Chapter 2
Application of LCA Results to Network-Level Highway Pavement Management

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Abstract Environmental life cycle assessment (LCA) is a method developed in the 1960s for identifying environmental objectives, defining the system to be analyzed, quantifying environmentally important inputs and outputs to the system over a life cycle, and assessing the impacts. The application of LCA to pavements is a relatively new development. Pavement management systems (PMS) have been developed and implemented since the 1970s to manage pavement network asset inventories, collect condition data, predict performance for various management decisions and report the results to support decision-making needed to meet performance and cost objectives. This chapter discusses the relationship between LCA and PMS and benefits of integrating LCA into PMS. An example is provided for the objective of reducing greenhouse gas emissions on a state highway network. Gaps in implementation are identified, and recommendations are made for future work.

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2.1 Framework, Objectives and Needs

2.1.1 Background: Pavement Management Systems and Life Cycle Assessment

2.1.1.1 Pavement Management Systems

Pavements are a fundamental part of modern societies. Movement of goods and people, using vehicles that currently primarily burn fossil fuels, depends on networks of reliable highway pavements. The management of these networks to meet the objectives of a society within various constraints is an essential activity. Pavement management involves all the activities involved in planning, design, construction, maintenance and rehabilitation (M&R) for a network of roadways, in order to optimize the overall pavement conditions over the entire network, usually with constrained resources (Shahin 2005). Pavement management systems (PMS) have been developed and implemented since the 1970s to manage pavement network asset inventories, collect condition data, predict performance for various management decisions and report the results to support decision-making needed to meet performance and cost objectives. Since the 1980s, most road owning organizations in North America have moved towards performing this work through a PMS, and the use of asset management systems in general is increasingly required by law.

Pavement management systems and sustainability considerations are discussed in general in another Chapter of this book. The following introductory discussion of PMS is focused on background information for implementation of LCA in network level considerations, with particular focus on environmental impact trade-offs between materials production and construction for M&R treatments and vehicle use impacts.

A PMS has been defined as consisting of three major components:

1. a system to regularly collect highway condition data
2. a computer database to sort and store the collected data
3. an analysis program to evaluate repair or preservation strategies and suggest cost-effective projects to maintain highway conditions (Federal Highway Administration 2013a).

PMS analysis programs typically include a set of tools or methods which help to identify current pavement conditions, predict future pavement conditions, estimate costs, and identify and prioritize pavement M&R projects. Most PMS also include processes for regularly collecting and loading into the database information about construction (treatment type, structural change, location, date and cost), traffic and climate, as well as extensive software tools for visualization and reporting.

A generic PMS can be split into two main functions: storing data about the current and past conditions of the network, and tracking current and future projects

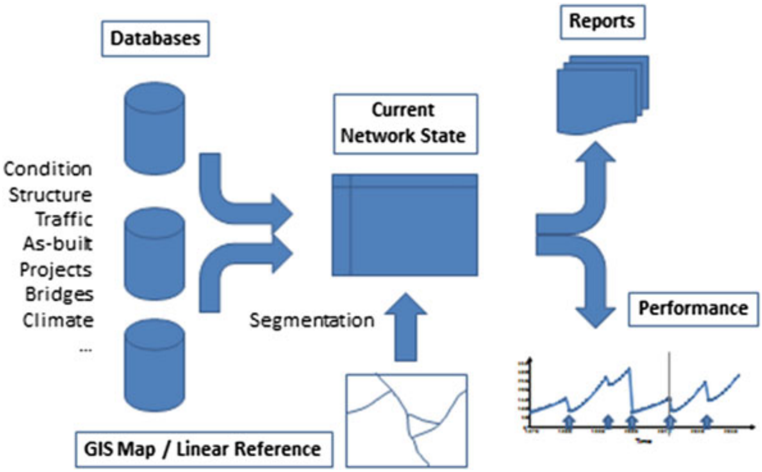

Fig. 2.1 Generic PMS

to change the network. Figure 2.1 shows the first aspect of a generic PMS, including the division of the network into segments with similar structure, traffic and climate, which is the level at which treatment decisions are made. Figure 2.2 shows the typical PMS work flow for the second aspect. This tracking of projects is performed continuously, both as the network changes and as projects are executed. However, most agencies work on an annual cycle to develop annual pavement repair/preservation programs with the goal of meeting the defined objectives for the pavement network within budget and political constraints. Defining those objectives and constraints and performing some sort of optimization is part of many PMS, and there are various kinds of objectives and optimization that are used, as is discussed later in this chapter.

Treatment decision-making at the network level in the PMS typically results in the selection of a general treatment type based on the data available. In the broader sense, pavement management also includes the policies, processes and tools used to perform in-depth evaluation and design for the network segments selected for treatment, which is referred to as project-level pavement management. Outcomes of project-level pavement management are the details of the treatment, such as material types and layer thicknesses, more precise cost estimates and construction specifications.

Data collected at the network level is typically selected from the following:

- Ride quality data in terms of the International Roughness Index (IRI). In some cases IRI is translated back to previous ride quality indices to provide continuity in time histories; and
- Surface distress data, which can include:

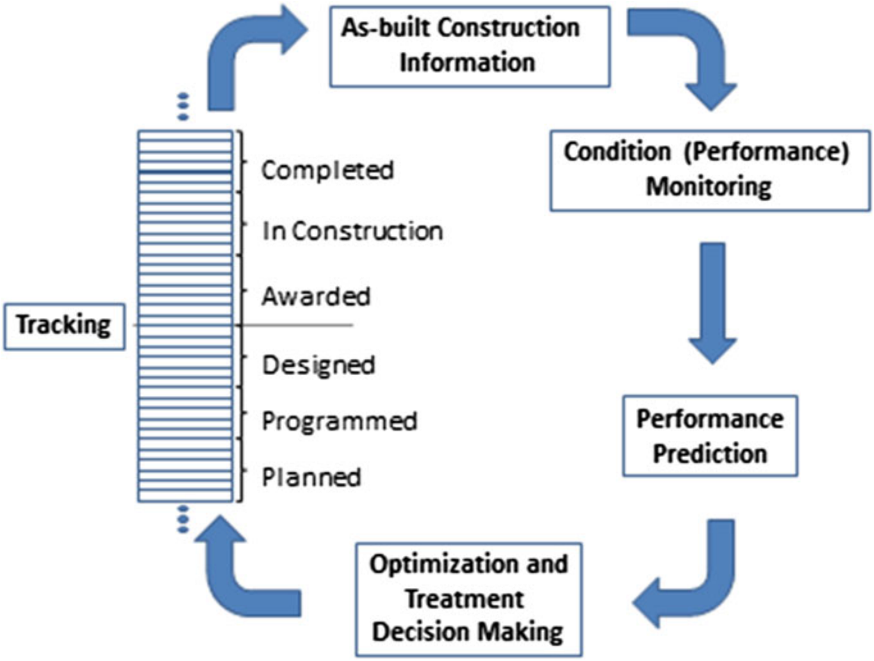

Fig. 2.2 Generic annual work flow of PMS

– Cracking

  Traffic load related cracking in the wheelpaths and non-load related cracking out of the wheelpath for asphalt surfaced pavements caused primarily by environmental conditions such as low temperatures, rapid changes in temperature, and aging of the asphalt due to exposure to heat and air.

  Various types of cracking (transverse, corner, longitudinal) for concrete surfaced pavement caused by interaction of traffic loading and environmental loading such as temperature gradients, drying shrinkage gradients.

– Load related surface problems such as rutting, raveling and potholes, often accelerated by moisture damage for asphalt surfaced pavements, and faulting and punchouts for different kinds of concrete surfaces.
– Other climate or materials related problems such as raveling for asphalt pavements and D-cracking for concrete pavements.

The data collected are dependent on the pavement management network-level objectives of the agency, and may also support other types of required reporting and improvement of project-level objectives. Research starting in the late 1950s at the AASHO Road Test (Highway Research Board 1961) has shown that the users of the pavement primarily care about the ride quality, and generally do not care much about surface distresses unless they are severe. However, pavement engineers need to pay attention to surface distresses because ride quality is affected when they reach an advanced state, and because surface distresses lead to more rapid and serious deterioration of the pavement structure. Pavements can have poor ride quality from the time of construction, which can be managed through design and specifications for construction smoothness, whether it is new construction, rehabilitation or maintenance. Specifications that are based on measurement of IRI, as opposed to older methods of profile control, such as the profilograph, have been shown to be more effective in obtaining smooth pavement (Karamihas 2004). Ride quality is often not affected when initial cracking or other distress mechanisms first appear on the pavement surface, and only deteriorate rapidly when the surface distresses move to an advanced state. For this reason, ride quality is a lagging indicator of deterioration within the pavement.

