicle, whereas manufacture and maintenance CO_2 emissions for the CGV and the HEV are roughly similar. GHGs and VOC patterns are similar to the CO_2 emissions, with the exception that VOC emissions are less significant in fueling stage for all three types of vehicles.

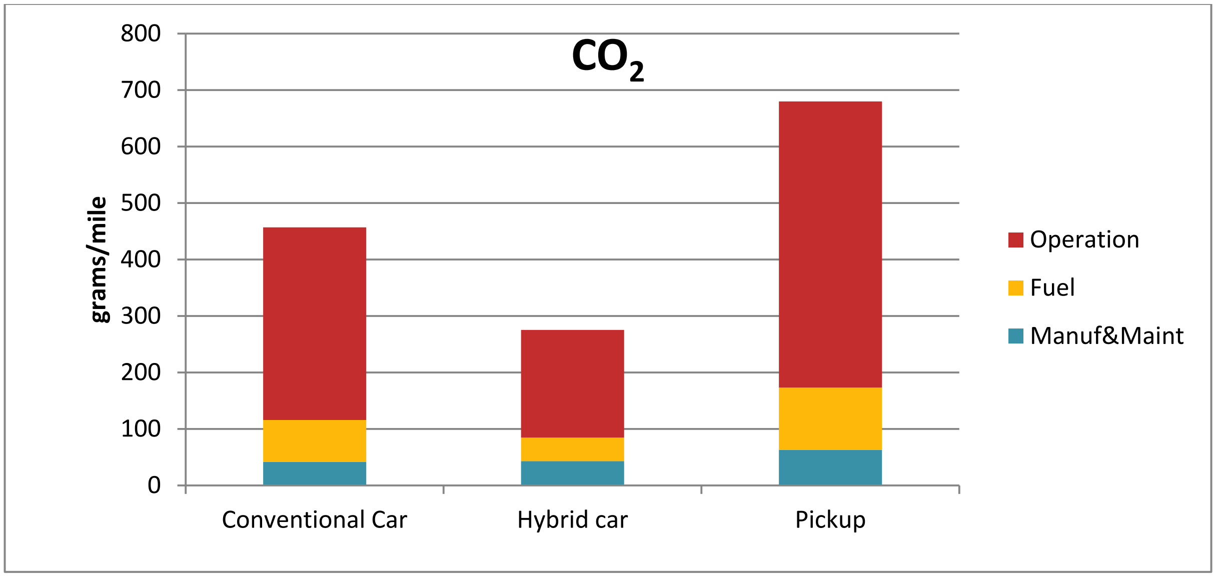

Figure 4 . Life cycle results: $C0_2$ emissions per vehicle attribute.

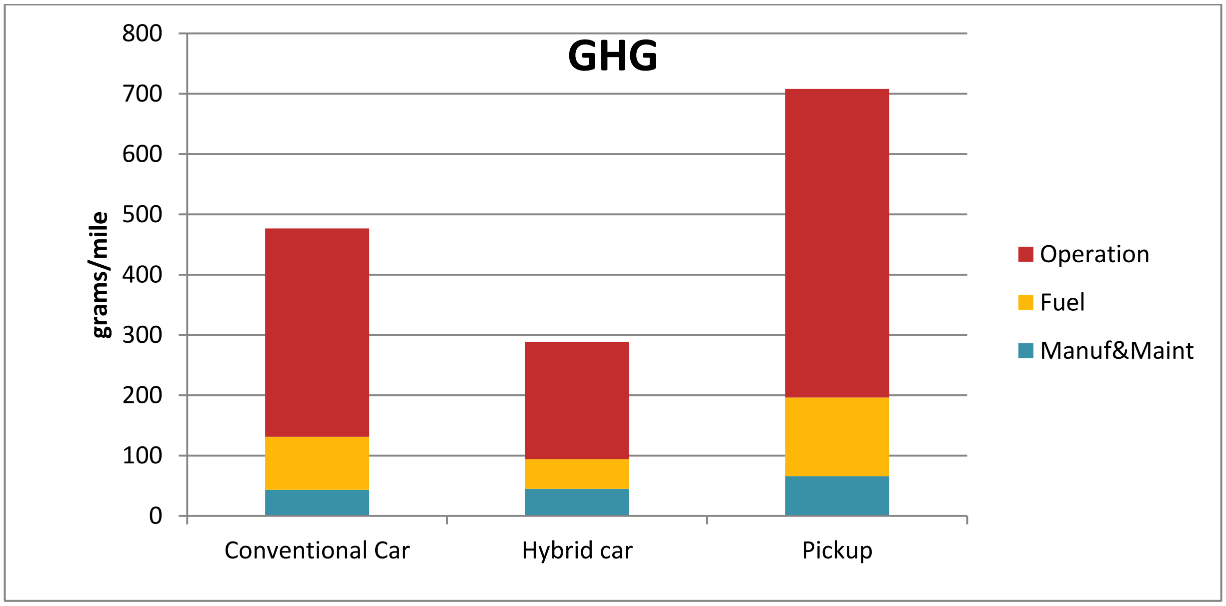

Figure 5 . Life cycle results: GHG emissions per vehicle attribute.

