

Background and Significance of Work

Overview

Need for Overhaul of the Highway Network

The Eisenhower Interstate and Defense Highway System, billed as the biggest infrastructure project ever undertaken, was originally estimated to cost \$25 billion over 12 years. However, it ended up costing \$114 billion and took 35 years to complete. The cost of building and maintaining the nation's highway infrastructure has increased significantly since then, primarily as a result of increased energy costs. In its 2013 edition of the America's Infrastructure Report Card, the American Society of Civil Engineers (ASCE) gave the nation's highway system a grade of D. In that same report, ASCE reported the National Surface Transportation Infrastructure Financing Commission estimate to improve the nation's highways. The annual investment to improve the nation's highway network between 2008 and 2035 is projected to be \$165 billion each year, in 2008 dollars. An additional \$131 billion will be needed annually to maintain and preserve the network. The challenge of funding improvements to the nation's highway system is exacerbated by the inadequacy of the funding available from traditional sources, primarily fuel taxes. These financing challenges dictate the implementation of novel approaches to design and construct the next generation of highways that have to be longer lasting and have a lower life-cycle cost. The current expected lifespan of a flexible pavement surface is considered to be around seven years. Future highway systems must be designed to last much longer in order to keep annualized life-cycle costs at manageable levels.

The initial highway construction cost is large. However, due to the long life-cycle of highways that is expected to be several decades, design and investment decisions must also incorporate maintenance, rehabilitation as well as road user costs. Figure B.3 illustrates a schematic of a typical pavement life-cycle along with associated highway agency and user costs. All these factors must be included in highway design decisions, particularly in a scenario where even longer life-cycles are to be achieved.

Resource Utilization

The highway infrastructure, particularly the flexible pavements that make-up over 90 percent of the country's four million miles of highways, consume massive amounts of energy, water and raw materials. Due to the high energy demand for highway construction, the environmental impact from the highway industry is also very significant. As shown in Figure B.4, the construction industry, and highway industry in particular, consumes by far, the most amount of raw materials in this country [1]. Some energy savings are being achieved through the adoption of warm-mix asphalt, but much needs to be done to make the next generation highway construction technologies to be significantly more sustainable. Also, it is unlikely that the nation's raw materials supply can meet the demands of a total overhaul of the nation's highway system that is badly in need of overhaul. The next generation of pavements needs to have better quality, lower sustainability footprints and must also be significantly longer lasting in order to achieve substantial improvements in the performance of flexible pavement service conditions.

Changing Climate Patterns

In a report published recently by the National Cooperative Highway Research Program (NCHRP), the impact from changing climate patterns on the transportation infrastructure was presented [2]. NCHRP Research Report 750 highlighted the following important observations on future climate change impacts in transportation infrastructure.

1. The evidence points to likely increase in very hot days and heat waves and they will continue to become more intense, longer lasting, and more frequent in most regions during this century. They will lead to premature deterioration of infrastructure. Temperature increases can reduce the life of asphalt pavements through softening of asphalt and traffic-related rutting.

2. Warmer winters will lead to less snow and ice on roadways compared to today, but may possibly increase the incidence of slippery road, while the incidence of frost heave and road damage caused by snow and ice in southern locations is likely to decline.
3. Warmer winters may also lead to an increase in freeze-thaw conditions in northern states, creating frost heaves and potholes on road and bridge surfaces that increase maintenance costs.
4. Pavements built on expansive clays will see the soil movement given the extended periods of wet weather or drought. Repairing such damage is already estimated to cost hundreds of millions of dollars in the United States annually.
5. Precipitation, both rain and snow, will vary widely across the various regions in the United States. These changes are expected to affect highways in several ways, depending on specific regional precipitation levels and geographic conditions.