Based on this relationship between ride quality and surface distresses, and the road users' concern about ride quality and not distresses, it might be surmised that treatment should only be applied when the ride quality is bad enough for the users to notice. However, the caveat is that the cost of treating a pavement to bring it to an acceptable ride quality condition when it is in an advanced state of deterioration is much higher than when damage mechanisms are just beginning to appear as surface distresses. The cost of a rehabilitation treatment can be approximately two to ten times greater than that of a maintenance treatment (Galehouse et al. 2003; Sinha et al. 2005; Smith et al. 2005). Applying treatments at about the time that cracking is appearing and before the cracks let water into the pavement and accelerate the damage process is referred to as "pavement preservation" (Federal Highway Administration 2005). Rough pavements also accelerate the damage process by inducing dynamic effects in the suspension of the heavy vehicles which causes them to bounce as the move down the pavement, applying heavier loads than would be indicated by the static load of the wheels, by as much as 20 % (OECD 1998; Cebon 1999). The difference in the cost of the treatments does not mean that the life cycle cost is two to ten times less for preservation than rehabilitation, because preservation treatments must be applied more frequently than rehabilitation treatments. However, research has provided preliminary indications that a strategy of applying several properly timed pavement preservation treatments between rehabilitation treatments can reduce life cycle cost by up to about 20 % (Smith et al. 2005; Lee 2010; Harvey et al. 2012b). Preservation treatments can also be used to help maintain the smoothness of the pavement surface, particularly when there is a construction smoothness specification.

Most state and provincial departments of transportation and some local government road agencies in North America use life cycle cost analysis (LCCA) to help them make decisions at the project level, such as selection of pavement structure type, design life and rehabilitation type. Life cycle cost considers the cost of the initial construction and project management, and the expected sequence of future maintenance and rehabilitation treatments that are dependent on the initial new pavement or rehabilitation decisions. LCCA may also include road user costs such as traffic delay or total road user costs including vehicle operating costs and safety

(Federal Highway Administration 1998; Bennett and Greenwood 2002). An example plot of life cycle costs is shown in Fig. 2.3 (Federal Highway Administration 2002). The plot includes the costs to the pavement owner of initial construction and the maintenance and rehabilitation that follow in the analysis period and whatever road user costs are included in the analysis. All of these costs are summed, typically considering a discount rate, either as the Net Present Value or an Equivalent Uniform Annual Cost. If the rehabilitation or maintenance retains value past the end of the analysis period then a "salvage value" is subtracted from the summation of the costs.

Although there has been a great deal of academic research on optimization in network level pavement management, selection of a program of treatments for a year or for a multi-year horizon in practice today typically does not include life cycle cost optimization directly. The reason for this is that LCCA requires a future stream of activities, but the goal of network-level PMS decision making is to determine this set of activities. There are no optimization algorithms that allow for the simultaneous selection of optimal future actions on a segment and the selection of actions across segments within a given time period. Network-level PMS research has focused on using generic performance models and treatment types to determine optimal intervention strategies (such as "place a thin overlay every eight years", or "grind the pavement when the roughness reaches 170 in/mi"). These are then implemented within the software as decision trees that trigger a project when the criteria are met. This theoretically results in an optimal selection of projects across the network.

However, in most cases, the agency using the PMS is interested in determining specific locations in need of treatment and constraining the cost of treatment to some budget. As a result it is necessary to perform an additional constrained optimization within each time period to select the specific treatments to implement, and this requires some basis to rank treatments. For this purpose, many states and

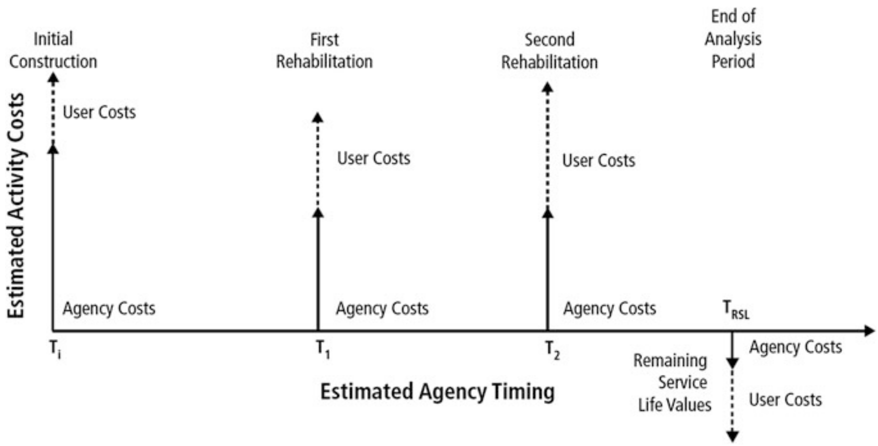

Fig. 2.3 Example LCCA plot (Federal Highway Administration 2002)

local agencies use various types of benefit/cost analysis, where the benefits are calculated in terms of the difference in pavement condition over the analysis time horizon between treating the pavement and not treating it, in terms ride quality or surface distresses or a combination of the two (Hudson et al. 2011). The difference in condition between treating and not treating the pavement is estimated using performance prediction equations, that are typically based on empirical regression of past ride quality and surface distress data.

2.1.1.2 Life Cycle Assessment

Environmental life cycle assessment (LCA) is a method developed in the 1960s for identifying environmental objectives, defining the system to be analyzed, quantifying environmentally important inputs and outputs to the system over a life cycle, and assessing the impacts (Guinée 2012). LCA is used to analyze the environmental impacts of an industrial product, and is used for the following four purposes (International Organization for Standardization 2006):

- Identifying opportunities to improve the environmental performance of products at various points in their life cycle.
- Informing decision-makers in industry, government or non-government organizations (e.g., for the purpose of strategic planning, priority setting, product or process design or redesign).
- The selection of relevant indicators of environmental performance, including measurement techniques.
- Quantifying product information (e.g., implementing an eco-labeling scheme, making an environmental claim, or producing an environmental product declaration).

LCA examines a product from cradle to grave, evaluating all the inputs and outputs from raw material production to the final end-of-life. LCA can be used for comparing products, and identifying the benefits and impacts of changes in the production, use and end-of-life (EOL) of a given product. LCA can help identify unintended negative consequences that can occur when making changes in a system or product, such as a pavement network, to help reduce the environmental impact. LCA helps identify unintended consequences of changes by applying the concepts of system analysis and consideration of effects over longer time horizons included in the decision-making process. LCA can also be used to support decision-making when tradeoffs between competing environmental goals must be considered.

The system boundaries for LCA are often determined by the goal of the assessment, which can be grouped into the following two categories, although both types of goals may be included in the assessment:

1. Modeling and quantitative assessment of the inputs and outputs from production and use of an industrial product that considers total system-wide environmental

burdens and the entire life cycle of the product, and then assesses the impacts on humans and the environment, referred to as *attributional analysis*, and
2. Modeling and quantitative assessment of the consequences of changes in the systems, through calculation of the resultant inputs and outputs over the life cycle and assessment of the corresponding impacts, referred to as *consequential analysis*.

For pavement environmental assessment, the life cycle includes the material production, construction, use, M&R, and end-of-life (EOL) phases. Figure 2.4 shows an example of a generic pavement life cycle for LCA.

The materials production and construction phases of both new pavement construction and M&R are discussed in detail in other chapters in this book. Practices for minimization of virgin materials use through recycling, shorter materials transportation distances, and use of lower impact materials are the primary means of reducing environmental impact. As can be seen in Fig. 2.4, there are a number of different sources of environmental impacts that can be considered in the use phase.

Decisions must be made when performing an LCA regarding what will be considered in the assessment and what will be left out, depending on the goal of the assessment. Of the impact sources shown in the figure, vehicle operation is the one that is applicable for all of the pavements in a road network, and is the primary one considered in this chapter. Lighting and heat island effects primarily have to do with selection and maintenance of the reflectivity of the pavement surface. Stormwater runoff can be influenced by pavement maintenance but is mostly affected by drainage and stormwater treatment design and maintenance. In the end-of-life

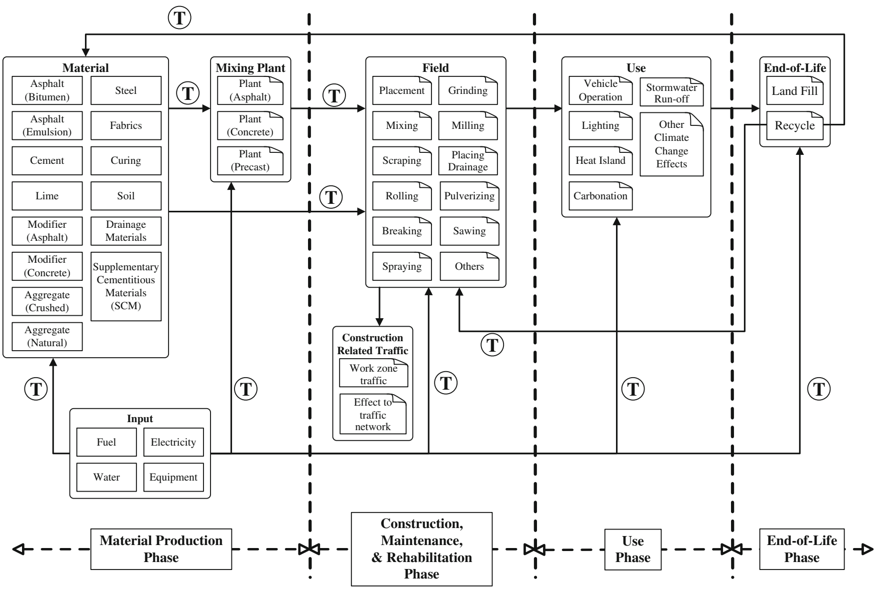

Fig. 2.4 Example diagram of generic pavement life cycle system (Wang et al. 2012a)

phase, recycling brings materials from the existing pavement or from other pavement sources into the new treatment and includes consideration of any transportation, processing and mixing with virgin materials during construction. Some materials remain in place for the entire analysis period.

