LIFE CYCLE ASSESSMENT THROUGH A COMPREHENSIVE SUSTAINABILITY FRAMEWORK: A CASE STUDY OF URBAN TRANSPORTATION VEHICLES

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ABSTRACT

The strong influence of transportation on the environment, economy and society strongly support the call of incorporating sustainability into transportation planning. Comparison of different types of vehicles and technologies with conventional gasoline based vehicles in a sustainability context requires a life cycle assessment. In turn, LCA results assist decision makers to evaluate transportation plans and policies based on sustainability properties. This paper describes a long-term sustainability-based framework for the life cycle assessment of urban transportation modes.

The sustainability framework acts as a filter that decomposes the elements of a transportation mode to reveal its sustainability properties. A set of life cycle sustainability criteria and indicators for five sustainability categories are quantified for different urban transportation vehicles to compare their performance. The vehicles include six popular light-duty vehicles and two types of public transit buses. The bus rapid transit (BRT) is found to be the most sustainable transportation mode overall. It attains sustainability goals by 64%, while the Fuel Cell Vehicle (FCV), the Hybrid Electric Vehicle (HEV), the Electric Vehicle (EV), the Diesel Bus (DB), the Internal Combustion Engine Vehicle (ICEV) and the Gasoline Pickup Truck (GPT) achieve 89%, 83%, 82%, 73%, 70% and 38% respectively of the BRT's sustainability value.

1. BACKGROUND

Road transportation contributes in the consumption of significant quantities of energy and materials and in the deterioration of air quality. Two promising factors that have the potential to alter the increasing trend of energy consumption and emissions, are the fuel economy and the transformation of propulsion used in road transportation. The large impacts of the transportation sector on the environment and economy, and the social effects of transportation on communities necessitate the incorporation of sustainability into the transportation planning process. In this way, more comprehensive outcomes and predictions become available to decision makers.

Sustainability 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. It expanded to include energy, economy and social issues. The energy aspects are of major interest to the analysis of transportation modes because they require a considerable amount of energy to be built –both for the vehicles and for the infrastructure on which they operate. Additional energy is required for the vehicles to be operated, maintained, refurbished and eventually disposed. All these processes also generate a large amount of pollutants emission.

Sustainability has been used extensively in development and transportation due to the environmental, social and economic impacts that these sectors have on communities. Several governmental and regional agencies have applied sustainability to their transportation programs. Jeon and Amekudzi [1] studied sustainability initiatives in North America, Europe and Oceania and reported that a standard definition of transportation system sustainability is unavailable. 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.

Attempts at incorporating sustainability into transportation planning have resulted in research on the development of variables defined as measures, indicators or indices representing elements of sustainability [2,3,4,5,6]. Transport sustainability indicators that measure impacts on mobility, safety and environmental effects are applied mainly to the operation of the transportation system. However, major components of sustainable transportation are omitted in this approach, including infrastructure construction, vehicle manufacture and maintenance [3,4,5,6]. Past studies that assessed transportation sustainability, consider only personal vehicles or all modes present on a section of a network by using aggregated measures to evaluate sustainability performance. The aggregation of transportation performance measures limits the principal role of sustainability, which is to assist agencies in evaluating new transportation modes which are proposed for introduction in a network.

The development and introduction of vehicles with alternative propulsion require a detailed breakdown of vehicle components for the proper understanding of their performance and of their impacts over their entire life cycle. Disaggregation per vehicle type in a transportation network and life cycle sustainability assessment may lead to more accurate planning and policy making. Vehicle types and propulsion options examined herein include internal combustion engine vehicle, hybrid electric vehicle, fuel cell vehicle, electric vehicle, plug-in hybrid vehicle, gasoline pickup truck, diesel bus and bus rapid transit.

A traditional transportation mode evaluation is based on demand and supply comparisons, cost and benefit evaluations, financial risks analysis, and cost-effectiveness analysis. Recent assessments tend to focus on detailed energy requirements and emissions during operations. Other applications attempt to internalize the cost of accidents and travel delays. 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. Importantly, a long-term sustainability-based comprehensive framework for the monitoring and the life cycle assessment 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.

This paper proposes a sustainability framework that acts as a filter, which decomposes the elements of a transportation mode to reveal its sustainability categories. The sustainability categories are divided into three controllers (users, legal framework, and local restrictions) and four layers (environment, technology, energy, and economy). The proposed framework for urban transportation modes is implemented in an in-depth life cycle sustainability assessment of eight different vehicle types. A complete methodology for developing the sustainability categories and quantifying the life cycle sustainability indicators which are required to assess any urban transportation vehicle follows. Findings of this analysis are discussed and additional suggestions for further research are made.