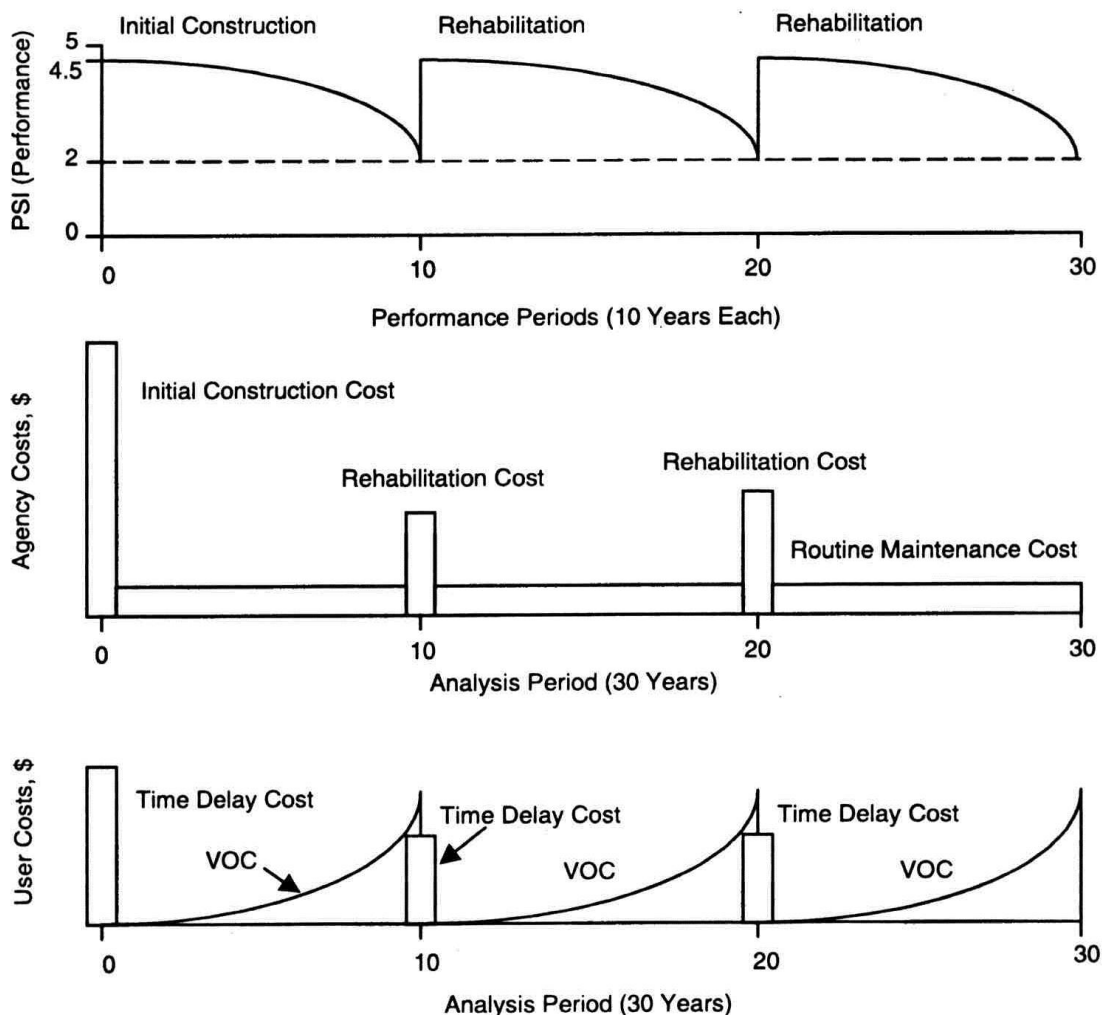


Figure B.3 Schematic of Pavement Life-Cycle and Associated Agency and Road User Costs

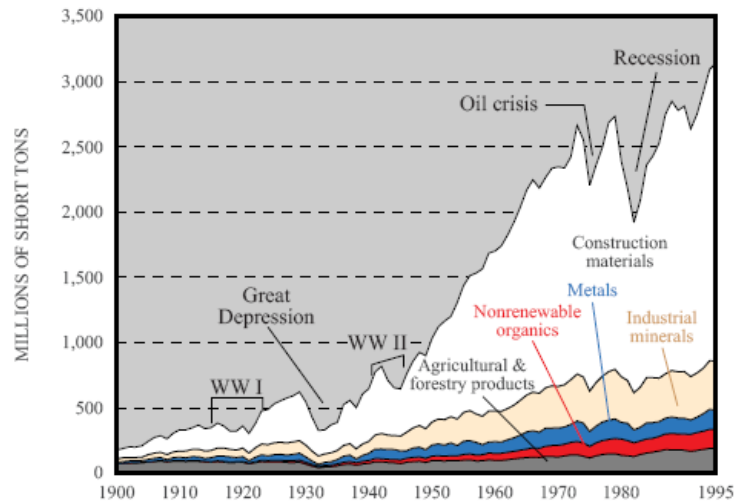


Figure B.4 Raw Materials Consumed in the United States, 1900-1995 [1]

It is the goal of this research project to achieve the following primary objectives to develop novel material systems for the next generation of flexible pavement systems that use asphalt on the surface layer.