Vehicle operation in the use phase is typically considered in terms of the effects of the pavement on the fuel efficiency and emissions of vehicles through three mechanisms which together can be called the pavement related rolling resistance, although that is not a precise definition of rolling resistance. The pavement influences can be summarized as follows:

1. Consumption of energy through the working of shock absorbers, drive train components, and deformation of tire sidewalls as the wheels pass over deviations from a flat surface with wavelengths between 0.5 and 50 m in the wheelpath—converting mechanical energy into heat which is then dissipated into the air—and thus requires greater work by the engine. This mechanism is managed by maintaining smoother pavement as measured by IRI. Models for this mechanism are well established and there has been validation by direct measurement.
2. Consumption of energy through viscoelastic working of the tire rubber in the tire/pavement contact patch as it passes over positive macrotexture of the pavement surface and converts it into heat that is dissipated into the tire and the air. Positive macrotexture is caused by stones or grinding/grooving features protruding above the average plane of the pavement surface. Pavements for high speed vehicles must have a minimum amount of macrotexture on the surface, and/or be permeable, in order to remove water films from the pavement surface and to provide frictional resistance for steering and braking. This mechanism is controlled by design of surface treatment, asphalt and concrete mixes and by concrete surface texturing. Raveling on asphalt surfaces and matrix loss on concrete surfaces can increase macrotexture after construction. Models for this mechanism are well established and there has been validation by direct measurement.
3. Consumption of energy in the pavement itself through viscoelastic deformation of pavement materials under passing vehicles, primarily heavy trucks, which has also been modeled in terms of the geometric relationship between the shape of the deflected pavement under the wheel and the wheel itself. The significance of this mechanism for different types of pavement, different vehicles and vehicle operations, and climate regions, has not been clearly established. Experiments have shown that this mechanism can have a significant effect for slow moving heavy vehicles operating on hot viscoelastic pavement, but the significance and models for other vehicles and conditions is not yet well verified. Models with different approaches have been developed, but have not been comprehensively compared or validated with direct measurement.

The relative importance of these mechanisms varies depending on pavement type, climate, materials, traffic characteristics (vehicle types, speeds, chain use) and surface roughness and texture management practices. Other effects of the pavement on vehicle operation, such as the environmental impact of more frequent replacement of tires, vehicle components, and the life of the vehicles themselves are generally not considered, but could be.

2.1.2 Objectives of Current Pavement Management Systems and Consideration of Environmental Objectives

The objectives of a pavement management system can include many important goals, and are selected based on what is most important to each road owning agency. To a degree, traditional pavement management objectives can be grouped into two categories, with the titles borrowed from the Strategic Plan of the California Department of Transportation (Caltrans) (Caltrans 2007):

- Mobility, which can related to "functionality", meaning keeping the pavement safe and efficient for the road user, which is what the user cares most about;
- Stewardship, which can be related to maintaining the structural condition of the pavement, which is what the owner often cares most about.

A review of the objectives of a sample of state and provincial pavement management systems by the authors revealed that the most common mobility objective is articulated in terms of ride quality, as quantified by the IRI. This can be included in the optimization and constraint functions of the PMS in terms of minimizing IRI over the network, IRI trigger values in decision trees for M&R, or maximization of IRI benefits for a given cost. Since mobility objectives have to do with maximizing the benefits of network operation for the road user, IRI objectives are sometimes weighted based on traffic levels. At a next level, total road user cost equations as a function of IRI and vehicle types in the traffic flow can be used for optimization (Harvey et al. 2012a). IRI is the pavement condition parameter that the states are required to report by the Federal Highway Administration (FHWA) as part of the Highway Performance Monitoring System (HPMS). The MAP-21 transportation funding legislation increases the scope of the National Highway System to include principal arterials, which might be managed by local government, and would require annual IRI measurements on these routes. In addition, MAP-21 requires performance based management of all roads receiving federal funding, and it is highly likely that IRI will be the primary performance measure used.

The most common stewardship objectives seen in state PMS implementation are articulated in terms of the level of surface distresses. These may be expressed in terms of particular distresses, such as load related cracking in the wheelpaths for asphalt surfaced pavements and cracking in concrete pavements, or in terms of an aggregation of surface distresses with various scales and weighting equations reported in terms of a Pavement Condition Index (PCI), typically normalized to a 100 (best condition) to zero (worst condition) scale. When the objectives are in terms of specific surface distresses, the implementation can be in terms of constraints for maximum allowable extents for different severities of the most important surface distresses and optimization of the amount of the network with those distresses. Typical implementation of PCI based objectives is in terms of constraints for minimum PCI values, or optimization to maximize the PCI on the network.

Consideration of environmental indicators in pavement management is receiving increasing attention due to the growing concern regarding the environmental impact of pavement management and practices, particularly with regard to human causes of climate change. Currently, environmental indicators are generally not included in the evaluation of alternative strategies at the network level. Life cycle assessment is one of the approaches commonly adopted to evaluate environmental impacts. However, most effort to date has focused either on project level assessments, with most of those focused on the materials production and construction phases according to a relatively recent review by Santero et al. (2011b). Recent work has included more focus on environmental impacts of pavement condition and structure on vehicle use. Pilot studies have been performed to incorporate LCA results within the traditional cost-based framework in pavement management using multi-criteria optimization (Lidicker et al. 2013).

It will be seen in the remainder of this chapter that traditional mobility and stewardship objectives for PMS decision-making result in different environmental impacts, which can be dealt with through implementation of LCA at the network level.

2.1.3 Selection of Objectives for Network-Level Analysis of Environmental Impacts

According to ISO standards, a complete LCA study should include life cycle impact assessment (International Organization for Standardization 2006). Life cycle impact assessment is the part of LCA where various life cycle inventory results are translated into the evaluation of potential human health and environmental impacts. The LCA guideline published by the U.S. Environmental Protection Agency (EPA) has selected eleven commonly used life cycle impact categories (U.S. Environmental Protection Agency 2006), including:

1. Global warming
2. Stratospheric ozone depletion
3. Acidification
4. Eutrophication
5. Photochemical smog
6. Terrestrial toxicity
7. Aquatic toxicity
8. Human health
9. Resource depletion

10. Land use
11. Water use.

The ISO has used nine similar categories (International Organization for Standardization 2006). A number of studies have selected the commonly used impact categories and developed the detailed methodology for impact assessment, such as the TRACI impact assessment methodology (Bare 2011; U.S. Environmental Protection Agency 2012) and the CML methodology (Guinée et al. 2002). TRACI is the most commonly used methodology for impact assessment. The most recent version of TRACI (v2.1) was released in 2012, using midpoint indicators on ten impact categories and detailed methods for characterization. Normalization and weighting are not included in TRACI due to their high uncertainties. The CML methodology is another widely used global impact assessment method, with detailed guidelines regarding impact category selection, characterization, normalization and weighting.

As can be seen, there are a large number of impact categories that can be considered, and some assessment should be made in decision-making to check that optimization of one or more categories does not cause unintended large increases in others. However, it is clear that only a few objectives can formally be included in decision-making in a PMS and that many of the categories will not be significantly affected by most PMS decisions. Most LCA databases include information needed to consider most of these impact categories quantitatively although they often do not fully account for regional variability of impact and can become out of date as practice changes.

Many road owning agencies have developed objectives that are considered environmentally beneficial, but have not necessarily been tested in terms of their life cycle impacts, or in terms of their effects on the impact categories used by the US EPA and ISO that are listed above. Some typical objectives that can be seen today are for the amount of recycled material to be used, which is part of the life cycle that by itself does not determine how it affects the total life cycle impacts. For example, inclusion of some types of recycled materials into pavement treatments may result in increases in resource depletion as well as other impacts over the life cycle because the recycled material poses toxicity problems that prevent future recycling of the pavement, or it causes poor performance which results in more frequent need for treatment. For these reasons it is recommended that a life cycle analysis be performed, and that each impact category be at least cursorily considered in the assessment.

