Life Cycle Analysis for Sustainability Assessment of Road Projects

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Abstract

Road infrastructure has been considered as one of the most expensive and extensive infrastructure assets of the built environment globally. This asset also impacts the natural environment significantly during different phases of life e.g. construction, use, maintenance and end-of-life. The growing emphasis for sustainable development to meet the needs of future generations requires mitigation of the environmental impacts of road infrastructure during all phases of life e.g. construction, operation and end-of-life disposal (as required).

Life-cycle analysis (LCA), a method of quantification of all stages of life, has recently been studied to explore all the environmental components of road projects due to limitations of generic environmental assessments. The LCA ensures collection and assessment of the inputs and outputs relating to any potential environmental factor of any system throughout its life. However, absence of a defined system boundary covering all potential environmental components restricts the findings of the current LCA studies.

A review of the relevant published LCA studies has identified that environmental components such as rolling resistance of pavement, effect of solar radiation on pavement (albedo), traffic congestion during construction, and roadway lighting & signals are not considered by most of the studies. These components have potentially higher weightings for environment damage than several commonly considered components such as materials, transportation and equipment.

This paper presents the findings of literature review, and suggests a system boundary model for LCA study of road infrastructure projects covering potential environmental components.

Keywords: Sustainability, Environmental Indicators, Life Cycle Analysis (LCA), Global Warming Potential (GWP), System Boundary.

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1. Introduction

The Rio+20 UN Conference on Sustainable Development (UNCSD) held in Rio de Janeiro, Brazil in 2012 focused on “green economy”, to deliver equitable improvement in living standards without eroding natural resources. The green economy is an economy or economic development model based on sustainable development and knowledge of ecological economics (Brand, 2012). Construction and operation of various road infrastructure projects have been a great concern for green development as they comprise a big part of the development activities around the world. Different phases of a road infrastructure e.g. construction, use, maintenance and demolition have significant environmental impacts (Stripple, 2001). Sustainable development of road assets is, therefore, a growing international concern (Soderlund, 2008).

Sustainability in infrastructure comprises of three dimensions- environment, social wellbeing and economy (Shaw et al., 2012b). The changing climate phenomenon as a consequence of growing level of greenhouse gas (GHG) emissions is drawing more attention to the environment dimension. The identification of key environmental indicators is a complex exercise, which needs life cycle analysis (LCA) of the service or product system. LCA science of road infrastructure is at a nascent state. This paper reviews LCA studies with a view to develop a well-defined system boundary for future road projects towards green road development.

2. Sustainability of Roads

The emergence of “Green roads” concept initiates the development of various sustainability assessment schemes or tools in different parts of the world. Some of these schemes relevant to roads are: Invest (Australia), AGIC (Australia), GreenLITES (USA), Greenroads (USA), Envision (USA) and CEEQUAL (UK). These schemes are developed on sustainability indicators covering the three components of sustainability (Shaw et al., 2012a).

Road projects involve considerable land use, energy input and resource consumption, which often results in substantial impacts to environment and community. In addition, there are road characteristics e.g. road geometry, pavement structure and surface conditions and traffic congestion during road works, which impact fuel consumption patterns and consequent emission levels (Lepert and Brillet, 2009). The relevant conventional “environmental factors” are emission and pollution, air and water quality, biodiversity, habitat and species protection, landscape design and aesthetics. However, over the years new “environmental factors” like impact on communities in long run, climate change adaptation, efficiency in resource use, sources of materials, whole of life considerations, waste management and future proofing have been emerged, which implies a growing and complex boundary of the sustainability concept (Griffiths, 2008). Conventional environmental assessments often overlook this complexity, leading to conclusions based on incomplete study. As a result, recent studies have identified the need of a comprehensive life cycle assessment (LCA) framework for road projects to facilitate identification of improved sets of sustainability indicators for the environment component (Santero et al., 2011, Yu and Lu, 2012). This can generate comprehensive and scientifically-defensible strategies for lowering emissions, reducing waste, and minimizing energy, water, or natural resource consumption.

3. Life Cycle Assessment (LCA)

LCA is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle. The ISO-EN-UNE-14040 (2006) regulation defines life cycle as the ‘‘consecutive and interrelated stages of a product system, from the acquisition of raw materials or the generation of natural resources until its final disposal’’(p. 2).