1. Significantly extend the pavement performance period (by 50-100%) using the following approaches.
 - a. Improve asphalt material properties using cost-effective polymer modification
 - b. Use thermal control techniques (reducing solar radiation and/or using phase change materials) to maintain pavement temperature within a stable range
 - c. Improve construction quality by adopting modular construction of flexible pavement surface layer
2. Significantly improve key sustainability indicators for highway construction, maintenance and rehabilitation as directed by USDOT and TxDOT
3. Evaluate the feasibility of using asphalt pavement surfaces to generate solar energy

A layered flexible pavement system, similar to that shown in Figure B.5 deteriorate over time due to the following external influences.

- Repeated loading from vehicles
- Influence from ambient climatic conditions such as temperature, precipitation, solar radiation and aging
- Natural ground soil (subgrade) movement with moisture variation in areas of Texas with significant expansive clays present

This research team proposes a pavement configuration illustrated in Figure B.6 that incorporate precast asphalt concrete panels for the surface layer, and a self-leveling material that will effectively seat the precast slab panel on the underlying base layer. It is also proposed to explore novel design and material systems that can mitigate sustainability impacts from the pavement system as well as on the pavement layer system from movements of the natural ground soil (subgrade).

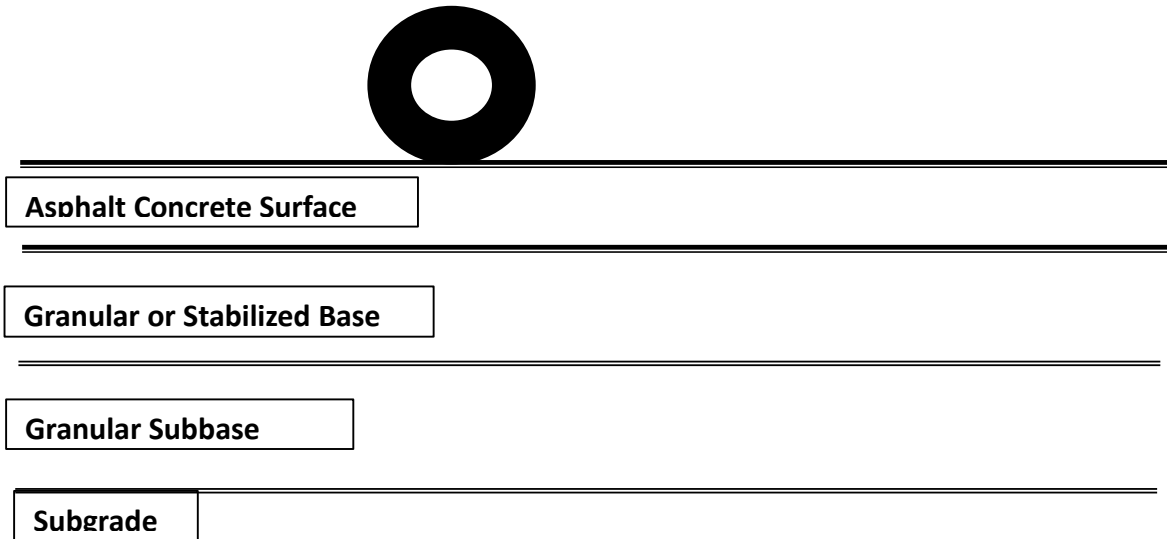


Figure B.5 A Typical Conventional Flexible Pavement Configuration

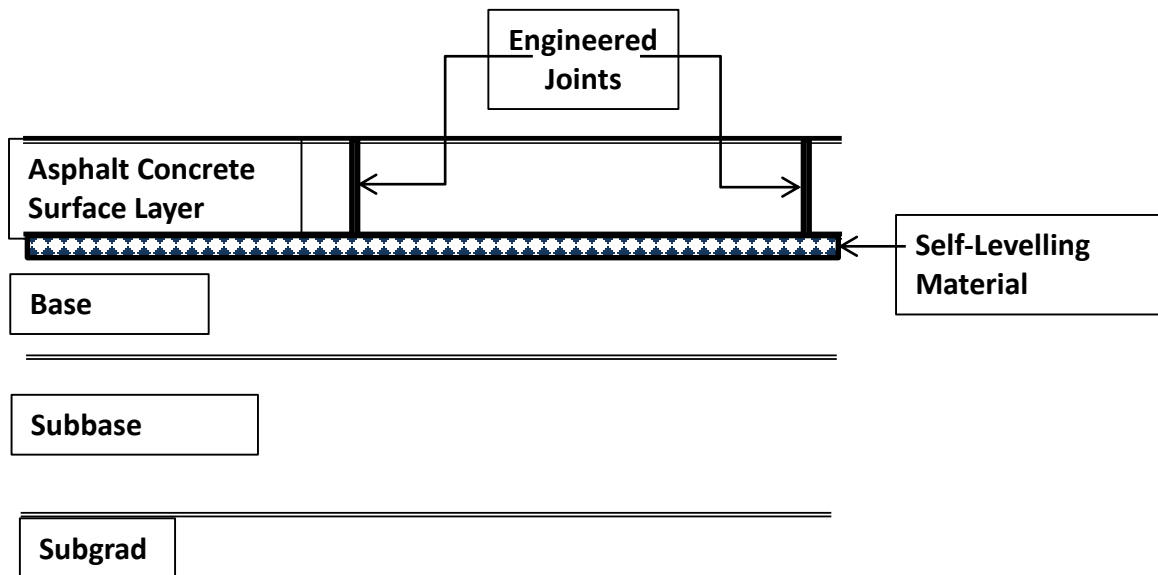


Figure B.6 Novel Layer Configuration Proposed for Flexible Pavements.

Figure B.7 shows detailed schematic of embedded tubes containing phase change materials (pcm) that will be developed in Task 4 of this research. These pcm's will help maintain the temperature of asphalt within a range that will allow the asphalt pavement to perform satisfactorily for a much longer duration than the conventional asphalt concrete does now.