It can be argued that the most important impact category affecting all species of life and the underlying ecology of the entire planet is global warming, and that it has overlapping effects on many of the other categories such as acidification of ocean waters, photochemical smog (through increases in temperature), impacts on terrestrial and aquatic life (through changes in climate conditions), human health (through increases in temperature, severe weather events, climate change affecting agriculture and sea level rise) and water use (through climate induced drought reducing supply). Pavement management can have a definite impact on global warming (and related energy use) and resource use (aggregate, asphalt, cement, lime, steel and other resources to a lesser degree), as two important measures of environmental impact affecting sustainability. Global warming reductions in the transportation sector caused by reductions in burning of vehicle fuels derived from oil will also have positive impacts on photochemical smog, terrestrial toxicity, aquatic toxicity, human health and resource depletion. Reductions in ethanol based fuels will also have positive impacts in other categories including land use, water use and human health through increases in food prices. Other impact categories are also important, with the importance varying depending on local conditions and practices which should be taken into consideration when prioritizing the goals of the LCA.

2.1.4 PMS System Requirements to Meet Objectives

2.1.4.1 Network-Level Decisions

A number of different decisions can be made to achieve network-level environmental impact objectives in the PMS. In each case the life cycle must be considered, including the effects of materials production, construction, performance in the use phase including the functional life, and the end-of-life considering the ability to recycle and any constraints on future decisions imposed by the current decision. The decisions can be supported by analyses performed directly in the PMS, or through analyses performed outside of the PMS and then included as policy in the PMS. Some types of decisions include:

- M&R design life selection for inclusion in the PMS decision trees, or comparison in the PMS of alternative design lives for each segment.
- M&R treatment selection for inclusion in the PMS decision trees, or comparison in the PMS of alternative design lives for each segment.
- M&R trigger levels based on pavement condition for inclusion in the PMS decision trees, or comparison in the PMS of alternative design lives for each segment.
- Allocation of funding for M&R of pavement versus other transportation investments; this decision would be made at the level of allocation of transportation funds, but the PMS can be used to compare the environmental impacts of pavement M&R versus other transportation investments to help determine pavement funding levels.

In all of these cases, the decisions need to be based on comparison of the environmental impacts of different treatments for the situations that occur in the network, considering pavement type and condition, traffic levels, climate and availability of materials and contractor capabilities. These will likely be very different between networks, as well as within networks.

2.1.4.2 Required Data and Modeling

Life cycle inventory (LCI) data is needed for the M&R treatments included in the PMS. LCI data is the "accounting" of inputs into the life cycle, such as materials, energy and other resources, and the environmental outputs of emissions, pollution and waste. These input and output data that are needed depend on the impact categories that are being quantitatively assessed.

The LCI data is typically organized by constituent materials, such as aggregate, asphalt and cement, used in pavement materials. Some of the current gaps in LCI data for pavement materials, as well as efforts and approaches to fill those gaps, are discussed elsewhere in this book, and in references such as Harvey et al. (2011), Santero et al. (2011a), Federal Highway Administration (2013b) and Lee (2013). LCI data for materials production and construction should be relevant to the region where the PMS has been implemented, and updated to consider changes in materials production and construction data over time. LCI for the use phase should be relevant to the vehicle fleet, traffic operating speeds, climate and other regional conditions.

Treatment selection and triggering models are also needed to determine what decisions regarding treatment will be made for different pavement conditions.

Pavement performance models are needed to determine when treatments will be triggered. Pavement performance models in many PMS are in terms of Pavement Condition Index. Additional performance models for roughness, texture and/or deflection are needed for the use phase for consideration of vehicle energy use, depending on which mechanisms of vehicle fuel use are being modeled.

Additional data may be needed to support models in the PMS including traffic data (volume, vehicle composition, speeds, and hourly flows) and climate data (temperatures and rainfall). Cost data are needed to be able to bring economic considerations into the environmental assessment, and can include road user costs as well as road owner costs.

2.2 Example Application to a PMS System

2.2.1 Goal, Impact Category and Network Considered

2.2.1.1 Goal and Impact Category

The example is taken from a study performed for the California state highway network (Wang et al. 2014). Global warming is the focus of the example presented in this chapter, with energy use selected as a secondary impact category. The goal of the application is to develop the optimal roughness value (indicated by IRI) to trigger a maintenance treatment that brings the largest GHG emission reduction on the state highway pavement network in California compared to no strategic intervention on the pavement condition (*Do Nothing*), for inclusion in the PMS.

The GHG emission reduction were also calculated to compare with recently implemented Caltrans IRI trigger values.

In this example, a set of common M&R treatments used by California Department of Transportation (Caltrans) was included in the analysis. The set is not exhaustive, but the approach developed can be extended to consider other M&R treatments as data become available and as common practices change.

Global warming was selected in this example because of passage of California Assembly Bill 32 (AB 32) in 2006 which commits the state to meeting the following goals for reducing GHG emissions:

- By 2020: return to 1990 emission levels
- By 2050: reduce emissions to 20 % of 1990 levels.

It is clear from the Scoping Plan for AB 32 (California Air Resources Board 2013) that these goals cannot be met with a handful of strategies, and that they require contributions from nearly every sector of the economy. Lutsey indicated that meeting the 2050 goals will be difficult for the transportation sector with existing proposed strategies and that additional strategies are needed (Lutsey 2008). One strategy not previously considered is reducing fuel use by on-road vehicles caused by the three pavement mechanisms described previously, roughness, rough textures, and high deflections, which can have an important impact because of the large contributions to environmental degradation from road transportation in North America. An example is shown in Fig. 2.5, which shows GHG emissions produced

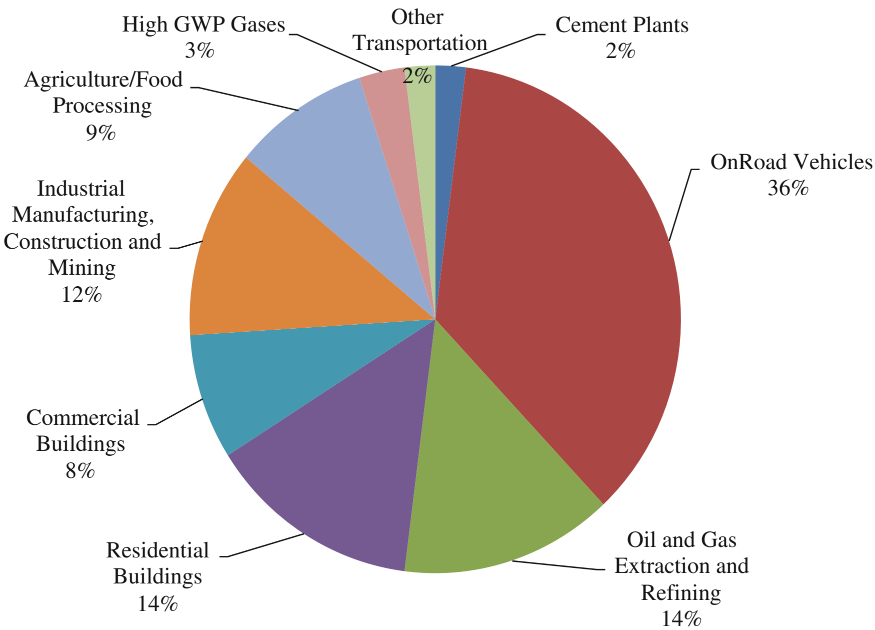

Fig. 2.5 California's greenhouse gas emissions (2002–2004 average), direct emissions based on end use (California Air Resources Board 2008)

in California by different industrial sectors in 2008 (California Air Resources Board 2008). Note that each state will exhibit a different distribution than is shown in Fig. 2.5, depending on climate, energy sources and other factors), and the US national average for on-road vehicles is about 22 % of total GHG emissions (U.S. Environmental Protection Agency 2013).

Pavement maintenance and rehabilitation treatments can reduce pavement roughness and positive surface texture, and pavement rehabilitation or reconstruction can reduce vehicle energy consumed by deflections, and therefore lower fuel use and GHG emissions in the on-road vehicle sector shown in Fig. 2.5. However, performing these treatments also requires energy and produces emissions. Specifically, maintenance, rehabilitation and reconstruction of pavement requires materials production and construction, which also contribute to the following three other GHG-emissions source categories shown in Fig. 2.5:

- Extraction and refining of oil: a portion of this sector's emissions come from the production of paving asphalt.
- Cement plants: a portion of this sector's emissions includes the manufacture of cement used for pavements.
- Industrial manufacturing, construction and mining: a portion of this sector's emissions includes some of the processes used for pavement M&R and reconstruction, including mining and transportation of aggregate, manufacture and transportation of lime and construction equipment operations.