Typically, upstream (extraction, processing, transportation and construction), service life (use and maintenance), and downstream (deconstruction and disposal) flows of a product or system are inventoried. Subsequently, global and regional impacts are calculated based on energy consumption, waste generation and a select series of other impact categories (i.e., global warming, ozone depletion, & acidification). This is often termed as a “cradle-to-grave” approach.

3.1 Road LCAs To-date

Recent trends indicate that sustainability is being considered in roadway construction and operation (Muench, 2010). Santero et al. (2011) compiled fifteen road LCA studies from 1996 to early 2010 conducted in Australia, Canada, Finland, Korea, Sweden, UK and USA with a view to identify their system boundary levels. The findings are:

- Materials extraction and production is included by all the LCAs (15).
- Transportation of materials is considerably less studied (9).
- Onsite equipment used in construction is covered by most of the studies (11).
- Traffic congestion due to road works is mostly omitted (3)
- The use phase is almost neglected (2 and partially).
- The complicated maintenance is portrayed as a simplified series of events over the analysis period (10).
- The End-of-life phase is least considered (1).

Based on above findings Santero et al. (2011) found that inclusion of only selected phases and components of the life cycle in a given analysis undermines the utility of the results, as the omitted elements often contribute significantly to the overall life-cycle impact and potentially change the conclusions from a given study. Muench (2010) and Chan et al. (2011) also identified the lack of a comprehensive system boundary for conducting proper LCA of road projects.

The variation in system boundary makes it difficult for proper comparison of the LCA studies and does not provide representative sustainability assessments of road projects. It is, therefore, important that sustainability related LCA studies use equal and consistent system boundaries (Klöpffer, 2003). This observation is also reflected in the “Agenda 21” of 1992 UN Conference on Environment and Development (UNCED), as it defines “S*ustainable* *construction as a comprehensive cycle from the extraction and beneficiation of raw materials, through the planning, design and construction of buildings and infrastructures, until their final deconstruction and management of the resultant waste"* (p. 6).

Considering the above scenario, the road LCA studies published since 2010 are evaluated for the system boundary considerations and are presented in Table -1. It is seen that despite some improvement most of the recent road LCA studies did not consider phases like use, maintenance and end-of-life. The findings of the LCA studies are summerized in the following sections to draw a qaulititatve conclusion towards develpoing a road LCA system boundary.

Table 1: A list of published road pavement LCA studies with their system boundaries.

Authors	Location	Life-cycle components in pavement LCAs.						
		Material Phase		Construction Phase		Use Phase	Maintenance Phase	End-of-life Phase
(√ = Component Included)		Extraction & Production	Transportation	Construction Equipment	Traffic Congestion	Rolling Resistance, Albedo, Lighting, Carbonation Leachate	Material, Construction	Equipment, Transportation, Recycling
Zhang et al (2010)	USA	√	√	√	√	√	√	√
Muench (2010)	Different	√	√	√			√	
Cross et al. (2011)	USA	√	√	√				
Cass and Mukherjee (2011)	USA	√	√	√				
Tatari et al. (2012)	USA	√	√	√				
Yu and Lu (2012)	USA	√	√	√	√	√		√
Ting et al. (2012)	USA	√	√	√		√		

3.2 Research Methodology

There are varying analysis period from 20 years to 100 years considered for the road LCA studies, with 50 years as the most perferred one. Santero and Horvath (2009) states that using a 50 year analysis period allows the impact from each component to fully materialize. However, conversion of findings of LCA studies other than 50 year analysis period to a 50 year analysis period is not a simple arithmetic as the various factors include: maintenance considerations, use phase impacts, different traffic levels, different material compositions, varying transport and equipment requirements, varying layer thicknesses, and design parameters etc. This study, therefore, considers a qualitative approach for comparing different impact levels.

The findings of different LCA studies presented in tables, graphs, results' discussions and conclusions are evaluated following Seidel's noticing, collecting and thinking model for qualitative data processing (Seidel, 1998). The environment components covered by a LCA study is segregated into high impact (H) and low impact (L) based on relative levels of impacts of the components for different environmental indicators covered by the study. From quantitative considerations, the general boundary is above average impact level for the ‘H’ category and below average impact level for the ‘L’ category, though the differences are generally high and easily visible from the graphs and tables.