2. LIFE CYCLE ASSESSMENT AS PART OF TRANSPORTATION SUSTAINABILITY ASSESSMENT

Life Cycle Assessment (LCA) is a methodology first used in 1960s in U.S by Harold Smith to estimate energy requirements for the production of chemical products [7]. Since then, LCA has been used in many different fields such as agriculture, water technologies, construction, domestic product production, energy production, and transportation to estimate energy requirements and emissions generation. The environmental performance of technology has become an important issue in its development, operation, maintenance and disposal. LCA is 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 a product's lifetime from the extraction and collection of raw materials for its manufacture, use, and maintenance, to its final disposal or recycling [8].

LCA can be implemented in sustainability assessment as it can provide detailed measures to assess partially the environmental dimension (emissions, energy) 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, lithium-ion batteries, electric vehicles, and fuel types [9,10,11].

Urban transportation mode characteristics that are associated with energy requirements and emissions generation can be studied throughout a mode's life cycle. An extensive assessment of future fuel/propulsion system options used LCA methodology to analyze energy usage and emissions associated with more than 100 fuel production (well-to-pump) and vehicle operation (pump-to-wheels) activities, concluded that fuel production and vehicle operation are the key stages in determining well-to-wheels energy requirements and emission outcomes [12].

In past studies LCA was used as a tool to assess the environmental dimension of products, systems or processes in terms of emissions generated and energy required in their life cycle. LCA tools become an important component of the sustainability assessment but they typically provide results which cover only a part of the environmental dimension – which is one of the three dimensions of sustainability. The social and economic dimensions need to be assessed separately, or be omitted which occurs frequently in most LCA applications. To remedy these omissions, this paper proposes a framework which uses LCA to assess the environmental dimension of sustainability and additional methodologies to embrace the social and economic dimensions of sustainability in a complete life cycle sustainability assessment of urban transportation modes. Different LCA tools are used within equal and consistent system boundaries to quantify lifecycle sustainability indicators for vehicle manufacturing, fueling, operation and maintenance for eight different types of vehicles.

3. LIFE CYCLE SUSTAINABILITY ASSESSMENT IN TRANSPORTATION

3.1 Methodology

The goal of the methodology is twofold: theoretical and practical. The theoretical part of the methodology aims to set the foundations of the analysis by a) decomposing a transportation system into its components and attributes and studying their interactions with the defined sustainability categories and b) developing a complete set of criteria and indicators for each combination of the components-attributes to assess a set of urban transportation modes. The practical part of the methodology implements suitable tools to quantify the proposed set of criteria and indicators indentified in the theoretical part that compare urban transportation modes in a sustainability context.

3.2 Sustainability Framework and Criteria

In developing a conceptual framework of sustainability for urban transportation modes, the generic structure components of a transportation system and the restrictions that may be faced in its development and implementation are considered. The proposed sustainability framework consists of three controllers that manage the deployment of a system and four fundamental layers.

- The three controllers are: (1) Users and other stakeholders; (2) Legal framework and (3) Local restrictions.
- The four layers are: (1) Environment; (2) Technology; (3) Energy; (4) Economy.

According to the proposed framework, a prism is used as a visual representation of the hierarchy of the four layers that structure the system to depict the dependence that each category exerts on the next one. The four layers of the prism represent the essential components for the development of a 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.

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 the environment. 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. Energy is a part of technology, but only a fraction of technology components are 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 and the availability of technology and energy.

An urban transportation mode is a system that is composed of components and attributes; with the vehicle and the infrastructure being the components. 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 characteristics. The attributes of vehicles and infrastructure are the manufacture, fuel, operation, and maintenance for the vehicle, and construction, fuel, operation, and maintenance for the infrastructure. Consideration of such attributes becomes more important when different technologies and fuel types are used. In this approach, the attributes of the mode are usually omitted and a very significant portion of impacts on a community are not appraised.

In the context of our sustainability 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 and infrastructure. Eventually, each criterion is disaggregated into indicators to capture the complexity and importance of sustainability. For example the indicators that are selected to reflect the emissions are CO_2 (carbon dioxide), CH_4 (methane), N_2O (nitrous oxide), GHGs (greenhouse gases), VOC (volatile organic compound), CO (carbon monoxide), NO_x (nitrogen oxides), PM_{10} (particulate matter) and SO_x (sulphur oxides). A full list of the defined criteria and sample indicators are included elsewhere [13].

The above framework was applied for the assessment of six light-duty vehicles and two public transit buses. In the analysis that follows, all vehicles are assumed to use the same infrastructure (roads,) so the criteria that are used herein focus on the component vehicle, the four sustainability layers, and the controller users. The remaining two controllers (legal framework and local restrictions) are imposed by communities and they are applicable to specific projects. The selected criteria for the life cycle sustainability assessment of the transportation vehicles, their definitions, the assumptions considered and the procedures which were followed for their quantification are presented below.

