ENVIRONMENTAL RESEARCH
LETTERS

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To cite this article: Ting Wang *et al* 2014 *Environ. Res. Lett.* **9** 034007

OPEN ACCESS
IOP Publishing

Environmental Research Letters

Environ. Res. Lett. **9** (2014) 034007 (10pp)

doi:10.1088/1748-9326/9/3/034007

Reducing greenhouse gas emissions through strategic management of highway pavement roughness

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Received 23 September 2013, revised 11 February 2014
Accepted for publication 11 February 2014
Published 6 March 2014

Abstract

On-road vehicle use is responsible for about a quarter of US annual greenhouse gas (GHG) emissions. Changes in vehicles, travel behavior and fuel are likely required to meet long-term climate change mitigation goals, but may require a long time horizon to deploy. This research examines a near-term opportunity: management of pavement network roughness. Maintenance and rehabilitation treatments can make pavements smoother and reduce vehicle rolling resistance. However, these treatments require material production and equipment operation, thus requiring a life cycle perspective for benefits analysis. They must also be considered in terms of their cost-effectiveness in comparison with other alternatives for affecting climate change. This letter describes a life cycle approach to assess changes in total GHG (measured in CO_2-e) emissions from strategic management of highway pavement roughness. Roughness values for triggering treatments are developed to minimize GHG considering both treatment and use phase vehicle emission. With optimal triggering for GHG minimization, annualized reductions on the California state highway network over a 10-year analysis period are calculated to be 0.82, 0.57 and 1.38 million metric tons compared with historical trigger values, recently implemented values and no strategic intervention (reactive maintenance), respectively. Abatement costs calculated using \$/metric-ton CO_2-e are higher than those reported for other transportation sector abatement measures, however, without considering all benefits associated with pavement smoothness, such as vehicle life and maintenance, or the time needed for deployment.

Keywords: pavement, network, life cycle assessment, pavement management system, smoothness, roughness, maintenance

S Online supplementary data available from stacks.iop.org/ERL/9/034007/mmedia

1. Introduction

The national pavement network is a key component of the transportation infrastructure that the modern US economy depends on for mobility and movement of goods. The vehicles that use the network are responsible for nearly a quarter of the US's greenhouse gas (GHG) emissions [1]. In the state of California, on-road vehicle use contributes to an even larger share, comprising about 35% of the state's GHG emissions [2].

In 2006, the California State Legislature passed Assembly Bill 32 (AB 32), the Global Warming Solutions Act, to reduce GHG emissions throughout the state [3]. The California Air

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Resources Board (CARB), the lead agency for implementing AB 32, estimated the year 2020 baseline emissions at 507 million metric tons (MMT) of CO_2-equivalent (CO_2-e), with 168.1 MMT of CO_2-e from on-road traffic [2].

Although the implementation of AB 32 has led to studies that focus on GHG emission reduction strategies and their cost-effectiveness in many industrial sectors, to date there has been no evaluation of pavement management strategies to help meet its objectives. Pavement management includes the measurement of pavement condition and the programming of maintenance and rehabilitation (M&R) treatments to achieve goals for the pavement network such as maintaining or restoring smoothness, eliminating cracking (which eventually leads to roughness), and improving vehicle fuel economy at minimum cost to the agency and taxpayers.

Numerous studies have demonstrated a life cycle assessment (LCA) approach is needed to provide a comprehensive evaluation of the environmental burdens of a product or process, and to reduce the risk of unintended negative consequences [4]. For pavements, a typical life cycle includes material production, construction, use, M&R, and end-of-life (EOL) phases.