Environmental concerns of road projects in general are resource depletion, human health, global warming, acidification, depletion of stratospheric zone, eutrophication, photo-oxidant formation and ecotoxic impacts (Häkkinen T, 1996). However, most of the studies consider energy consumption and global warming potential (GWP) as the two major environmental indicators. This study also includes these two types of indicators for assessing the impact levels of different road LCA components. Quality road material is a depleting resource because of demand from the growing massive built environment around the world. So, apart from energy use and emissions, the demand of virgin material in road projects is also an important environmental indicator. This study, therefore, considers material resources as an important indicator.

Only primary energy to assess the impact levels of LCA components are considered in this analysis, as most of the LCA studies exclude feedstock energy assessment. Bitumen possess significant feedstock energy and inclusion of feedstock energy in a comparative LCA study gives cement concrete pavement considerable edge over asphalt pavement because of its very high consumption level of non-renewable energy in the material component (Zhang et al., 2010, Yu and Lu, 2012). Since, the scope for bitumen to be used as an energy source is still limited, feedstock energy in road LCA studies are generally not considered.

3.3 Road LCA Components

The life cycle of a road pavement can be divided into five phases, which are materials, construction, use, maintenance and end-of-life. Each phase comprises of several environmental components as listed in Table -2. ‘Transportation’ and ‘Onsite Equipment’ components are common to all phases except the use phase. For the materials phase ‘onsite equipment’ is considered inbuilt with the ‘extraction and production’ component and for the construction phase ‘transportation’ is excluded as most of it usually considers under the materials phase. The components of the construction phase and the maintenance phase are the same except when the materials of the existing pavement are processed onsite (recycling). For a new road ‘traffic congestion’ is unlikely during the construction phase, while its intensity during the maintenance phase depends on the nature of intervention and scope for detouring.

The materials phase comprised of the total upstream supply chain required to deliver processed materials for road construction and maintenance activities and can be broadly categorised as extraction and production. As the primary component of any road pavement, this phase has been considered as fundamental to all the LCA studies irrespective of system boundary definition.

Table 2: Road life cycle assessment components.

LCA Phase		**LCA Components**
Materials	:	(a) Extraction and Production, (b) Transportation
Construction	:	(a) Onsite Equipment, (b) Traffic Congestion
Use	:	(a) Rolling Resistance (Roughness), (b) Rolling Resistance (Structural), (c) Albedo (Radiative forcing), (d) Albedo (Heat Island), (e) Signage and Lighting, (f) Drainage and Land Cleaning, (g) Carbonation, and (h) Leachate.
Maintenance	:	(a) Material (Onsite recycling), (b) Transportation (c) Onsite Equipment, (d) Traffic Congestion,
End-of-life		(a) Onsite Equipment, (c) Transportation, (c) Material (Recycling)

Transportation is required to carry materials from the extraction sources to the production plants. The factors to be considered are: mode of transportation (road, rail or water), location of the project, and the mass of material to be transported.

Onsite equipment (including trucks) and construction related traffic use non-renewable energy and make emissions during the construction, maintenance and end-of-life phases.

Implementation of road works under safe and efficient conditions often needs closure of one or several lanes; such situation temporarily disrupts traffic flow and may cause congestion during peak periods. On heavily-used routes, traffic congestion at work sites can drastically increase energy consumption and emissions (Lepert and Brillet, 2009).

Pavement surface roughness and structural properties related to rolling resistance accounts for about 12% of the total fuel consumption of vehicles (Chupin et al., 2012). The impact of rolling resistance becomes significant as it affects every vehicle using the pavement (Ting Wang et al., 2012). Increasing roughness causes more vibrations and reduces driving speed, and thus increases fuel use and emissions of vehicles (Yu and Lu, 2012). At low speeds and under summer conditions, changing stiffness and visco-elastic properties of asphalt pavement increases fuel consumption significantly (Chupin et al., 2012).