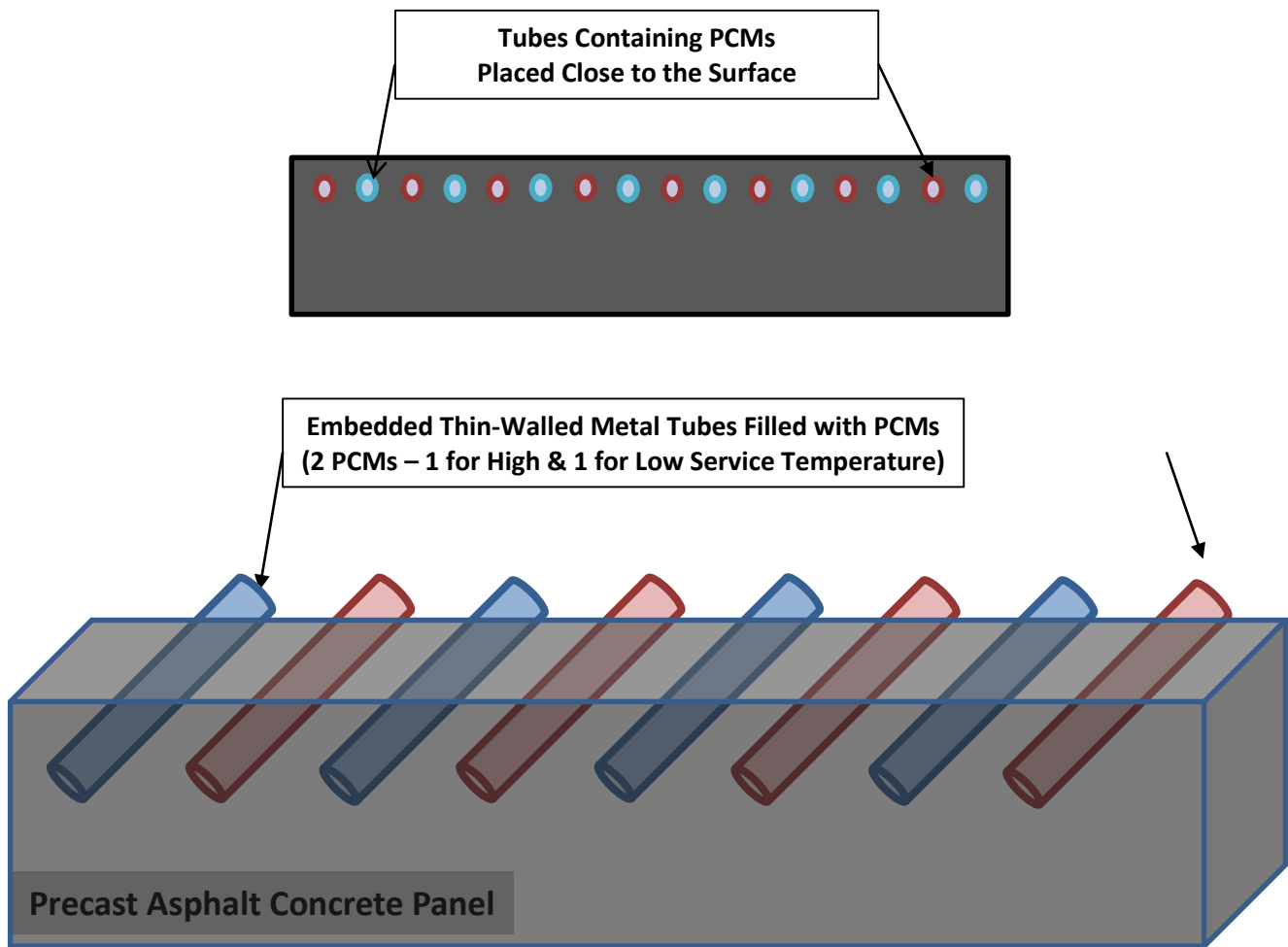


Figure B.7 Schematic of Embedded Tubes Containing Phase Change Materials

Texas has some of the most highly-expansive soils in the United States. These soils underlie almost the entire State, and by extension, most of the Texas roadway network. To illustrate, census data show that about 45 percent of Texas' residents live over soils with "abundant clay having high swelling potential" (shown as *red* in Figure B. 8). In addition to these highest-severity areas, most of the remaining population centers in the State overlie expansive clay soils that swell to a lesser degree (*blue* in Figure B.4). The highly expansive soil deposits contain a significant percentage of clay minerals known as smectites. These minerals have a very high affinity for water and causes the subgrade soils to expand (or swell) when they absorb moisture. Shrinkage occurs as the soil loses moisture, a phenomenon most prominent in the vicinity of trees and other vegetation. Such shrink-swell behavior causes pavement structures (roadways) to develop roughness. Increased pavement roughness in turn leads to greater dynamic loads and premature pavement

failure. Expansive soil subgrades are characterized by their high plasticity indices (PI) and high Potential Vertical Rise (PVR) values¹.

In a State such as Texas where there is significant damage to the highway system due to highly expansive clay, improved design and materials technology can result in significant cost savings. The proposed novel pavement configuration is illustrated in Figure B.6. The system revolves around a new