The list of eight vehicles examined is as follows: Internal Combustion Engine Vehicle (ICEV), Hybrid Electric Vehicle (HEV), Fuel Cell Vehicle (FCV), Electric Vehicle (EV), Plug-In Hybrid Vehicle (PHEV), Gasoline Pickup Truck (GPT), Diesel Bus (DB), and Bus Rapid Transit (BRT).

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 prerequisite is a healthy environment. The European Commission [14] 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". Our criteria for Environment are:

a. Emissions are an outcome of all attributes (manufacture, fueling, operation and maintenance) of component-vehicle; they have a direct impact on the environment. Emissions are divided into two sub-criteria based on the set goals; greenhouse gases (GHG) and air quality. Specific indicators are developed for each one of the emissions sub-criteria; CO_2, CH_4, N_2O, and total GHGs for greenhouse gas assessment, and VOC, CO, NO_x, PM_{10} and SO_x for air quality assessment. The life cycle tools which are used to quantify the emission indicators are presented in section 4.
b. Noise is an outcome of all attributes and it has an impact on human health. Herein, noise is measured in decibels (dB) and its value for each vehicle type is assumed to be representative for average urban speeds of 45 km/hr at a distance of 15 m. At speeds greater than 50 km/hr vehicles with advanced propulsion offer negligible noise benefits because at higher speeds noise is generated mostly by the tire/road interaction [15] and vehicle aerodynamics. Noise levels at 45 km/hr are estimated from existing literature [16,17].

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 a 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. Our criteria for Technology are:

a. Life expectancy refers to the expected lifetime of the vehicle. This is fundamental to developing annual measures based on proposed indicators. Although the average lifetime of new vehicle technologies (e.g., fuel cell vehicles) has not been established yet, it is assumed to be the same with the vehicle's battery lifetime which reflects FreedomCAR Program Research and Development goals of a 15-year lifetime. Average lifetime for the rest of the vehicles is taken from the literature (Table 1)[18,19].

b. Capacity refers to the relative passenger carrying ability compared with the maximum capacity of a vehicle class; it is expressed as a percentage for each vehicle type. For transit buses the total number of passengers (i.e., sitting and standees) is considered based on the assumption that the internal vehicle design should maximize the number of passengers that each bus can carry [20,21,22,23,24].
c. Frequency of fueling refers to the time a user spends during fueling/charging of a vehicle over its lifetime; a higher number is less desirable for the user. This criterion is significant for short range modes. It is estimated by dividing the lifetime kilometers of a vehicle by the product of fuel tank capacity and fuel efficiency. For EVs the fuel tank is replaced by a battery array. PHEVs are assumed that they are driven a fixed number of kilometers in electric mode before the gas generator is introduced to create electricity for additional kilometers. A user needs six minutes in a gas or hydrogen station to complete the fueling. For EVs it is assumed that 10% of the annual charging requirements obligate the user to stop for 26 minutes to charge the vehicle [23]. The remaining 90% of charging requirements occur while the vehicle is parked.
d. Maintenance frequency refers to the time a user spends on vehicle maintenance. The ICEV is considered as the base vehicle and the required maintenance intervals include only parts replacement and not inspection. The base vehicle requires to be maintained 22 times throughout its lifetime and each owner spends at two hours each time to drop-off and retrieve the vehicle. Additional time losses due to mode shift are not included. Maintenance intervals for the rest of the vehicles are estimated based on their additional or fewer mechanical parts [27,28, 29]. For example three battery changes are assigned for the base vehicle, two for the PHEV and none for the EV, the FVC and the PHEV. For the public transit buses it is assumed that each one requires an average of 260 hours per year for maintenance [30].

e. Vehicle storage when not in use is a fundamental requirement. The space occupied by the vehicle depends on the operational characteristics of the vehicle, such as hours of operation, headway, etc.

f. Supply refers to the number of persons that can be moved per hour per vehicle. It is a generalized term for vehicular mode capacity and it is measured in passengers per hour vehicle.

Layer 3: Energy - Energy availability, demand, price and actual consumption have short term and long term impacts on lifestyles. Technology satisfies a broad spectrum of human needs, and the generation and distribution of energy are part of these needs. Over utilization of non-renewable energy sources, deprives energy sources from future generations. Energy criteria are measured in mega Joules (MJ) per km and they are quantified by using tools presented in section 4 [31]. Our criteria for Energy are:

a. Manufacturing energy refers to the energy related to the following processes: raw material recovery and extraction, material processing and fabrication, vehicle component production, and vehicle assembly.
b. Fueling energy includes the following processes: primary energy production, transportation, and storage; fuel production, transportation, storage, and distribution.

c. Operation energy includes the energy required to run and idle the vehicle and the energy consumed for processes that support the lawful usage of vehicles such as insurance, registration, license and taxes.
d. Maintenance energy refers to the energy required to maintain the vehicle over its lifetime and finally dispose it.