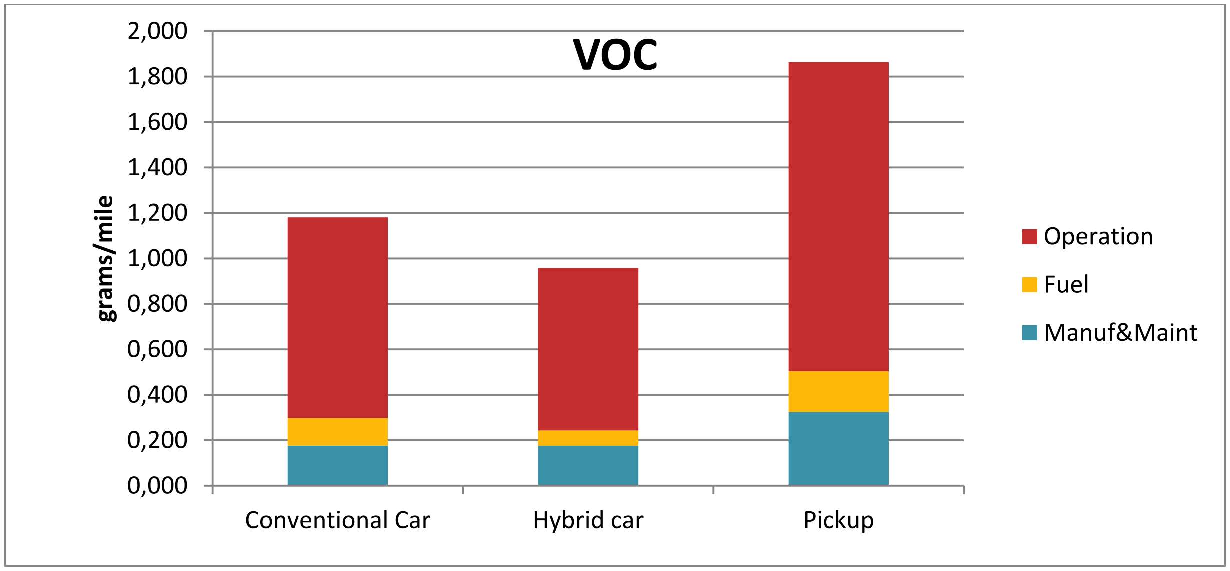

Figure 6 . Life cycle results: VOC emissions per vehicle attribute.

As shown in Figure 7 CO emissions are generated entirely during the vehicle operation, whereas the majority of SO_x and PM_{10} emissions are generated during the manufacture-maintenance stages. SO_x emissions are greater for the manufacture-maintenance attributes and appear to be higher for HEV compared with the CGV due to the production and fabrication processes of materials such as aluminum and copper that are used for the traction motor, the generator and the electronic controller. Additionally, NI-MH batteries that are used for HEV are responsible for higher SO_x emissions than for lead-acid batteries that are used for CGV.