Akbari et al. (2009) estimated that for every 0.01 increase in albedo (solar radiation reflected off the surface) can offset 2.55 kg of emitted CO_2 for every square meter earth surface. The solar radiation absorbed by the pavement increases the ambient temperature, resulting in the urban heat island effect and increases the energy demand for cooling devices in urban areas.

Carbonation is a naturally occurring phenomenon that sequesters a portion of the CO_2 that was originally liberated from the limestone during cement production. The rate of carbonation varies based on concrete properties and the exposure to the environment.

Leachate is the substance drained out from some pavement materials that may contaminate water bodies and potentially pose a threat to drinking water.

Roadway signage and lighting is usually used in urban roads. The amount of lighting required varies based on the reflective properties of the surface material. Stripple (2001) reported the energy consumption to be as high as 12 TJ per km by this component when assessed for a period of 40 years.

Maintenance phase has the potential to be a significant contributor to the overall environmental impact, as effective maintenance can minimize environmental impacts by providing a smooth and robust pavement over a longer period, thus reducing the negative impacts of the use phase.

The End-of-life (EOL) phase includes environmental burdens of dismantling old pavement, processing materials for reuse and transportation (Yu and Lu, 2012). The scope for using materials from the old pavement to the new pavement relates EOL phase to the material phase and the construction phase.

3.4 Recent LCA studies

Santero and Horvath (2009) studied eight different components of road LCA using global warming potential (GWP) as measured by units of carbon dioxide equivalents (CO_2e) as the environmental indicator. The study presents (Figure-1) the range of GWP for different components based on a functional unit of one lane-kilometer with a standard lane width of 3.6m for an analysis period of 50 years. The thick, gray bars represent the probable ranges and the thin, black lines represent the extreme ranges. This study shows that components e.g. rolling resistance (roughness), rolling resistance (structure), traffic delay, albedo (radiative forcing), materials and transportation can have high impacts. On the other hand, onsite equipment, carbonation, albedo (urban heat island) and roadway lighting can have low level of GWP impacts.

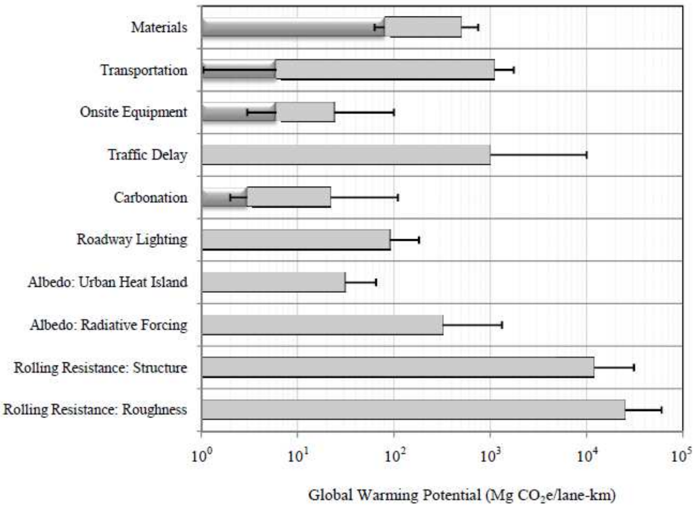

Figure 1: GWP impact ranges for components of pavement life cycle.
(Santero and Horvath, 2009)

The other recent road LCA studies are discussed briefly below and the corresponding LCA findings are presented in Table- 3 considering environmental impact levels as high impact

(H) or low impact (L) from a qualitative point of view as stated in the section- 3.2: Research Methodology.

Zhang et al. (2010) studied LCA of three overlay options, (a) Engineered cementitious composites (ECC), (b) Portland cement concrete (PCC), and (c) Hot-mixed asphalt (HMA), on a badly cracked reinforced concrete pavement for an analysis period of 40 years with Michigan DOT maintenance strategies.

Muench (2010) reviewed 14 LCA papers published from 2000 to 2009 and studied ecological impacts of road construction and generalized maintenance projections.

Cross et al. (2011) studied LCA to compare the environmental burden relating construction of different reactive maintenance options using CIPR (cold in-place recycling), mill and fill with HMA and HMA overlay.

Cass and Mukherjee (2011) studied rehabilitation of a jointed plain concrete pavement using a hybrid LCA method. They found that the equipment and transportation components together represent only 6-10% of the total GHG emissions and the rest (90%) lies with the materials component.