Layer 4: Economy – Economic development that does not fall within environmental limits used to be a practice for eons and this practice continues in several regions. However, global restrictions such as the Kyoto protocol have begun to externalize the costs of pollution and energy consumption. The creation of a sustainable economy requires the utilization of energy, technology and development within environmental limits. An unsustainable economy results in the destruction of environment, affects poor social groups disproportionally and leads to social instability. Cost is the monetized cost of all attributes. Our criteria for Economy are:

a. Manufacturing cost represents the invoice price of a vehicle. The invoice price is the price a car dealer pays to the manufacturer; it is constant for every dealer in the U.S. For public transit buses the invoice price was 90% of the Manufacturer Suggested Retail Price (MSRP) [32, 33].
b. Operation cost includes the cost for fueling/charging the vehicle, insurance, license, registration and taxes [34, 35, 36]. The ICEV is considered as the base vehicle, and insurance, license, registration and tax costs for the rest of the vehicles are estimated based on their weights. AAA based its insurance costs on a full-coverage policy for a married 47-year-old male with a good driving record, living in a small city and commuting 3-10 kilometers daily to work. License, registration and taxes costs include all governmental taxes and fees payable at the time of purchase, and annual fees. Costs are computed on a U.S. national average basis.
c. Maintenance cost refers to the average cost that it is required to maintain the vehicle over its lifetime. Mechanical parts and tires are included for all vehicle types [31,36].
d. Public subsidy refers to the portion covered by taxpayers. For light-duty vehicles it refers to the federal tax credits and for public transit buses it refers to the subsidy required to operate and maintain each vehicle [37,38]. We assumed that the same federal income tax credit will be applied to all advanced vehicles including the FCV when it will be available for purchasing. (In 2009, two types of light duty FCVs became available only for lease and only in California.)
e. Parking cost refers to the national average monthly unreserved parking rate per vehicle [39]. For owners of advanced vehicles (FCV, EV, PHEV) it is assumed that free parking is offered to individuals or small businesses in designated downtown parking garages and surface parking lots [40].
f. Job opportunities refer to the number of new job positions that will be created when a new transportation vehicle is introduced. It is measured in number of job opportunities when increasing share of new vehicles by 1% on current market. This criterion accepts input only for local transportation projects.

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) and public agencies (e.g., regulatory, operation-and-maintenance agencies.) 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. Our criteria for Users are:

a. Mobility is the provision of social and economic opportunities by the transportation network. The mobility indicator is expressed as the sum of hours users require to travel (PHT) within the origin-destination pairs with the heaviest demand for a transportation network by using the same mode type. Criterion values reflect specific projects.
b. Demand refers to the type of vehicle users choose to satisfy their mobility needs and is expressed as a percentage of vehicle type shares. This criterion becomes important when forecasting vehicle choice given the supply for each mode [41].
c. Delay is defined as the travel time of a vehicle when it travels at 50 km/hr minus the real travel time which includes access to the vehicle, recurrent, weather related, incident and work zone congestion plus the time to park; it includes walk, wait and commute by mass transit. It is expressed in minutes per trip for specific origin-destination trips or in vehicle hours for a network. This criterion values reflect specific projects.
d. Global Availability refers to the time during which a vehicle is not available to its potential users during a day. It is expressed as an annual percentage. It is estimated by dividing the total hours a vehicle is unavailable per year by the total number of hours in a year. The unavailable hours for light-duty vehicles are estimated by multiplying the time it takes to fuel/charge a vehicle times the fueling/charging frequency per year. We assumed that public transit buses are not in operation for five hours per day (from midnight to 5 am).
e. Reasonable Availability refers to the time during which a vehicle is not available to its potential users during the 19 hours (5 am to 12 am) per day when 98.8% of total trips occur [42]. It is expressed as an annual percentage. It is assumed that an EV requires 7 hours and a PHEV 4 hour per charging cycle at 220/240V starting from a depleted battery. It is assumed that public transit buses are fully fueled upon start of service and they do not require fueling until the end of their shift [20, 23].
f. Equity of access refers to the number of types of vehicles that serve specific origin-destination pairs with heaviest, lightest and average demand. It is expressed as the sum of vehicle types serving an origin-destination pair (i.e., 1 if service is provided, 0 if not) and it is applicable only to local projects.
g. Comfort and Convenience criterion is expressed with four different indicators. Passenger and cargo space available to each user in a vehicle, which is expressed in liters per passenger; the leg room space which is expressed in centimeters and the seated probability indicator which is expressed as the possibility a passenger to be seated during his/her trip. For public transit buses it is assumed that the space under seats is the cargo space assigned to each passenger and for passenger space it is assumed that the internal height of buses scales from 2.44 meters to the front to 1.96 meters to the back and its width is 2.54 meters for its whole length. [20,21,22,23,24,25,43]
h. Fueling opportunities refer to the available locations for fueling or charging a vehicle. It is expressed by the number of gas stations, hydrogen stations, or public electric stations. For hydrogen and electric stations both private and public stations in operation are considered. [44,45]. This criterion is not applicable to public transit modes.