Despite its omission from many previous LCA studies as identified in [4, 5], the pavement use phase is critical to modeling life cycle GHG emissions. Vehicle fuel consumption and emissions are affected by pavement surface characteristics, namely roughness (or 'smoothness' from another perspective) as typically measured by the International Roughness Index (IRI), and to a lesser extent by macrotexture as measured by the mean profile depth (MPD) or mean texture depth (MTD). Pavement roughness and macrotexture are the deviations of a pavement surface from a true planar surface with the wavelengths of deviations ranging from 0.5 to 50 m, and from 0.5 to 50 mm, respectively [6, 7]. Roughness characterizes the primary wavelengths that excite shock absorbers in vehicle suspension systems, drive chain components and cause deformation of tire sidewalls for a moving vehicle. Macrotexture influences the tire–road contact patch, which consumes energy through viscoelastic hysteresis of the rubber in the contact patch of a moving tire [6]. Therefore, both wavelengths dissipate energy, lost as waste heat, as a vehicle moves along the pavement. This process is experienced as rolling resistance by vehicles, of which roughness can account for over 80% for a typical California highway.

IRI values can range from about 0.5–5 m km^{-1} (32–315 in $mile^{-1}$) on a paved high-speed highway, with lower values indicating a smoother surface. The US Federal Highway Administration (FHWA) defines high-speed highway pavements with an IRI greater than 2.7 m km^{-1} (170 in $mile^{-1}$) as being in 'poor' condition [8], which accounts for about 15% of the pavement network in both the US and California [8, 9].

Because an improvement in smoothness immediately affects every vehicle traveling over the pavement, the cumulative effects on GHG emissions can be substantial in the near term compared to the changes in vehicle technology or land use policy, which may take years to implement. Therefore, this study examines the California pavement network's potential contribution to reducing GHG emissions from on-road traffic through targeted M&R treatments to reduce roughness, by identifying the IRI value that should trigger an M&R event to minimize GHG emissions, as measured by CO_2-e emissions.

The tradeoff on triggering M&R treatment is that if the roughness trigger value is set too low, 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. This study also assesses the cost-effectiveness of using the optimized triggers and compares them with other GHG mitigation strategies studied in the existing literature for the transportation sector.

Few, if any, pavement management systems (PMSs) adopted by state transportation agencies have included environmental impacts in their analysis frameworks. However, several academic studies have attempted to integrate pavement management operations with LCA to reduce environmental impacts. These studies, including Lidicker *et al* [10] and Zhang *et al* [11], attempted to minimize the environmental impacts in the pavement life cycle for project-level case studies and a very small local road network, respectively, and used relatively simple emission models by optimizing the M&R frequency and intensity through multi-criteria decision analysis.

This letter demonstrates a network-level study of state-owned highways in California that builds on a pavement LCA model described by Wang *et al* [12]. Although it is implemented on the California network, the approach can be generalized to any pavement network and any set of treatments to assess environmental impacts and support network-level decision-making. This study includes a subset of common M&R treatments used in California for which sufficient information has been observed and collected. The treatments considered are two pavement preservation treatments extensively used in the California Department of Transportation's (Caltrans') Capital Preventive Maintenance (CAPM) program [13]: (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. A rehabilitation treatment, replacement of concrete lanes with new concrete pavement when there are more than 10% shattered slabs, is also included. This last treatment is used far less often than the CAPM treatments.

2. Methods

The pavement network is composed of segments, each of which is described by a set of characteristics that influence the optimal IRI trigger for M&R treatments to reduce GHG emissions, such as traffic volume, traffic composition, and pavement surface condition. Each pavement segment presents a unique combination of these characteristics. Figure 1 shows the analytical approach used in this study, detailed in the following sections.