generation of high-quality, factory precast asphalt concrete panels that will have embedded systems to enable effective control of the service climate conditions at desirable levels, thus resulting in longer lasting pavement surfaces. Asphalt must play a significant major role in the next generation of highways because there will continue to be an abundance of asphalt produced from the oil refining process that will continue to be a significant driver of economic growth over the next 50-100 years. On one hand, it is important to research for novel materials that can replace asphalt, but that will not be a socially sustainable solution because the asphalt will then have to be disposed in landfills. A better engineering solution is to significantly increase the service life of asphalt concrete. That is the singular aim of this proposal.

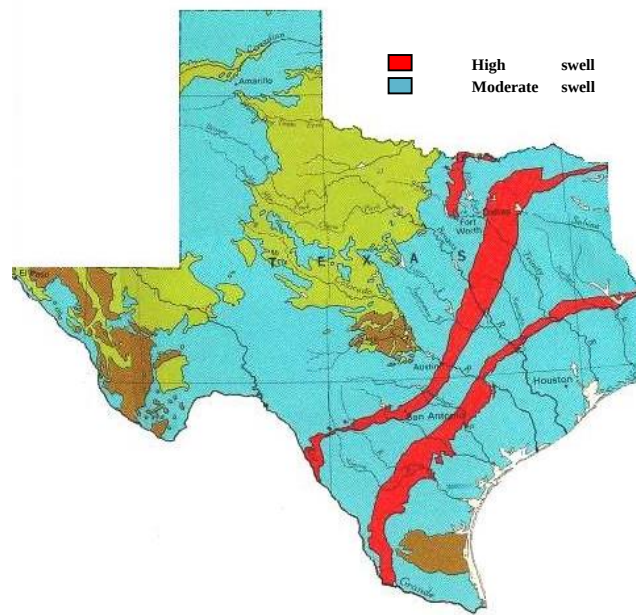


Figure B.8 Geographic Distribution of Expansive Soils in Texas [2]

Modular Technology for Pavement Systems

Pavement repair, rehabilitation and reconstruction are major activities for federal and state highway agencies with a significant impact on their budgets and resources. Lane closures in urban areas are serious and ongoing challenges for DOTs due to construction-related traffic congestion and safety concerns resulting from them. Effective use of modular pavement technologies, principally precast concrete pavement (PCP) systems, shows promise in providing for rapid repair and rehabilitation of pavements and resulting in durable, longer-lasting pavements [3]. Precast pavement systems are fabricated or assembled