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, coast line management and other laws. This controller has no role in a limited generic evaluation of urban models.

Controller 3: Local restrictions – Feasibility constraints, cultural heritage and archeological sites may not be represented as legal restrictions (in Controller 2.) Therefore, local conditions form a set of restrictions for the deployment, upgrade or expansion of a system. This controller has no role in a limited generic evaluation of urban models.

Table 2 presents the quantified life cycle sustainability indicators for each vehicle type. Due to the multidisciplinary character of sustainability, integration of sustainability indicators, into summary indices becomes a sensitive task that has to ensure that 1) the final result is understandable to decision makers and stakeholders and 2) it has included all the considered sustainability indicators.

The proposed sustainability indicators are first separated into indicators with positive (+) impact, and indicators with negative (-) impact. Aggregation of indicators into a single sustainability category index per vehicle type, since indicators are expressed in different units, can be done by normalizing the value of each indicator for each vehicle type by using equations 1a and 1b and then combining these normalized values by assigning weights [46].

$$N_{ij}^{+} = \frac{I_{ij}^{+} - I_{min,j}^{+}}{I_{max,j}^{+} - I_{min,j}^{+}} \qquad (eq.1a) \qquad\qquad N_{ij}^{-} = \frac{I_{min,j}^{-} - I_{ij}^{-}}{I_{min,j}^{-} - I_{max,j}^{-}} \qquad (eq.1b)$$

Where N_{ij}^{+} is the normalized indicator with positive impact achieved by the *ith* alternative with respect to the *jth* indicator of sustainability. I_{ij}^{+} is the indicator value achieved by the *ith* alternative when evaluated based on the *jth* indicator, $I_{min,j}^{+}$ is the indicator with the worst value achieved by the *jth* indicator of sustainability and $I_{max,j}^{+}$ is the optimum value of *jth* indicator of sustainability obtained.

The normalized values are dimensionless and range from 0 to 1; therefore the greater the absolute value of the normalized indicator, the more sustainable it is. Hence, on a relative scale, the most sustainable vector for each vehicle type is $\mathbf{I}_{\mathbf{max}} = (1, \ldots 1)$ and the least sustainable vector is $I_{min} = (0, \ldots 0)$ where its components equal the number of the sustainability categories.

Aggregation of normalized indicators into sustainability category and overall sustainability indices per vehicle type is performed by using the weighted sum method (WSM) [47]. The value of alternative A_i with assigned weight w_j for each indicator *j* can be expressed mathematically as:

$$V_i = \sum_{j=1}^{n} w_j N_{ij} \qquad i = 1, \ldots, m \qquad (eq.2)$$

In this analysis equal weights were assigned to each indicator and sustainability category. Table 2 presents the sustainability category index and the overall sustainability index per vehicle type.

3.3 Sustainability Assessment of Light-Duty Vehicles and Public Transit Buses

The analysis focused on six light-duty vehicles as these modes account for approximately of 85% of daily trips in U.S. [51] and two public transit buses. The selected sustainability indicators are used to assess different vehicle types and fuels.

Table 1 includes sample brand names and types of vehicles. These were necessary for extracting impacts based on specific vehicle characteristics. For existing vehicle technology, such as the ICEV, the HEV and the GPT, U.S car sales [52] suggested the three top selling models that were used in our analysis, Toyota Camry, Toyota Prius and Ford F-150, respectively. For the FCV, EV, and the PHEV the Honda Clarity, the Nissan Leaf, and the Chevy Volt were selected as the most representative of their type. For public transit buses a 12 m and an 18 m NewFlyer bus were used as representative of the DB and the BRT, respectively.