Table 3: Qualitative impact assessment of LCA components.

Authors	**Indicators**		**Life-cycle components' impact levels**						**Legend:** H = High impact L = Low impact √ = Indicator Considered
	Energy Use	GHG Emission	Materials	Transportation	Const. Equipment	Congestion	Rolling Resistance	Albedo	**Remarks**
Santero and Horvath (2009)	-	√	H	H	L	H	H	H	Level assessed from the ranges as shown in Figure-1
Zhang et al (2010)	√	√	H	L	L	H	H	-	EOL studied for land filling only
Muench (2010)	√	√	H	L	L	-	-	-	Maintenance phase findings omitted for generalized values
Cross et al. (2011)	√	√	H	L	L	-	-	-	
Cass and Mukherjee (2011)	-	√	H	L	L	-	-	-	Study limited to construction phase only.
Tatari et al. (2012)	√	√	H	L	L	-	-	-	Resource consumption studied, which reflects similar findings.
Yu and Lu (2012)	√	√	H	L	L	L	H	H	EOL done for 10-20% recycling and found as low impact.
Ting et al. (2012)	√	√	L	L	L	-	H	-	Only preventive maintenance, so less material requirement.

Tatari et al. (2012) studied a hybrid life cycle analysis of continuously reinforced concrete (CRCP) and hot-mix asphalt (HMA) pavements for resource consumption and emissions up to the construction phase only.

Yu and Lu (2012) conducted LCA of three overlay options, a) 250 mm PCC replacing old PCC pavement, (b) 225 mm HMA replacing old PCC pavement, and (c) Crack and seat of existing PCC pavement followed by 125 mm HMA overlay (CSOL) with major preservation works over an analysis period of 40 yrs. The study shows that exclusion of usage module reduces energy consumptions for PCC, HMA, and CSOL options by 40%, 50%, and 44% indicating the significance of the use phase components.

Ting et al. (2012) conducted LCA case studies to evaluate the effect of rolling resistance on the life cycle performance of different pavement rehabilitation strategies. The study reveals significant energy and GHG savings with the reduction of rolling resistance.

The findings presented in Table- 3 identify materials (extraction and production), traffic congestion, rolling resistance and albedo as high impact components, while transportation and construction equipment as low impact components. The findings of Figure -1 (Santero and Horvath, 2009) for the transportation component differ with those of other studies, which is based on elaborated study considering cases like long-haul material supply, requirment of high emission road-way transportation, and large new construction using virgin materials etc. In addition, there are issues like noise and dust pollution, toxicity of tranport leachate, traffic safety, and LCA consideration of high transporation need of regular maintenace and operation activities. Therefore, this study recommends transportation as a high impact component. Most of the transporation component occurs under the materials phase, which includes transportation of materials from the sources (including part of the dismantled materials from the old pavement during the EOL phase) to the production plants and then from the production plants to the work sites. As such, for a simplified study envionmental impacts of transporation only for the materials phase can be considered.

It is also seen that the End-of-life (EOL) phase has not been considered by most of the LCA studies and hence less understood for a comparative assessment. This is in contrast to Rajendran and Gambatese (2007) study that EOL accounts for more than 50% of the total amount of waste generated over the entire life of a roadway. Ventura et al. (2008) found that except for the toxicity (human being) and ecotoxicity (other living species), all other impact indicators e.g. GHG emission, energy use, eutrophication, acidification, and tropospheric ozone formation shows a trend of decreasing potential environmental impacts with an increasing recycling rate. However, the toxicity levels in the storm water runoff are small and less likely to be injurious (Santero et al., 2011). As such, considering the depleting resources around the world and the level of waste generation, the ‘recycling’ activity of the EOL phase can be considered as a high impact component to promote extended use of recycled materials in future road works and thus resource preservation for future generations. Land and drainage cleaning component has not also been considered in any of the studies. It involves mostly onsite equipment use and likely of low impact category.