As shown by Lidicker et al. (2013) and Wang et al. (2014), optimization of pavement treatments requires balancing of the GHG emissions caused by pavements needing treatment, and the emissions caused by performing those treatments.

GHG emissions are measured in terms of equivalent metric tons of carbon dioxide (CO_2-e), which is the most common indicator used for global warming. This indicator is a midpoint indicator (as opposed to an endpoint indicator such as human health impacts due to sea level rise or damage to ecosystems), and its use is supported by various scientific studies (IPCC 2007a). Although energy consumption is closely tied to GHG emissions through the burning of fossil fuel, there are some situations where GHG emissions are not generated from burning fossil fuel, such as the pyro process in cement production and CH_4 emissions that occur during construction equipment usage. Each type of GHG can be converted to CO_2-e based on its contribution to the radiative forcing compared with CO_2 (IPCC 2007b).

2.2.1.2 Description of the Network

Table 2.1 gives a brief description of the highway network based on the Caltrans PMS.

Figure 2.6 shows some descriptive statistics of the highway network in terms of pavement surface type, traffic levels and IRI. The traffic levels are in terms of passenger car equivalent (PCE), where each truck is 1.5 equivalent passenger cars (Transportation Research Board 2010). The different types of pavement and the

Table 2.1 Summary statistics of the state highway network

Pavement type	Lane-miles	Maximum AADT	Minimum AADT	Mean AADT	AADT standard deviation
Asphalt	37,233	210,600	48	37.065	39.730
Concrete	10,721	225,551	675	79.708	37.988

Note: AADT = Average Annual Daily Traffic

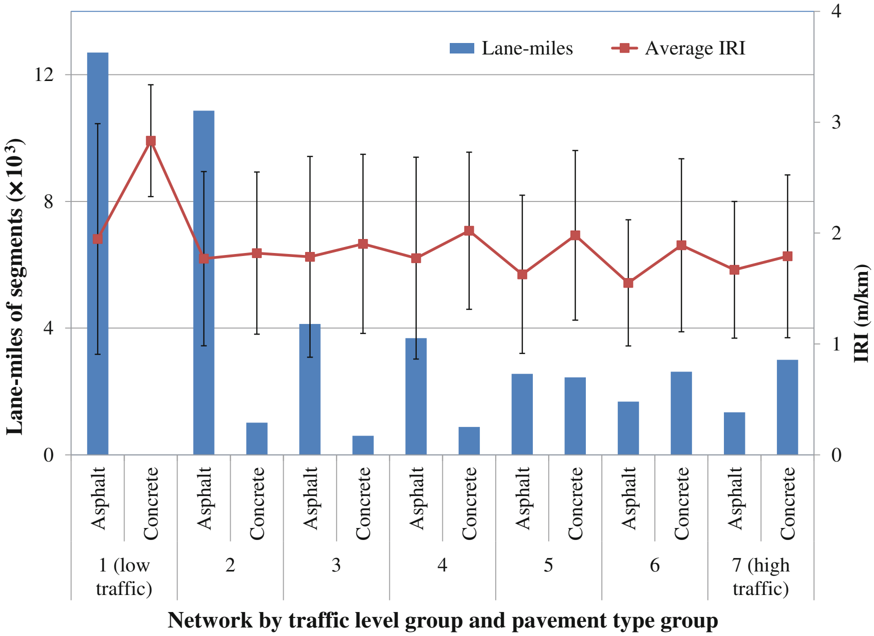

Fig. 2.6 Descriptive statistics of IRI and lane-miles on each traffic level (PCE) group, *Note1* Traffic level groups are *Group 1* PCE lower than 2,517; *Group 2* PCE from 2,517–11,704; *Group 3* PCE from 11,704–19,108; *Group 4* PCE from 19,108–33,908; *Group 5* PCE from 33,908–64,656; *Group 6* PCE from 64,656–95,184; *Group 7* PCE higher than 95,184., *2* The error bar shown with the average IRI value is the standard deviation of the IRI in each group., *3* There are only 0.9 lane-miles of concrete pavement in Group 1 (lowest traffic), so the average IRI value in that group combination is very high and may not be representative. *4* The PCE is only used to divide the network into groups. When calculating pavement deterioration and vehicle fuel economy, segment-specific algorithms and emission factors for each type of vehicle are applied

pavements in each traffic group have different demographics in terms of pavement age and time since last surface treatment. They also reflect some design practices used when much of the network was built in the 1950s through 1980s. The IRI values on the network were extracted from the 2011 Caltrans Automated Pavement Condition Survey (APCS) and used as the initial condition of the network in this example.

The relatively even distribution of IRI across the different pavement types and traffic categories shows the results of an historical use of a stewardship type PMS objective, where treatments were triggered based on the extent of surface cracking rather than IRI, with the traffic level primarily determining the type of treatment. This type of objective helped to ensure that the network was kept in reasonable structural condition regardless of traffic level. A mobility or functional type of PMS objective may have resulted in lower levels of IRI on segments with higher traffic levels, considering that many treatments for low-volume highways do result in much improvement in smoothness. If an IRI objective was traffic weighted, it would have likely resulted in lower IRI values for the higher traffic segments than for the lower traffic segments.

2.2.2 Network-Level Considerations for GHG Example

Previous studies have shown that performing an M&R treatment on a rough pavement can lead to significant energy savings and GHG reductions (Wang et al. 2012b). However, the question of what level of roughness should trigger the M&R activity so the GHG reduction can be maximized over an analysis period was unanswered. Figure 2.7 demonstrates this interaction: if the triggering roughness is set too low (Fig. 2.7a), the materials production and construction processes required to maintain a smooth pavement with frequent M&R treatments can exceed the CO_2-e reduction from improved fuel economy in the use phase. On the other hand, if the triggering roughness is set too high (Fig. 2.7b), the additional CO_2-e due to vehicles operating under rougher conditions may exceed the theoretical material and construction emissions that would occur from more optimal pavement M&R.

Considering the heterogeneity of the highway network, setting one IRI triggering value for the whole network may lead to large differences in environmental impact. Each segment in the network has its unique traffic level, traffic composition, and pavement characteristics, and theoretically, developing an IRI triggering value for each segment in the network within the PMS can improve the precision of the optimized result. However, such complexity may not be practical for an approach to be implemented at the network level at this time. The example summarized in this chapter adopted traffic level as the indicator to divide the network into groups as discussed in the last section, and then developed the triggering value for each group in the network for inclusion in decision trees.

To identify the optimal IRI trigger, each segment in the network is evaluated through two scenarios with a series of IRI triggers: the *M&R* scenario and the *Do Nothing* scenario. In the *M&R* scenario, when the IRI of a segment reaches the triggering value, a treatment is performed and brings down the IRI. The emissions from the material production and construction are calculated based on the material quantity and construction activity. The GHG emissions in the use phase are calculated based on vehicle operation under the corresponding pavement conditions. In the *Do Nothing* scenario, the pavement is preserved using routine maintenance

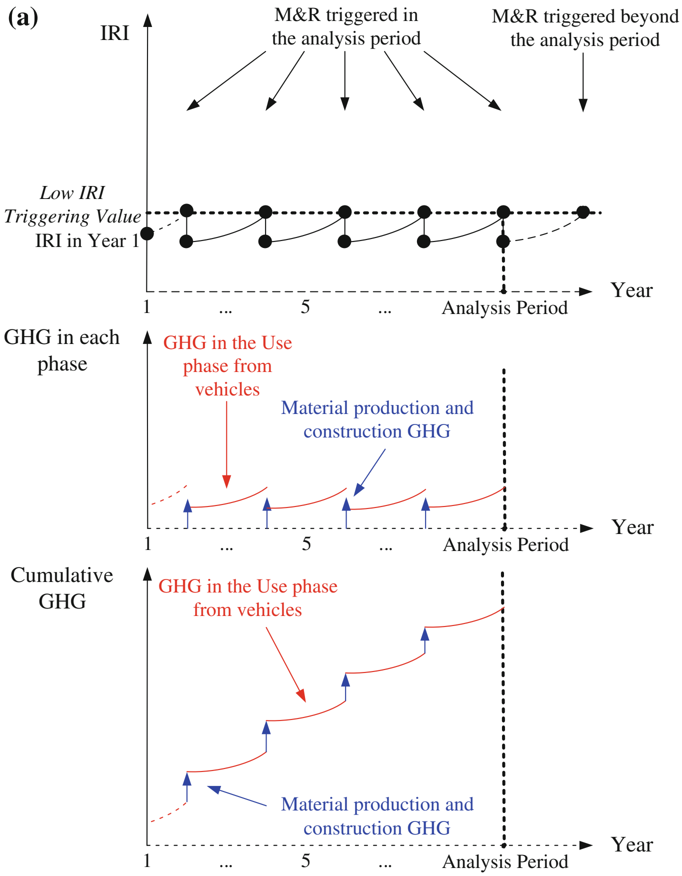

Fig. 2.7 How IRI triggering value affects the M&R activities and the resultant GHG: **a** a low IRI triggering value; and **b** a high IRI triggering value

such as localized patching and digouts (patching of the wheelpaths) to maintain its current roughness and macrotexture. The environmental impacts from material production and construction phases are assumed to be zero. The use phase emissions for the *Do Nothing* scenario are calculated similarly to the *M&R* scenario. The difference in GHG emissions between these two scenarios is summed over the analysis period and all segments in each traffic group. The IRI trigger that leads to the highest GHG reductions is considered the optimal IRI trigger.