Table 1 - Vehicle Parameters Summary [19,20,21,22,23,24,25,34,48,49,50,51]

	Units	**ICEV (V1) Camry**	**HEV (V2) Prius**	**FCV (V3) Clarity**	**EV (V4) Leaf**	**PHEV (V5) Volt**	**GPT (V6) F-150**	**DB (V9) New Flyer**	**BRT (V10) New Flyer**
Weight	*kg*	1,500	1,380	1,625	1,587	1,715	2,413	11,795	22,226
Average occupancy	*passenger*	1.59	1.59	1.59	1.59	1.59	1.49	10.5	23.9
Average lifetime	*year*	10.6	10.6	15.0	15.0	15.0	9.6	12.0	12.0
Average Annual distance traveled	*km*	16,254	16,254	16,254	16,254	16,254	15,128	67,056	67,056
Lifetime kilometers	*km*	172,296	172,296	243,815	243,815	243,815	145,227	804,672	804,672
Cost to buy (MSRP)	*$ US*	$22,225	$23,050	$48,850	$32,780	$40,000	$22,060	$319,709	$550,000
Fuel Price (Jan. 2010 - W.Coast)	*$ per unit*	$2.85	$2.85	$4.90	$0.16	$2.85	$2.85	$2.94	$2.94

*per kg, **per kWh

The outcomes in Table 2 provide an comparison for estimating the total impact of any fleet mix scenario containing these eight vehicle types. If expanded, it may provide evaluation of the impact of any transportation infrastructural and management scheme.

4. ANALYSIS AND RESULTS

The selected indicators that are quantified extensively in this study provide comprehensive comparable estimations for the six different types of light-duty vehicles and the two public transit buses. Criteria and indicators are indentified for the five sustainability categories, including: (1) Environment, (2) Technology, (3) Energy and (4) Economy and (5) Users.

The Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) 1.7 and 2.7 models developed by the Argonne National Laboratory, the MOBILE6.2 model developed by the U.S Environmental Protection Agency (EPA) and the Economic Input-Output Life Cycle Assessment developed in the Carnegie Mellon University were used for the analysis and quantification of the lifetime energy and emissions related indicators. GREET 1.7 and 2.7 were used to obtain the emission and energy inventories for the attributes of manufacturing, fueling and disposal [18]. MOBILE6.2 was used to simulate operations and produce vehicle emissions [53]. Urban average speeds of 45 km/hr, 20 km/hr and 70 km/hr were used for light-duty vehicles, buses and BRT systems, respectively [26,38]. EIOLCA was used to estimate the emissions and energy requirements associated with maintenance, vehicle insurance, car registration, license and taxes [54].

The quantified indicators and their units are shown in Table 2 for each sustainability category. The five sustainability categories are the goals for urban transportation vehicles which guide decision makers in enhancing sustainability performance. The sustainability category and overall sustainability index for each vehicle is used to compare the eight vehicle types. Plus and minus signs show the positive and negative utility for the corresponding sustainability indicator (i.e., the greater the absolute value of the indicator the more positive or negative impact it has).

Based on the sustainability category indices, in the categories of Environment, Technology and Energy the BRT was ranked first with scores equal to 85%, 63% and 99%, respectively. In the sustainability category Economy, the EV was ranked first with a score equal to 61%. In the sustainability category Users, the GPT was ranked first with a score equal to 51%.

When the five sustainability categories are used with the proposed criteria, equal weights for each sustainability indicator and category are assigned and when indicator values are weighted for passenger kilometers traveled (PKT) to develop an overall sustainability index, then the most sustainable transportation mode is found to be the BRT. The BRT attained sustainability by 64% and the PHEV which was ranked second attained sustainability by 59% (i.e., 92% of BRT value). The FCV, the HEV, the EV, DB, the ICEV and the GPT achieved 89%, 83%, 82%, 73%, 70% and 38% of the BRT's value.

5. 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 modes. To achieve a complete assessment of any urban transportation mode, utilization of different methodologies, together with detailed input data from different sources for the life cycle of a mode are necessary to appraise and to monitor sustainability performance.

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. A more comprehensive appraisal of impacts and expenditures is necessary to facilitate the creation of urban sustainable transportation systems. Public concerns should be expressed by indicators that are easily understood, to make possible their implementation by decision-makers and their monitoring in the long-term by agencies and stakeholders. Transportation agencies may consider and partially prioritize and support their decisions on the sustainability framework for the introduction of a new mode that aims to alleviate transportation problems on a corridor or an area by comparing sustainability indicators.

As a first step, a comprehensive analysis was performed to quantify environmental, technological, energy, economic and user-based indicators associated with the six types of light-duty vehicles (internal combustion engine vehicle, hybrid electric vehicle, fuel cell vehicle, electric vehicle, plug-in hybrid vehicle, and gasoline pickup truck) and two transit buses (diesel bus and BRT) by providing specific traffic conditions, and life cycle parameters for each vehicle.