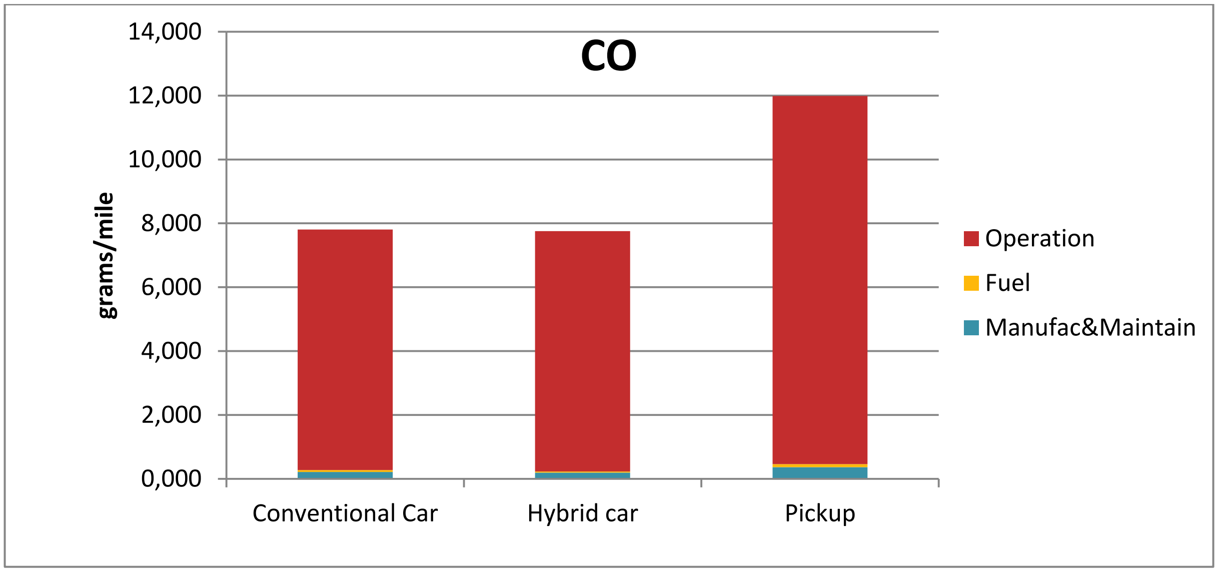

Figure 7. Life cycle results: C0 emissions per vehicle attribute.

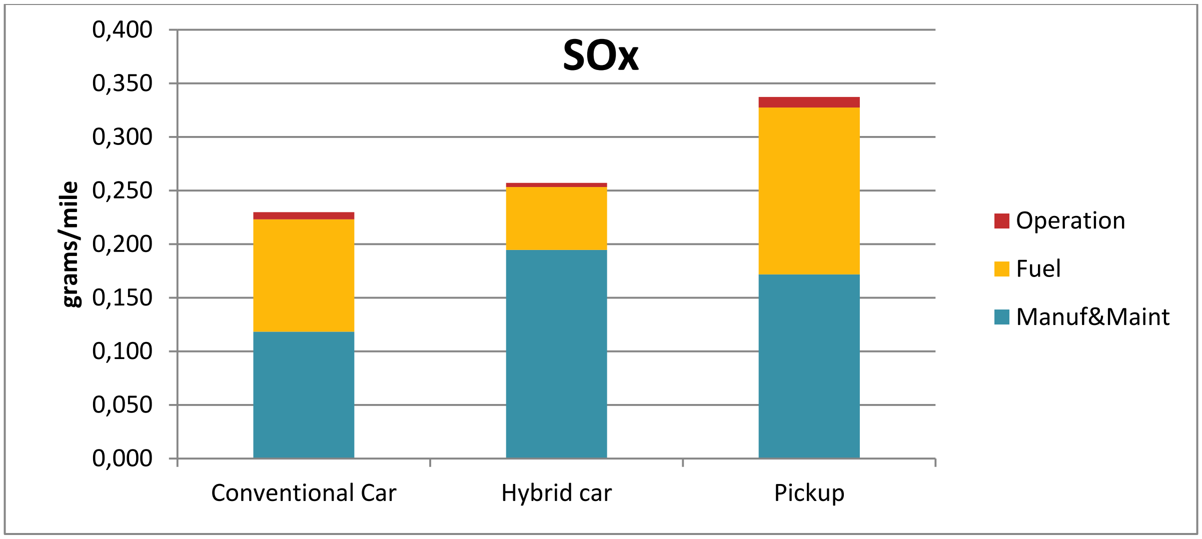

Figure 8. Life cycle results: SO_x emissions per vehicle attribute.