A ten-year analysis period, from the year 2012 to the year 2021, was chosen for this example. This is because this example focused on repeated pavement prevention treatments, and pavement prevention treatments have relatively short design lives compared to major rehabilitation treatments. Therefore, a ten-year analysis period is able to cover 1.2–1.5 times the common design life of the two main treatments, as recommended in *UCPRC Pavement LCA Guideline* (Harvey

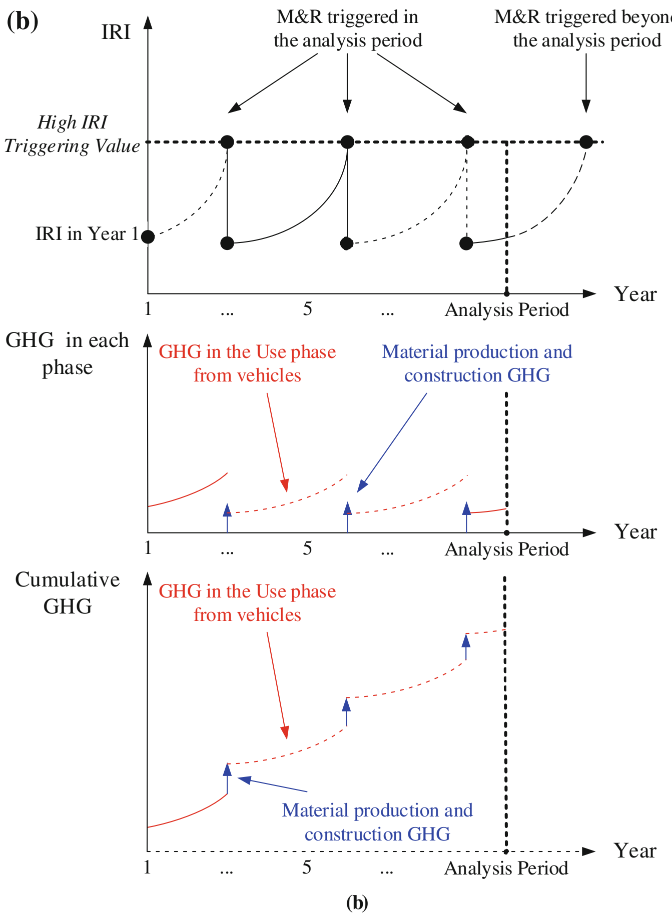

Fig. 2.7 continued

et al. 2011). Further, this example amortized the emissions from the last treatment event, and only included the parts of emissions that are within the analysis period. Therefore, this selection of analysis period was considered reasonable.

2.2.3 Specific Modeling and Data for the GHG Example

Some basic inputs are needed to evaluate the life cycle GHG emissions and energy consumption from pavement treatments on the network. These inputs include the emission factors for the treatments, emission factors from vehicles for different pavement IRI and macrotexture levels, pavement performance models for IRI and macrotexture (validated deflection models can be added to future analyses), traffic data, and pavement type data which helped determine treatment types. Treatment cost and some road user cost data were also used to provide economic comparisons of different IRI trigger levels for M&R.

2.2.3.1 Emission Factors and Cost of Treatment

Considering the life cycle of pavement, the emission factor of a treatment usually covers the material production phase and construction phase and should be calculated separately for each phase. However, on the network-level, the emission factors from these two phases can be combined and represented using a reference construction activity, such as one metric ton of asphalt or one lane-mile of concrete that is diamond ground.

Due to the temporal and regional uncertainty of various LCI data sources, multiple data sources for each material are recommended to be included in the development of PMS applications when possible. Some major data sources for pavement include the pavement LCI produced by Stripple et al. in Sweden (Stripple 1998), the asphalt inventory produced by the Athena Institute in Canada (Athena Institute 2006), EcoInvent (Swiss Centre for Life Cycle Inventories 2011), the U.S. Life Cycle Inventory produced by the National Renewable Energy Laboratory (National Renewable Energy Laboratory 2011), and the cement LCI study by the Portland Cement Association (PCA) (Marceau et al. 2006). Because different sources represent different local conditions, technologies, and system boundaries, each item needs to be disaggregated to the process and then recalculated based on local conditions and specifications, such as fuel source, electricity mix, and car and truck emissions per unit of fuel used before being used as the data source (Lee 2013).

In the construction phase, fuel use and GHG emissions are controlled by both construction equipment (including trucks) and construction-related traffic. These need to be summarized for consideration at the network level. A two-step method can be used to assess the impact from construction equipment. The first step is to simulate the construction schedule and equipment activities for typical projects on the network. Various construction scheduling modeling tools can be used to achieve this goal, based on controlling parameters such as pavement structure design, lane closure tactics, and resource availability. The basic procedure of construction scheduling is to first identify the equipment types and then hours of operation typically needed for each treatment type. The second step is to convert the equipment operating hours to GHG emissions and energy consumption using emission factors of construction equipment. Emission models for on-road transportation (for hauling trucks) and off-road construction equipment based on local conditions can be used in this step.

Depending on the scope of a study, the construction-related traffic can be included in the analysis although this will be highly variable. The additional fuel consumption and emissions from work-zone traffic are then analyzed with fuel economy and emission factors from local on-road vehicle emission models.

With material production phase and construction phase data, the emission factors of a treatment can be usually calculated through analyzing a construction activity on a reasonable scale, and normalizing the results to the reference unit for application to the functional unit of a network segment. When put in network-level analysis, the emissions from each treatment can be scaled for lane-miles to be treated or another reasonable factor based on the emissions from the reference unit.

2.2.3.2 Vehicle Emission Factors

In assessing the life cycle impact from pavement, the vehicle emission factors are used to address the changes of vehicle emissions due to the deterioration and M&R of pavement. In network-level analysis, the vehicle emission factors are developed as a function of pavement characteristics affected by deterioration and construction activities, which change the roughness and rolling resistance placed on the vehicle engine, eventually affecting the energy power, energy consumption, and emissions. In practice, the vehicle emission factors are developed as a function of all these variables. A factorial approach can be used to develop the vehicle emission factors considering vehicle type, engine technology (gas, diesel, hybrid and electric) and vehicle speed. Of these variables, road type (urban or rural) and road access type (freeway or highway) control the characteristics of vehicle speed including congestion, while calendar year and vehicle type control the engine technology and emissions control requirements of vehicles, and pavement type and pavement surface characteristics control the impact of pavement on vehicles' rolling resistance. Table 2.2 shows an example of the combination of the factorial variables. In this example, the vehicle emission factor is developed for each combination of variables. Therefore, the total number of the combinations was 2 pavement types × 2 road types × 2 road access types × 10 years × 5 vehicle types = 400. The emissions factors were developed based on integration by Wang et al. (2012b) of HDM-4 fuel use equations calibrated by Zaabar and Chatti (2010) with emissions factors included in the US EPA's *MOVES* models (U.S. Environmental Protection Agency 2010).

Table 2.2 Combination of the complete factorial variables used to develop the vehicle emission factors as a function of MPD and IRI

Pavement type	Road type	Road access type	Vehicle type mix	Pavement surface characteristics
Asphalt pavement; Concrete pavement	Urban roads; Rural roads	Restricted access road (freeway); Unrestricted access road (highway)	Passenger cars; 2-axle truck; 3-axle truck; 4-axle truck; 5 or more axle truck at Year 2012–2021 (10 years)	MPD and IRI
Categorical variable	Categorical variable	Categorical variable	Categorical variable	Continuous variable

2.2.3.3 Traffic

Traffic is a crucial input in evacuating the life cycle impact from pavement because traffic can affect the pavement from two perspectives: (1) pavement deterioration rate is a function of truck traffic; and (2) the pavement roughness affects fuel economy of every vehicle that uses it differently (both passenger cars and different types of trucks). Therefore, the traffic data acquired for network level pavement life cycle assessment needs to be able to reflect these two aspects. For the pavement performance models used in this example, the damaging effects of truck traffic were characterized in terms of 80 kN (18,000 lb) equivalent single axle loads (ESAL). Because different lanes carry different levels of truck traffic and therefore have different deterioration rates, the PMS uses lane-by-lane segmentation and the deterioration and emissions are calculated for each lane separately. Caltrans' traffic vehicle classification and flow data was set up to be used by the vehicle emissions equations, with lane assignments of trucks and cars for multi-lane roads made based on Caltrans' weigh-in-motion (WIM) data (Lu and Harvey 2006).