Our analysis revealed that BRT is ranked first in most of the sustainability categories, followed by the plug-in hybrid vehicle and the fuel cell vehicle. Environmental sustainability indices reveal large fluctuations in vehicle performance which ranges from 14% for the gasoline pickup truck up to 86% for the BRT. Between light-duty vehicles it can be seen that the fuel cell vehicle attains 84% of environmental sustainability which is similar to the BRT. SO_x emissions for hybrid electric vehicle, fuel cell vehicle, electric vehicle, and plug-in hybrid vehicle appear are higher than the internal combustion engine vehicle due to the high utilization of aluminum and copper during the manufacturing stage and the advanced batteries, which are used in these vehicles. The gasoline pickup truck is ranked first in the users' category due to the comfort and convenience indicators; it is the most spacious vehicle. The electric vehicle achieves the maximum economic sustainability score because of the low maintenance and fuel cost related to the rest of the vehicles. The "optimum" sustainability performance assigned to the BRT is the "relative optimum" rather than the "absolute optimum" sustainability performance because it is the result of the comparison between these eight alternative vehicles.

The primary contribution of this research is the development of a life cycle sustainability framework within which attributes of a transportation mode can be studied in detail. Criteria and indicators are generic tools that can provide an unbiased appraisal which in turn provides input for subsequent analysis and evaluation by selecting weights and combinations of indicators to facilitate the estimation of comprehensive scores. Combination of sustainability indicators into a single overall sustainability index or sustainability category index is achieved by normalizing indicator values and applying a multiple attribute decision making methodology to assess competing transportation modes.

The proposed criteria and indicators are integrated into a tool that is able to appraise transportation modes in a sustainability context and supports the decision making process for existing or new transportation modes. A sensitivity analysis may reveal how changes in the assumed parameters of vehicles can change the final outcome for assessing transportation modes and identify the switch-over point of assumed parameters where different modes provide marginal improvements. This tool can be utilized by policy makers and transportation agencies to study changes in the sustainability of a corridor, of origin-destination trips or of networks by altering the percentages of vehicles in the local fleet. Several case studies are being developed that include appraisal of traditional modes (e.g., car, bus, light rail), advanced modes (e.g., HOT lanes, electric vehicles, BRT systems, Advanced BRT,) and emerging modes (e.g., Car sharing, Personal Rapid Transit).

Table 2 - Sustainability Layers with Selected Sustainability Criteria, Indicators and their Values

Sustainability Category	Goals	Criteria	Indicators	Code	Units	ICEV (V1) Camry	HEV (V2) Prius	FCV (V3) Clarity	EV (V4) Leaf	PHEV (V5) Volt	GPT (V6) F-150	DB (V9) Newflyer	BRT (V10) Newflyer
Environment *	Minimize Global Warming	GHG	CO2 (w/ C in VOC & CO)	-	*grams/ PKT*	246	132	115	154	171	364	202	78
			CH4	-	*grams/ PKT*	0.34	0.20	0.35	0.24	0.19	0.52	0.16	0.06
			N2O	-	*grams/ PKT*	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00
		Total GHG	GHGs	-	*grams/ PKT*	257	138	124	161	177	380	210	82
	Minimize Air Pollution	Air Quality	VOC	-	*grams/ PKT*	0.42	0.38	0.03	0.03	0.38	0.80	0.14	0.07
			CO	-	*grams/ PKT*	0.48	0.44	0.18	0.19	0.28	0.87	0.55	0.26
			NOx	-	*grams/ PKT*	0.40	0.34	0.11	0.18	0.33	0.73	0.64	0.28
			PM10	-	*grams/ PKT*	0.08	0.07	0.08	0.22	0.07	0.14	0.04	0.02
			SOx	-	*grams/ PKT*	0.15	0.17	0.18	0.45	0.19	0.24	0.15	0.08
	Minimize noise	Noise	Average noise level	-	*dB*	61	57	57	57	57	69	78	78
	Environment sustainability index per vehicle type					**0.526**	**0.696**	**0.843**	**0.672**	**0.694**	**0.139**	**0.600**	**0.855**
Technology	Maximize lifetime service	Vehicle lifetime	Estimate average vehicle lifetime	+	*years*	10.6	10.6	15	15	15	9.6	12	12
	Maximize capacity of vehicle in the unit of time	Capacity	Accomplishment compared with the max. capacity of vehicle class	+	*percentage*	100%	100%	80%	100%	80%	100%	92%	99%
	Minimize time losses	Fuel frequency	Estimate time loss for fueling vehicle	-	*minutes/PKT*	0.006	0.004	0.008	0.011	0.006	0.006	NA	NA
		Maintenance freq.	Estimate time loss for maintaining vehicle	-	*minutes/PKT*	0.010	0.009	0.003	0.003	0.003	0.012	0.002	0.001
	Minimize land consumption	Space occupied	Estimate land occupied by vehicle	-	*square meters/passenger*	5.5	4.9	5.6	4.9	4.9	7.3	3.0	2.0
	Maximize supply	Supply	Estimate number of passengers that can be served per hour per vehicle	+	*passengers/hour/vehicle*								
	Maximize power	Engine power	Torque-weight ratio	+	*Nm/kg*	0.151	0.103	0.158	0.177	0.216	0.165	0.095	0.049
	Technology sustainability index per vehicle type					**0.438**	**0.455**	**0.439**	**0.569**	**0.556**	**0.330**	**0.576**	**0.629**
Energy *	Minimize energy consumption	Energy Consumption	Manufacturing Energy	-	*Mjoule/ PKT*	0.302	0.318	0.360	0.359	0.333	0.568	0.186	0.181
			Fueling Energy	-	*Mjoule/ PKT*	0.565	0.247	0.566	0.887	0.245	0.845	0.297	0.102
			Operation energy	-	*Mjoule/ PKT*	2.207	1.124	0.829	0.650	1.564	3.767	2.237	0.774
			Maintenance energy	-	*Mjoule/ PKT*	0.123	0.117	0.081	0.081	0.083	0.158	0.120	0.054
	Energy sustainability index per vehicle type					**0.483**	**0.676**	**0.657**	**0.570**	**0.713**	**0.014**	**0.649**	**0.990**
Economy	Reduce cost requirements	Cost	Manufacturing cost	-	*$/PKT*	0.073	0.079	0.117	0.081	0.095	0.096	0.034	0.026
			Operate (user costs)	-	*$/PKT*	0.110	0.077	0.090	0.078	0.096	0.188	0.210	0.217
			Maintainance cost	-	*$/PKT*	0.021	0.021	0.012	0.012	0.013	0.027	0.027	0.012
	Minimize governmental support	Subsidy	Any form of subsidy	-	*$/PKT*	0.000	0.000	0.019	0.019	0.019	0.000	0.168	0.074
	Minimize parking requirements	Parking Cost	Monthly expenditures for unreserved parking	-	*$/Passenger*	101.6	101.6	0.0	0.0	0.0	108.4	0.0	0.0
	Promote welfare	Job opportunities	# of job opportunities when increase vehicles by 1% on current market	+	*# of employees*								
	Economy sustainability index per vehicle type					**0.384**	**0.416**	**0.538**	**0.608**	**0.564**	**0.212**	**0.280**	**0.509**