¹ TxDOT *Department Material Specifications*. “Test Procedure for Determining Potential Vertical Rise,” TxDOT Designation TEX-124-E. Accessed online: ftp://ftp.dot.state.tx.us/pub/txdot-info/cst/TMS/100-E_series/pdfs/soi124.pdf

² Olive, et al. (1989). *US Geological Survey*. “Swelling Clays Map of the Conterminous United States” Accessed online: http://www.surevoid.com/surevoid_web/soil_maps/intro1.html

off-site, transported to the project site, and installed on a prepared foundation [4]. The main advantages of using PCPs versus cast-in-place (CIP) concrete pavements include better quality control, improved concrete curing conditions, and minimal weather restrictions on placement. Shorter construction time significantly minimizes the impact on the driving public, as lane closures and traffic congestion are kept to a minimum. Road user and worker safety is also improved by reducing road users' and workers' exposure to construction traffic.

Experimental use of PCP in the United States can be dated in the 1970s [5]. In late 1990s, the Federal Highway Administration (FHWA) and the Texas Department of Transportation (DOT) sponsored a study developing a concept for precast prestressed concrete pavement (PPCP) [6]. In March 2002, Texas DOT completed the first pilot project using PPCP along a frontage road near Georgetown, Texas [7]. In recent years, FHWA has actively promoted the PCP concept to state DOTs, and resulted in demonstration projects in California, Delaware, Iowa, Missouri, and Virginia.

The only reported non-rigid modular pavement system, RollPave, was developed by Dutch Ministry of Transport, Public Works and Water Management [8]. As 93% of paved roads and highways in the U.S. use asphalt [9], there is a critical need for developing parallel innovative precast technologies to reduce life cycle cost of flexible pavement by introducing new classes of materials and systems. Such innovations could potentially revolutionize the way that asphalt will be used in future highway construction and improve environmental sustainability.

Life Cycle Assessment (LCA)

Definition

According to ISO 14040 (2006), Life Cycle Assessment (LCA) is a tool that can be used to evaluate the environmental impacts of a product system over its life cycle, from material extraction to end-of-life treatments. The term product system includes physical products and services and the term environmental impacts cover major aspects of environment such as global warming, ozone depletion, energy consumption and land use [10]. The main application of LCA is in designing new products and selecting the friendliest product to the environment among a number of products [10].

LCA Processes

ISO 14040 states that LCA consists of four phases: (1) goal definition and scoping, (2) inventory analysis, (3) life cycle impact assessment (LCIA) and (4) interpretation. Furthermore, according to U.S. Environmental Protection Agency (EPA) (2006), the LCIA is composed by impact categories selection and definition, classification, characterization, normalization, grouping, weighting and evaluating and reporting.

Inventory analysis is the process of listing the quantity of pollutants and the amount of energy and materials consumed. The characterization process is the process of computing the magnitude of impact on a particular impact category caused by an input/output of a process by multiplying the quantity of that input/output by a characterization factor.

In order to allow us to compare the results of characterization process then the impacts are reduced to a common unit by using a reference value (normalization) and then the relative importance of impacts is quantified (weighting) so that they can be summed to produce a single value of environmental impact. Usually total impact of a given community, such as U.S., over a period of time is used as the reference system. For the weighting process, several approaches have been proposed such as distance to target method, panel approach [11, 12] and fuzzy logic [13].

According to ISO standard, normalization, grouping and weighting processes are optional. However, normalization and weighting can add valuable information to the decision makers because normalization allows impact to be compared among impact categories and weighting reflects stakeholders' goals and values (EPA, 2006).

Other important aspect in LCA is that the impacts are computed per product functional unit. For example, if the evaluated product system is asphalt pavement where its function is to provide a safe,

comfortable, economical and durable driving then the relevant functional unit is the area (m²) of the asphalt surface [14]. Expressing the impacts in terms of product's functional unit allows us to fairly compare the impacts of a product with other products.