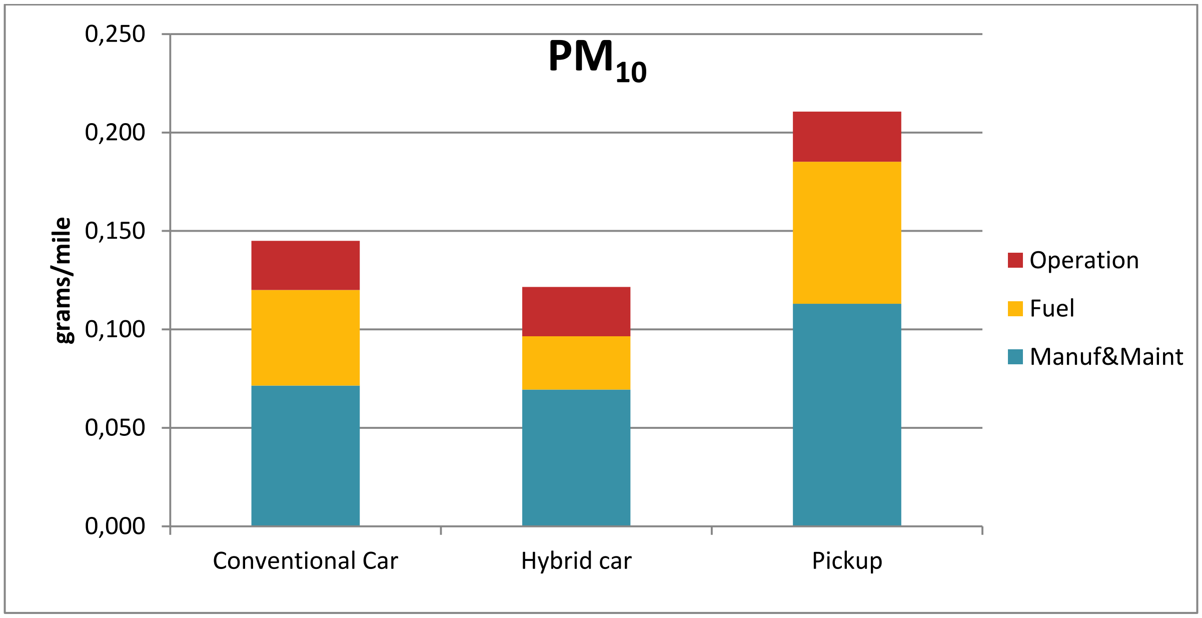

Figure 9. Life cycle results: PM_{10} emissions per vehicle attribute.

Figures 10and 11 show that per mile total energy and petroleum requirements are much greater for the pickup truck compared with the CGV and HEV for all life stages. Energy and petroleum needs for vehicle operation are significantly decreased for the CGV and the HEV due to improved fuel efficiencies they have in relation to the pickup truck.

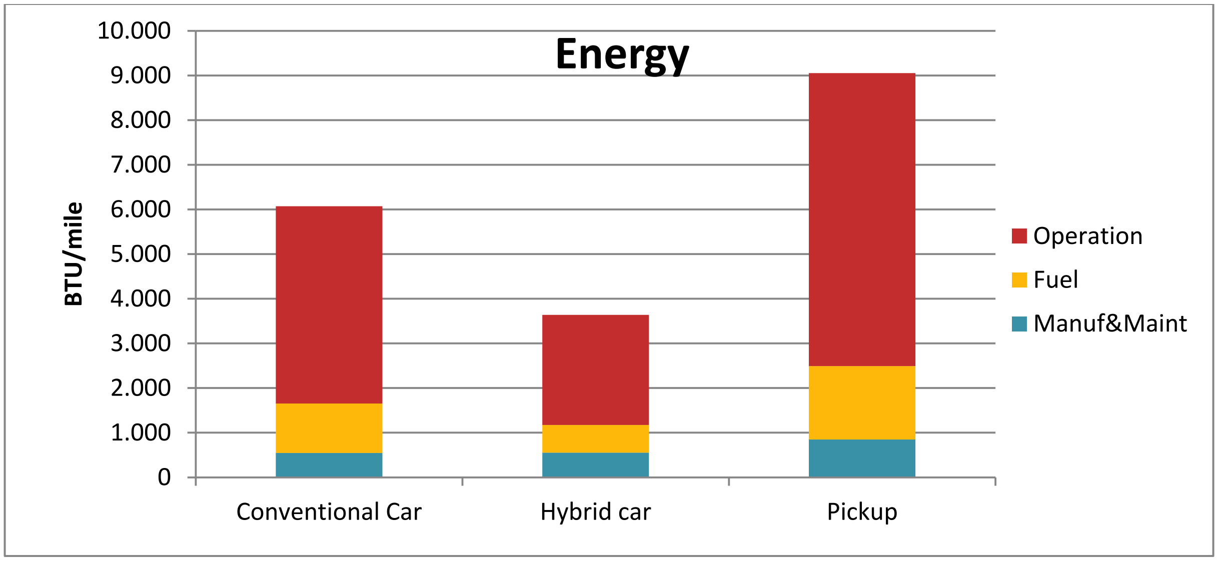

Figure 10. Life cycle results: Total energy requirements per vehicle attribute.