3.5 Proposed Road LCA System Boundary

Study of the road LCAs shows that low impact (L) environment components except ‘onsite equipment’ are hardly included in any LCA study. High impact (H) environment components are also less studied except ‘material’. The context of the studied road LCAs infers that inclusion of all the environment components in road LCA system boundary likely to be counter-productive in promoting LCA of road projects. The reasons are: (a) risk of data availability, (b) negligible influence of low impact components, and (c) longer LCA processing time with consequent delay in decision making . As such, a LCA system boundary comprising only high impact environment components will be more effective for extended and improved application of sustainability in road project development and management. Accordingly a road LCA system boundary comprising only high impact environment components as identified in this study is presented in Figure- 2.

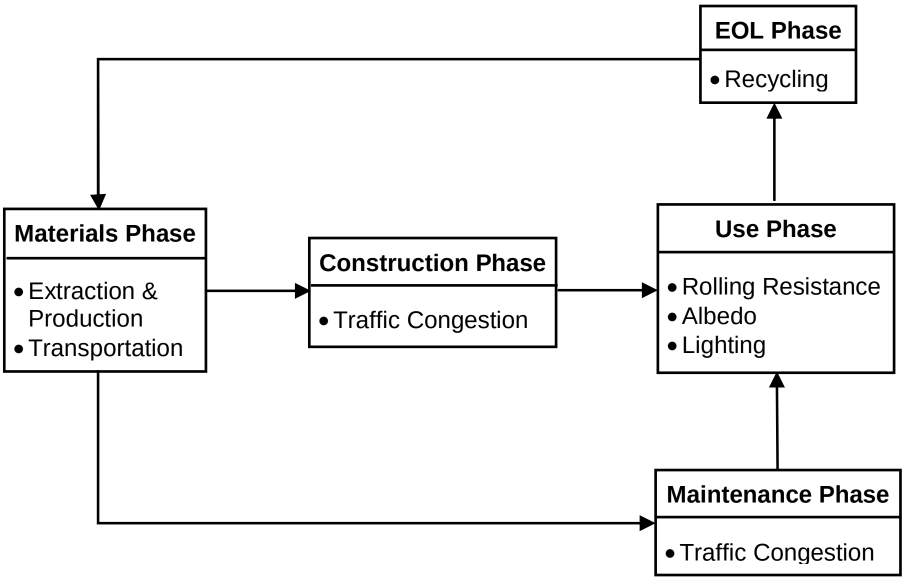

Figure 2: Proposed system boundary for road project LCA study.

4. Conclusion

To promote sustainable development of road infrastructure assets as part of global concern for green development, identification of key environmental indicators is paramount. Evolution of such indicators for the environment dimension of sustainability can only be possible through life cycle assessments of road projects. Such efforts have been frustrated to-date due to absence of any suitable system boundary covering most aspects of the life cycle of a road project. This research work on published LCA studies to date has identified the impact levels of various road LCA components through a qualitative assessment. Based on the research findings and the present practicies of road asset management, a comprehensive road LCA system boundary is presented. It is expected that future studies with possible quanititave assessment of various LCA components would improve the model further.

References

Agenda 21 for Sustainable Construction in Developing Countries. Pritoria, South Africa: CIB and UNEP-IETC.

AKBARI, H., MENON, S. & ROSENFELD, A. 2009. Global cooling: increasing world-wide urban albedos to offset CO2. *CLIMATIC CHANGE,* 94**,** 275-286.

BRAND, U. 2012. Green Economy - the Next Oxymoron? No Lessons Learned from Failures of Implementing Sustainable Development. *GAIA-ECOLOGICAL PERSPECTIVES FOR SCIENCE AND SOCIETY,* 21**,** 28-32.

CASS, D. & MUKHERJEE, A. 2011. Calculation of Greenhouse Gas Emissions for Highway Construction Operations by Using a Hybrid Life-Cycle Assessment Approach: Case Study for Pavement Operations. *JOURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT-ASCE,* 137**,** 1015-1025.

CHAN, S., LANE, B., KAZMIEROWSKI, T. & LEE, W. 2011. Pavement Preservation A Solution for Sustainability. *TRANSPORTATION RESEARCH RECORD***,** 36-42.

CHUPIN, O., PIAU, J. M. & CHABOT, A. 2012. Evaluation of the structure-induced rolling resistance (SRR) for pavements including viscoelastic material layers. 1-14.