Impact Categories

Before impacts are characterized, impact categories must be defined. Society of Environmental Toxicology and Chemistry (SETAC) working group has been defined the default impact categories of LCA. They are depletion of abiotic resources, land use, climate change, ozone depletion, human toxicity, ecotoxicity, photo-oxidant formation, acidification and eutrophication. Those impact categories are defined based on the mid-point or problem-oriented approach [10, 12]. Other choice of impact categories is based on the end-point or damage-oriented approach. The mid-point and end-point impact categories for LCA are illustrated in Figure B.9. One example of the end-point approach is Eco-indicator 99 proposed by [15]. Impact categories of the endpoint approach include carcinogenic effects on humans, respiratory effects on human, damage to human health caused by climate change and ozone layer depletion, damage to ecosystem quality caused by acidification and eutrophication, land use, and damage to resources cause by extraction of minerals and fossil. SETAC suggested that the main choice is in mid-point level because end-point approach is not comprehensive, still being developed and possess high uncertainty [10, 12]

Economic input output LCA

Since LCA consider the whole life cycle of product system then the problem in defining the boundary of the study emerges. Therefore most LCA study limits the boundary of the analysis to the significant inputs and outputs at each life cycle stage because collecting the data from the large numbers of related suppliers and processes consumes much time and cost [16]. To solve this problem, the concept of Economic Input Output Life Cycle Assessment (EIO LCA) was introduced. Moreover EIO-LCA also have capability in modeling the interdependencies among industrial sectors involved over product life cycle [16].

The core of EIO LCA is the economic input-output model proposed by Wassily Leontief, a Russian-American economist who won the Nobel Prize in Economics in 1973. His model explains the interdependency among industrial sectors. The basic structure of the economic-input output model is the following.

$$(\mathbf{I} - \mathbf{A})\mathbf{x} = \mathbf{d} \quad (\text{x})$$

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{d} \quad (\text{x})$$

$$\mathbf{A} = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \cdots & \cdots & \cdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix}, \quad \mathbf{x} = \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix}, \quad \mathbf{d} = \begin{pmatrix} d_1 \\ \vdots \\ d_n \end{pmatrix} \quad (\text{x})$$

Matrix $\mathbf{A}$ is called as technological matrix where its element, a_{ij} , represents how much of the i th commodity used to produce the j th commodity. The commodities produced by n industrial sectors are aimed to fulfill the final demand (open sectors), $\mathbf{d}$. Since the open sectors are not included in $\mathbf{A}$, then $\sum_{i=1}^n a_{ij} < 1, (j = 1, 2, \dots, n)$. The output of each sector that is satisfied the final demand is denoted as $\mathbf{x}$. If the environmental impact per dollar output of each sector is known then the vector of environmental outputs can be easily obtained and is given by the following [17].

$$\mathbf{b} = \mathbf{R}\mathbf{x} = \mathbf{R}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{d} \quad (\text{x})$$

$\mathbf{b}$ denotes the vector of environmental impacts and $\mathbf{R}$ is a matrix where its diagonal is environmental impact per dollar value of output.

Since monetary value is used in EIO LCA then price variability may distort physical flows within industrial sectors. To address this problem a hybrid approach (combining “conventional” LCA and EIO LCA) can be used [18].

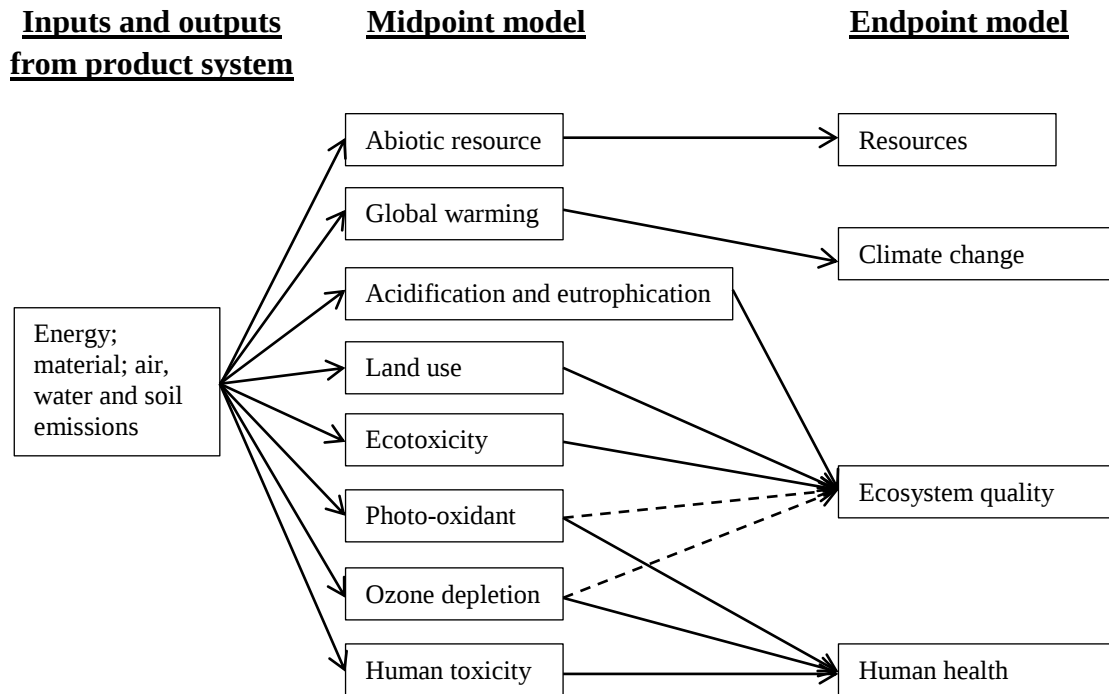


Figure B.9 Midpoint and endpoint impact categories [12]