2.2.3.4 Pavement Data

Pavement data includes the initial pavement condition and pavement performance equations. For this example, these data include pavement surface characteristics (IRI and MPD) and cracking (used to determine concrete slab replacements or concrete lane replacement). The results from the 2011 Caltrans APCS were used as the initial conditions. Pavement performance equations characterize how pavement conditions progress under difference situations, and include the expected initial change in IRI, MPD and cracking due to treatment. Detailed performance models for IRI and macrotexture in the use phase sub-model can be found in Wang et al. (2014).

The main treatments considered in this example are two *Capital Preventive Maintenance* (CAPM) treatments used by the Caltrans: (1) a medium thickness asphalt overlay applied on all asphalt surfaced pavements, and (2) diamond grinding with slab replacement on concrete surfaced pavement with less than 10 % shattered slabs. This study also includes another treatment, although not in the CAPM category; concrete lane replacements with new concrete when there are more than 10 % shattered slabs. This last treatment is used far less often than the CAPM treatments.

The use phase sub-model did not consider rolling resistance due to pavement deflection, which is the subject of other current research. Reasonable assumptions are made that pavement deflections under traffic would change very little for application of the M&R treatments considered. Macrotexture was considered, although macrotexture values on the California state network are generally low on all but lightly traveled highways where chip seals are used, and chain wear only occurs over a few mountain passes.

2.2.4 Network-Level Results from the Optimization

Using the procedure described in the previous sections, this application develops the optimal roughness trigger for each traffic category for the treatments modeled. As examples of network-level implementation in the PMS, the GHG reductions that can be achieved compared with maintaining the network at current levels of roughness (*Do Nothing*) and current Caltrans IRI triggering levels across all segments were compared [see Wang et al. (2014) for this comparison]. The cost per ton of CO_2-e reduction over a ten year analysis period compared to *Do Nothing* and current IRI triggering levels were also compared.

Figure 2.8 shows the result of GHG reduction in *M&R* scenario compared with *Do Nothing* scenario based on different triggering IRI values on each traffic group in the network. The x-axis shows the IRI value that triggers a treatment. The y-axis shows the total GHG reduction from the treatments compared to *Do Nothing* when a specific triggering value is implemented. It can be seen that if the triggering value is too low, the high GHG that comes with the frequent construction and material consumption can offset the GHG reductions during the use phase of pavement, even if the pavement is maintained at a very smooth level. If the triggering value is set too high, the pavement can get very rough which lowers the fuel economy of the

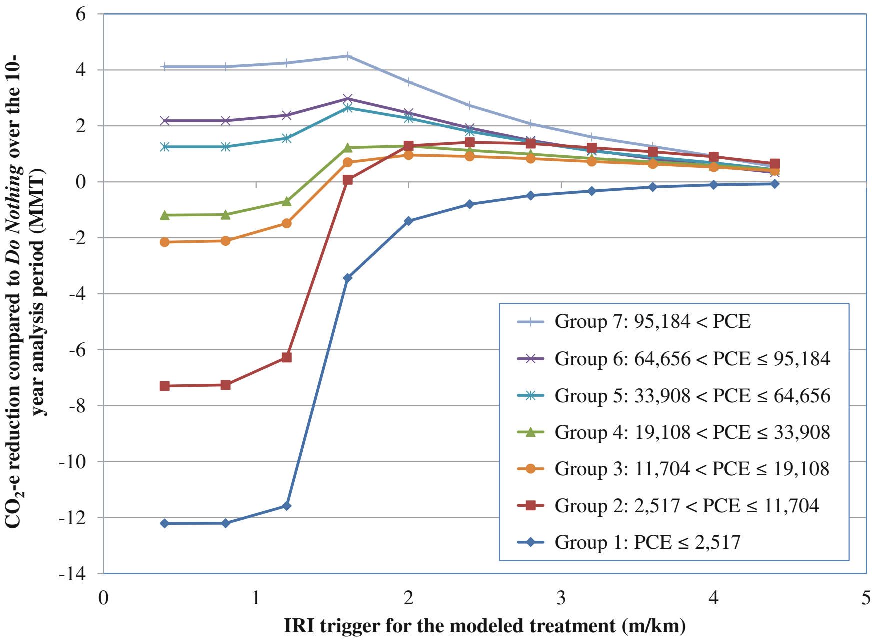

Fig. 2.8 GHG reductions versus IRI triggering value for different traffic level over the 10-year analysis period for each traffic group

vehicles. Therefore, there is an optimal triggering IRI value that can lead to the highest GHG reduction.

This is the trade-off between the environmental impacts that occur in the material production and construction phases and those that occur in the use phase. The result shows that the highest GHG reduction that can be achieved through performing the analyzed treatments comes from using different IRI triggering values for different traffic level groups in the network. The higher the traffic level is, the lower the triggering IRI value it needs to achieve the maximum GHG reduction. Table 2.3 shows the highest GHG reduction for each group of segments in the network and its corresponding IRI triggering value. It can be seen in Fig. 2.8 and Table 2.3 that the 10 % of the network with the highest traffic (Group 7) provide nearly 35 % of the emission reductions, despite similar or lower current roughness than other traffic groups. For segments with a daily PCE lower than 2,517 the net GHG reductions are negative for any IRI triggering value, indicating the GHG during the material production and construction phases can never get paid back during the use phase within the 10-year analysis period. For these segments retention of Stewardship type PMS objectives is needed to maintain minimal funding for connectivity of the network.

The total amount of GHG reductions that can be achieved if these optimal IRI triggering values are implemented on corresponding traffic levels is 13.77 million metric ton (MMT) CO_2-e over the 10-year analysis period compared to the *Do Nothing* scenario. For comparison, the California Air Resources Board has estimated that the average annual GHG from on-road vehicles is about 168.1 MMT CO_2-e between the 2006 and 2020 (California Air Resources Board 2011). Therefore, the GHG reduction estimated from this study can contribute about a 0.8 % reduction compared to the baseline over the 10-year analysis period in the on-road vehicles.

The cost-effectiveness of each IRI triggering value is also shown in Table 2.3. The *modified total cost* shown is the *agency cost* subtracting the cost of saved fuel consumption from the road users due to the improved fuel economy on smooth pavement. Consideration of *total road user cost* including all costs of vehicle operation on rougher pavement as well as safety would reduce the cost per ton of GHG saved. It can be seen the greatest cost effectiveness comes from applying frequent M&R treatments on the pavements carrying the highest traffic volumes.

These results show that a management objective that focuses on traffic-weighted IRI using the optimized IRI values is the most cost-effective approach to reducing GHG emissions using pavement management. However, as noted previously, because IRI is a lagging indicator of pavement distress, a “stewardship” type pavement preservation constraint that addresses cracking before it progresses to the point that it affects IRI will likely increase the cost-effectiveness of the M&R program. A stewardship constraint that addresses low-volume segments is also needed to preserve the connectivity of the network and mobility for rural areas.

The inventory data, impact calculations for each segment over the analysis time horizon and reporting of GHG savings (or increases) that come from treating a pavement or letting it continue to deteriorate have been implemented in the Caltrans PMS.

Table 2.3 IRI triggering value for the maximum energy and GHG reductions compared to *Do Nothing* over the 10-year analysis period for the entire network

Traffic group number	Daily PCE of directional segments	Total lane-miles in the network	Percentile range of lane-mile in the network (%)	Optimal IRI triggering value (m/km, inch/mile in parentheses)	Energy savings compared to Do Nothing (million MJ)	GHG reductions compared to *Do Nothing* (MMT CO_2-e)[1]	Modified total cost-effectiveness ($/metric ton CO_2-e)
1	<2,517	12,068	0–25	—-	0	0	N/A
2	2,517–11,704	12,068	25–50	2.4 (152)	1.43×10^4	1.41	1,169
3	11,704–19,108	4,827	50–60	2.0 (127)	1.01×10^4	0.96	857
4	19,108–33,908	4,827	60–70	2.0 (127)	1.40×10^4	1.28	503
5	33,908–64,656	4,827	70–80	1.6 (101)	2.94×10^4	2.64	516
6	64,656–95,184	4,827	80–90	1.6 (101)	3.33×10^4	2.97	259
7	>95,184	4,827	90–100	1.6 (101)	5.01×10^4	4.50	104
Total		48,271			1.51×10^5	13.77	416

NoteN/A not applicable since no GHG reduction

2.3 Gap Analysis for Implementation

2.3.1 Survey from the PMS System Capabilities

As stated in the beginning of this chapter, very few road owning agencies have begun to integrate LCA into their PMS, either directly through incorporation of inventory data, impact models, and assessment reporting, or indirectly through inclusion of LCA results into the policies embedded in the PMS, such as decision trees. The criteria for selecting treatment options are usually based on benefit/cost analysis with benefits defined in terms of PCI reductions, reductions of specific types of cracking and other distresses, or reductions in IRI, often without traffic weighting. Remaining service life increases or other measures of estimated structural capacity are sometimes used. Life cycle cost with these pavement condition objectives is seldom used at the network level. As consideration of environmental concerns becomes more important, inclusion of environmental indicators of pavement performance in the analysis capabilities that are included in pavement management systems should receive increasing attention.