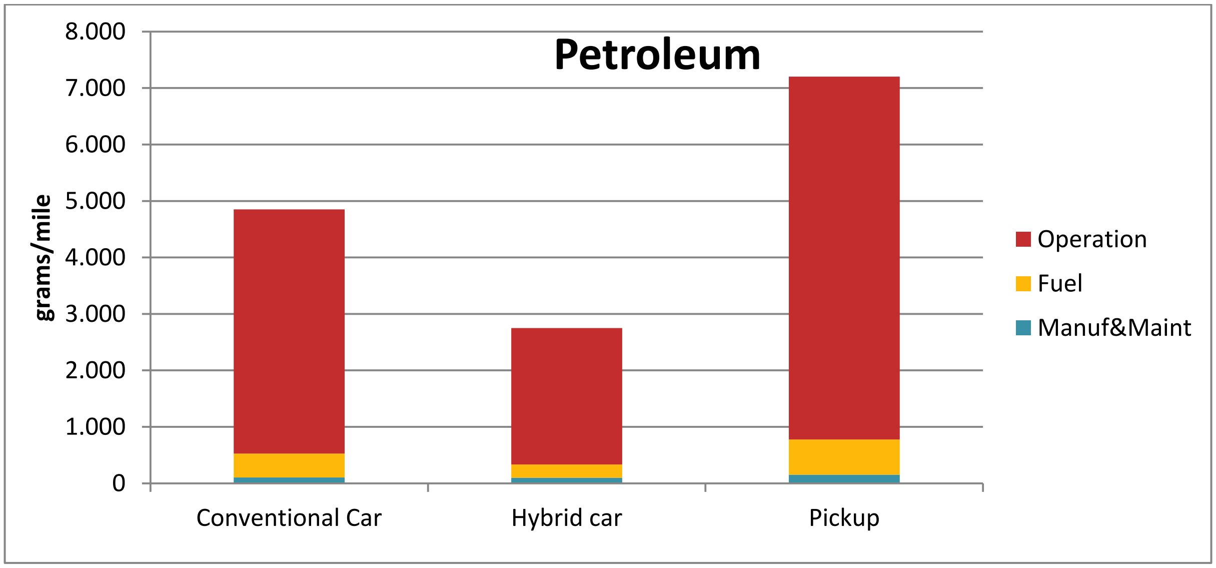

Figure 11. Life cycle results: Petroleum required per vehicle attribute.

The energy and emission estimates for the three types of vehicles are used to assess sustainability of urban transportation modes at a global level by considering all four attributes of vehicle; manufacturing, fueling, operation and maintenance. The manufacture, fuel feedstock and/or fuel production attributes can be omitted from the sustainability framework, to assess sustainability of urban transportation modes at regional or local level.

DISCUSSION AND CONCLUSION

Traditional evaluation of transportation modes is usually limited to extensive estimates and comparisons of demand and supply. In the new paradigm, the emerging requirement is moving regions and nations, including their transportation systems, towards sustainability. This necessitates a far more holistic analysis of transportation mode. To achieve a complete assessment of any urban transportation mode in a global level, utilization of different methodologies, together with detailed input data for all life cycle stages of a mode are necessary to monitor sustainability performance dynamically.

Consideration of mode attributes such as vehicle manufacture, infrastructure construction, fuel, operation and maintenance becomes more important when different mode technologies and fuel types are used. To facilitate the creation of an urban sustainable transportation system, a more comprehensive appraisal of impacts and expenditures is necessary.

As a first step, the life cycle assessment method was used to quantify two criteria of the proposed sustainability framework and provide a comprehensive analysis of energy and emissions associated with three types of vehicles, a CGV, a HEV and a pickup truck by providing specific traffic conditions, and life cycle parameters for each vehicle. Our analysis shows that CO_2, GHG and VOC emissions are greater during the vehicle operation stage compared with manufacture-maintenance and fuel stage, whereas CO emissions are entirely associated with vehicle operation stage. However, vehicle operation is not responsible for all emissions as SO_x and PM10 emissions are greater during the manufacture-maintenance stage. SO_x emissions for HEV are increased for the manufacture-maintenance stage compared with the CGV because of the use of aluminum, copper and NI-MH battery in HEV. Total energy requirements are greater for the operation stage for all three vehicles and all indicators appeared to be higher for the pickup truck compared with the CGV and HEV.

Criteria and indicators are generic tools that can provide an unbiased appraisal which in turn provides input for subsequent analysis and evaluation by selecting weighting and combining of indicators to facilitate the estimation of comprehensive scores, etc.

The primary contribution of this research is the development of a sustainability framework within which attributes of a transportation mode can be studied. Proposed criteria and indicators can be integrated into a tool that is able to appraise transportation modes in a sustainability context. Several case studies will follow that will include appraisal of traditional (e.g. car, bus, light rail), advanced (e.g. HOT lanes, electric vehicles, Bus Rapid Transit systems, Advanced Rapid system) and emerging modes (e.g. Car sharing, Personal Rapid Transit).

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