References

1. USGS (1998), “Materials Flow and Sustainability,” *Fact Sheet FS-068-98*, U. S. Geological Survey, U.S. Department of Interior.
2. Michael Meyer, Michael Flood, Jake Keller, Justin Lennon, Gary McVoy, Chris Dorney, Ken Leonard, Robert Hyman, Joel Smith, *Strategic Issues Facing Transportation Volume 2 : Climate Change, Extreme Weather Events, and the Highway System: Practitioner’s Guide and Research Report. Report No. 750*, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C. 2014.
3. Tayabji, S., Ye, D., Buch, N. 2013. Precast Concrete Pavement Technology, REPORT S2-R05-RR-1, Transportation Research Board, Washington, D.C.
http://onlinepubs.trb.org/onlinepubs/shrp2/SHRP2_S2-R05-RR-1.pdf. Accessed April 15, 2014
4. Federal Highway Administration. 2010. Precast Concrete Panels for Repair and Rehabilitation of Jointed Concrete Pavements. Tech brief. IF-09-003. FHWA, U.S. Department of Transportation, Washington, D.C. www.fhwa.dot.gov/pavement/concrete/pubs/if09003/if09003.pdf Accessed April 15, 2014
5. Simonsen, J. E. 1971. Concrete Pavement Joint Repair with Pre-Cast Slabs: Progress Report. Research report R-762. Michigan State Highway Commission, Lansing.
6. Merritt, D. K., B. F. McCullough, N. H. Burns, and A. K. Schindler. 2000. The Feasibility of Using Precast Concrete Panels to Expedite Highway Pavement Construction. Report TX-01/1517-1. FHWA, Texas Department of Transportation, Austin.

7. Merritt, D. K., B. F. McCullough, and N. H. Burns. 2002. Construction and Preliminary Monitoring of the Georgetown, Texas Precast Prestressed Concrete Pavement. Report TX-03-1517-01-IMP-1. FHWA, Texas Department of Transportation, Austin.
8. Houben, L. J. M., Van Der Kooij, J., Naus, R. W. M., & Bhairo, P. D. 2004. APT Testing of Modular Pavement Structure 'Rollpave' and Comparison with conventional asphalt motorway structures. *Accelerated Pavement Testing*, 1-24.
9. Federal Highway Administration. 2012. Highway Statistics 2012. FHWA, U.S. Department of Transportation, Washington, D.C. <http://www.fhwa.dot.gov/policyinformation/statistics/2012/>., Accessed April 15, 2014
10. Guinee, J., Gorree, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A., et al. (2002). Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Dordrecht: Kluwer Academic Publishers.
11. Lee, K. M. (1999). A Weighting Method for the Korean Eco-Indicator. *Int J. LCA*, 4(3), 161-165.
12. Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., et al. (2003). IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. *Int J. LCA*, 8(6), 324-330.
13. Afrinaldi, F., Zhang, H.-C. (2013). A Fuzzy Logic Based Aggregation Method for Life Cycle Impact Assessment. *Journal of Cleaner Production*, 57 (2014), 159 – 172.
14. Huang, Y., Bird, R., Heidrich, O. (2009). Development of a life cycle assessment tool for construction and maintenance of asphalt pavements. *Journal of Cleaner Production*, 17(2), 283-296.
15. Goedkoop, M., & Spriensma, R. (2000). The Eco-Indicator 99: A Damage Oriented Method for Life Cycle Impact Assessment. Amersfoort, The Netherlands: Pre Consultant b. v.
16. Joshi, S. (2000). Product Environmental Life-Cycle Assessment Using Input-Output Techniques. *Journal of Industrial Ecology*, 3 (2 & 3).
17. Hendricson, C.T., Lave, L. B., Matthews, H. S. (2006). Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach. Routledge.
18. Suh, S., Lenzen, M., Treloar, G. J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., Norris, G. (2004). System Boundary Selection in Life-Cycle.