Sustainability Category	Goals	Criteria	Indicators	Code	Units	ICEV (V1)	HEV (V2)	FCV (V3)	EV (V4)	PHEV (V5)	GTP (V6)	DB (V9)	BRT (V10)
User	Maximize transportation performance	Mobility	Identify N OxD pairs with heaviest demand	-	*Sum of person-hours for the N OxD demands*								
		Demand	Mode share	+	*% percentage*	90.80%	90.80%	90.80%	90.80%	90.80%	90.80%	2.08%	0.24%
		Delay	[TT as the crow flies at 50 km/h] minus [real TT including access to vehicle, recurrent, weather related, incident and work zone congestion plus TT to park; all walk, wait and commute by mass transit]	-	*minutes per trip for specific OxD, or vehicle-hours for a corridor or network*								
		Global Availability	% of time not available for user's usage based on 24h	-	*hours of down time or not operable per year expressed as an annual %*	0.03%	0.02%	0.04%	8.59%	1.29%	0.03%	20.83%	20.83%
		Reasonable Availability	% of time not available for user's usage based on 19h	-	*hours of down time or not operable per year expressed as an annual %*	0.04%	0.03%	0.05%	3.10%	0.04%	0.03%	0.00%	0.00%
	Improve accessibility	Equity of access	Service provided to N OxD pairs with heaviest, lightest and average demand.	+	*1 if service is provided, 0 if not. Compute sum.*								
	Maximize user comfort	Comfort and convenience	Passenger space	+	*liters/passenger*	574.3	530.7	713.6	521.0	651.3	615.4	936.4	825.0
			Goods carrying (cargo) space	+	*liters/passenger*	84.95	122.33	92.74	69.09	75.04	522.92	52.39	52.39
			Leg room front	+	*centimeters*	105.9	108.0	106.4	106.9	106.7	105.2	68.6	68.6
			Seated probability	+	*% percentage*								
	Maximize user confidence	Fueling opportunities	Locations for fueling/charging	+	*Number of stations in operation*	121,446	121,446	58	626	121,446	121,446	NA	NA
	Users sustainability index per vehicle type					**0.428**	**0.430**	**0.374**	**0.217**	**0.438**	**0.512**	**0.252**	**0.228**
	Overall sustainability per vehicle type			***Total***		**45.17%**	**53.47%**	**57.03%**	**52.72%**	**59.30%**	**24.13%**	**47.15%**	**64.20%**

***Environment and Energy indicators are not fixed but rather depend on project specific or regional inputs of vehicle average lifetime, annual kilometers traveled, weight and speed.**
Indicators in light grey cells can be changed based on regional-local specific requirements
Indicators in dark grey (hatched) cells can be changed only for local project.

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