The PMS coupled with pavement LCA then provides a practical and powerful tool to understand and report the environmental ramifications of pavement management decisions, and the costs associated with achieving environmental as well as mobility and stewardship objectives. Figure 2.9 shows a possible integration of PMS with pavement life cycle modeling. With a variety of rich data sources provided by PMS to the pavement life cycle modeling, this integration can help to solve the optimization problem, where there are multiple objectives in the optimization (condition, cost and environmental impact) subjected to either a cost budget or emission target.

With PMS coupled with LCA modeling, the M&R frequency (such as setting the trigger value of performing an M&R) and intensity (such as the overlay thickness, or the selection of maintenance versus rehabilitation) can be optimized to reduce environmental impacts. Several research studies have developed case study approaches to achieve these goals. These studies, including Lidicker et al. (2013) and Zhang et al. (2010), attempt to minimize the environmental impacts in the pavement life cycle by optimizing the M&R frequency and intensity based on the selection and scheduling of M&R events.

Zhang's study treated the M&R scheduling as a multistage decision-making problem and used dynamic programming to optimize the environmental impacts on a small set of segments in the theoretical network. The biggest limitation with this study is that it includes a very complex optimization procedure, resulting in a high computational intensity when used on a larger network. Further, this optimization developed segment-specific M&R strategies, making it difficult to implement on the network level. In comparison, Lidicker's study used a Pareto optimal frontier for a single treatment type on a segment to determine the relationship between total life cycle cost (road owner and road user costs calculated separately and then summed over the life cycle) and corresponding GHG emissions. A Pareto optimal frontier is

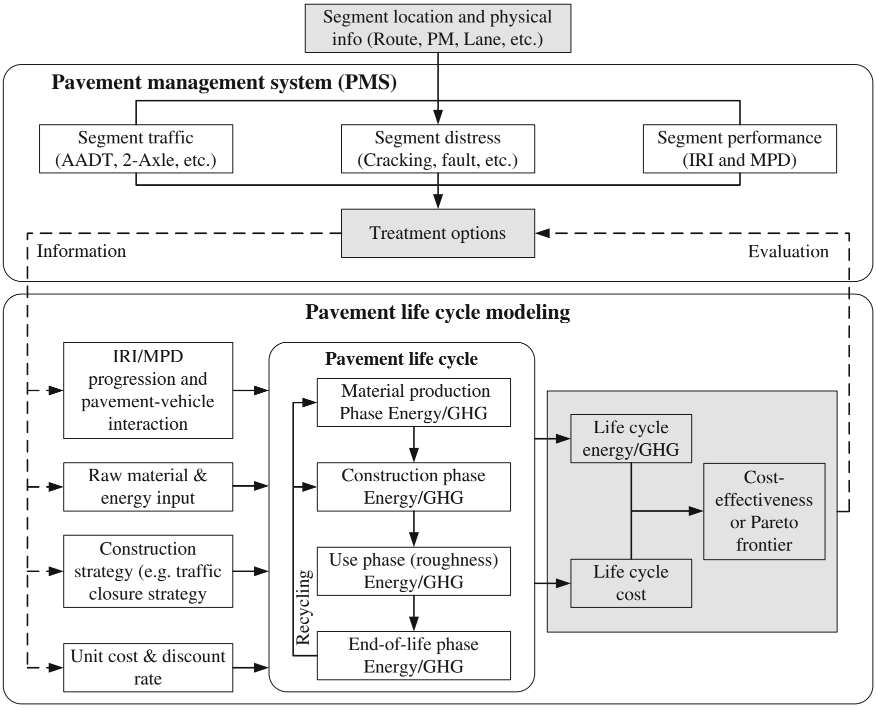

Fig. 2.9 Integration of the pavement LCA model in the PMS for example of GHG emissions (can be expanded to other impact categories based on available models and inventory data)

a collection of points which are considered optimal from a societal point of view in that one variable (cost or GHG emissions in this case) must be decreased for the other to be increased. The decision as to what is the best combination of benefits then becomes a quantitatively supported decision, and the marginal change can also be determined, in this case the cost of further reducing GHG emissions. The advantage of this study is that it adopted the "triggering roughness" concept, an approach used by many agencies, and therefore has the potential to be integrated and implemented into current PMS. However, this study was only performed on the project level and used a relatively simple emission model. A network-level analysis based on this approach is to be expected in the near future.

2.3.2 *What Needs to Be Done?*

The most important gap in the ability to integrate LCA into PMS is the need for reduction of available life cycle inventory data into regionally applicable, up to date, and simplified form that can be readily implemented, understood and maintained. Materials production are generally available, but must be related to treatments included in the PMS. This requires reviewing typical mix designs for pavement materials, sources of those component materials, transportation and other sources of resource use and emissions. Construction data can also be developed based on analysis of typical projects for each treatment type. These types of materials and construction databases take several years to implement initial results with an understanding of the uncertainty involved, and then can be steadily improved.

For local government to be able to incorporate LCA into PMS the following are some of the major gaps:

- Databases need to be expanded to consider the effects of utility maintenance on pavement performance.
- Where motorized vehicle use phase effects are considered, methods for collecting roughness at slow speeds for those pavements carrying sufficient traffic to warrant inclusion in the analysis.
- Additional use phase effects specific to wide-spread networks of pavements in urban areas should be evaluated to determine whether they warrant consideration.

Examples produced for project-level analysis are *Dubocalc* (Rijkswaterstaat 2012) produced by the national government of the Netherlands (Rijkswaaterstat) and *Ecorce* (IFSTTAR 2013) produced by the French national government (IFSTTAR). These types of databases can be the basis for developing the simplified data needed for PMS integration. Other agencies are working on similar databases in the United States and Canada. These databases need to be expanded to consider various end-of-life paths for pavements, and must be kept up to date as new technologies for re-using pavement materials are developed, and new materials are created. Allocation alternatives for assigning the environmental burdens for end-of-life scenarios must be turned into policy to be implemented in the PMS.

Use phase models for vehicle emissions based on roughness and macrotexture are available, such as those used in the example in this chapter. They can be expanded to consider other impact categories based on the energy sources used by the vehicles. Models for energy consumed by pavement deflection are available and are undergoing evaluation and calibration. Traffic data, including traffic volumes classified by vehicle type, speeds, congestion, and lane assignment data where the PMS uses lane by lane segmentation, are generally available within state department of transportation for use phase analysis.

From this review, it is clear that information is available. The main work is to review it and make it applicable to the specific agency, and then perform the work of integrating various data sources and implementing them within a PMS. Development of clear and politically supported objectives is also needed for each agency, since it is clear that only a few can be addressed in a PMS and not all impact categories are particularly relevant to pavement. The use of complete life cycle results is also important, since the performance of one phase in life cycle, such as recycling goals, may not produce the intended results in all cases.

2.4 Summary and Recommendations

2.4.1 Summary

The objective of this chapter is to demonstrate how LCA can be integrated into PMS to assess the environmental impacts from pavement and support network-level decision-making. The data required for such integration and the gap between current PMS and the implementation were also discussed. As an example, a simplified version of a life cycle assessment model was applied to the California state pavement network to evaluate a strategy of application of maintenance treatments and a small number of concrete lane replacements to rough pavement and its potential impact on GHG. The network was broken into different groups based on their traffic level. An IRI value for triggering CAPM treatment that can lead to the highest energy and GHG reductions was developed for each group.

2.4.2 Recommendations for Future Work

The LCA model and its application in the case studies and pavement network have shown that using LCA in pavement decision-making can be a powerful tool for assessing impacts of pavement M&R strategies on the environment. However, the results shown in the analysis are only the very beginning of this work for only one objective. Considerable work must be done to fill the gaps identified in this chapter. This work can be also be expanded to network-level management of rail and bridge networks. Project-level LCA studies have been performed for these that provide the basis for future databases and analysis frameworks.

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