CROSS, S. A., CHESNER, W. H., JUSTUS, H. G. & KEARNEY, E. R. 2011. Life-Cycle Environmental Analysis for Evaluation of Pavement Rehabilitation Options. *TRANSPORTATION RESEARCH RECORD,* 2227**,** 43-52.

GRIFFITHS, K. 2008. Project Sustainability Management in Infrastructure Projects. *2nd International Conference on Sustainability Engineering and Science.* Auckland, New Zealand.

HÄKKINEN T, M. K. 1996. Environmental impact of concrete and asphalt pavements. *Research Notes 1752.* VTT, Finland: Technical Research Center of Finland.

ISO-EN-UNE-14040 2006. Interantional Standard: Environmental management - Life cycle assessment - Principles and framework. Switzerland: International Organization for Standardization.

KLÖPFFER, W. 2003. Life-Cycle based methods for sustainable product development. *The International Journal of Life Cycle Assessment,* 8**,** 157-159.

LEPERT, P. & BRILLET, F. 2009. The overall effects of road works on global warming gas emissions. *Transportation Research Part D,* 14**,** 576-584.

MUENCH, S. T. 2010. Roadway Construction Sustainability Impacts. *Transportation Research Record: Journal of the Transportation Research Board,* 2151**,** 36-45.

RAJENDRAN, S. & GAMBATESE, J. A. 2007. Solid Waste Generation in Asphalt and Reinforced Concrete Roadway Life Cycles. *Journal of Infrastructure Systems,* 13**,** 88-96.

SANTERO, N. J. & HORVATH, A. 2009. Global warming potential of pavements. *Environmental Research Letters,* 4**,** 034011.

SANTERO, N. J., MASANET, E. & HORVATH, A. 2011. Life-cycle assessment of pavements. Part I: Critical review. *Resources, Conservation & Recycling,* 55**,** 801-809.

SEIDEL, J. 1998. *Qualitative Data Analyisis. The Ethnograph v5 Manual,* [Online]. Available: http://www.qualisresearch.com/ [12/11/2012].

SHAW, G., KENNY, J., KUMAR, A. & HOOD, D. 2012a. Sustainable Infrastructure Operations: A Review of Assessment Schemes and Decision Support. *25th ARRB Conference- Shaping the future: linking research, policy and outcomes, perth, Australia, 23-26 September 2012.*

SHAW, G., WALTERS, R., KUMAR, A. & SPRIGG, A. 2012b. Sustainability in Infrastructure Asset Management. *7th World Congress on Engineering Asset Management, Daejeon, Korea, 8-9 October 2012.*

SODERLUND, M., MUENCH, S. T., WILLOUGHBY, K., UHLMEYER, J., AND WESTON, J. 2008. Green Roads: A Sustainability Rating System for Roadways. . *Transportation Research Board Annual Meeting 2008 Paper #08-0803.*

STRIPPLE, H. 2001. Life Cycle Assessment of Road: A Pilot Study for Inventory Analysis. Second Revised Edition ed. Stockholm, Sweden.

TATARI, O., NAZZAL, M. & KUCUKVAR, M. 2012. Comparative sustainability assessment of warm-mix asphalts: A thermodynamic based hybrid life cycle analysis. *Resources, Conservation and Recycling,* 58**,** 18-24.

TING, W., IN-SUNG, L., KENDALL, A., HARVEY, J., EUL-BUM, L. & CHANGMO, K. 2012. Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance. *Journal of Cleaner Production,* 33**,** 86-96.

VENTURA, A., MONÉRON, P. & JULLIEN, A. 2008. Environmental Impact of a Binding Course Pavement Section, with Asphalt Recycled at Varying Rates. *Road Materials and Pavement Design,* 9**,** 319-338.

YU, B. & LU, Q. 2012. Life cycle assessment of pavement: Methodology and case study. *Transportation Research Part D-Transport and Environment,* 17**,** 380-388.

ZHANG, H., LEPECH, M. D., KEOLEIAN, G. A., QIAN, S. Z. & LI, V. C. 2010. Dynamic Life-Cycle Modeling of Pavement Overlay Systems: Capturing the Impacts of Users, Construction, and Roadway Deterioration. *Journal of Infrastructure Systems,* 16**,** 299-309.