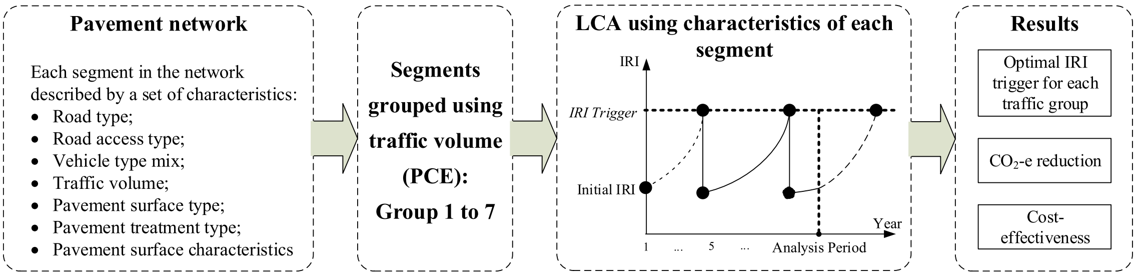

Figure 1. Analytical approach of this study.

Table 1. Characteristics used to describe each segment in the pavement network.

Characteristic	Pavement life cycle phases involved	Values
Road type	Use	Categorical: rural road; urban road (for consideration of congestion)
Road-access type	Use	Categorical: restricted access (freeway); unrestricted access (highway)
Vehicle type mix	Use	Categorical: passenger cars; 2/3/4/5-axle trucks at Year 2012–2021;
Traffic volume	Use	Continuous numerical: traffic volume of each vehicle type;
Pavement type	Material production, construction, and use	Categorical: asphalt pavement; concrete pavement
Pavement treatment type	Material production, and construction	Categorical: medium asphalt overlay; diamond grinding with slab replacement; concrete lane replacement
Pavement surface characteristics (pavement performance)	Material production, construction, and use	Continuous numerical: IRI performance; MPD performance

2.1. Network characterization

Because of the computational and practical complexity of developing thousands of segment-specific triggers, the network is divided into seven groups based on each segment's traffic level as measured by passenger car equivalents (PCEs) [14]. To calculate PCE, each truck is counted as 1.5 equivalent passenger cars regardless of the type of the truck [14]. Traffic level was identified as the most important segment characteristic for determining whether there is a net reduction of CO_2-e emissions from an M&R treatment [12]. Then, the life cycle CO_2-e emissions are calculated for each group over a range of IRI triggers to identify the optimal trigger for reducing CO_2-e emissions for each group. The approach is intended to maintain a balance between computational intensity and thoroughness.

Table 1 shows the characteristics that describe each segment in the network. A detailed description is included in section S.1 of the supplementary material (available at stacks.iop.org/ERL/9/034007/mmedia).

Traffic volume can affect CO_2-e emissions in two ways: first, the rate of pavement deterioration, as represented by the performance model of pavement surface characteristics in this study, is affected by the level of truck traffic; and second, pavement roughness affects the fuel economy of every vehicle that uses the pavement, including both passenger cars and trucks. Thus, this study uses the concept of PCE from the Highway Capacity Manual to assist in grouping segments of the network [14]. It should be emphasized that PCE is only used to divide the network into groups. When calculating pavement performance and vehicle fuel economy, segment-specific algorithms for truck traffic (in the form of Equivalent Single Axles Load [ESAL]) and emission factors for each type of vehicle are applied. Traffic volume data is taken from the Caltrans traffic volume report and Caltrans truck traffic database, which reports volume on all the lanes in one direction (termed 'directional segment') [15]. Section S.1 of the supplementary material (available at stacks.iop.org/ERL/9/034007/mmedia) provides additional information on the data sources and methods of traffic volume.

The cumulative distribution plot of total daily PCE on all directional segments in the network is the basis for grouping the segments into categories, as shown in figure 2. The network is first divided into quartiles, and then to improve calculation of traffic-induced emissions, a finer resolution of 10% intervals is used for those segments above the median. The dividing points are therefore at the 25th, 50th, 60th, 70th, 80th and 90th percentiles in the plot, which correspond to total daily PCEs on directional segments of 2517, 11 704, 19 108, 33 908, 64 656, and 95 184, respectively.

Pavement surface characteristics, i.e., the metrics that represent pavement performance in this study, are modeled with explanatory variables of treatment type, truck traffic (in terms of ESAL) and climate region. Each type of pavement treatment and surface characteristic has a specific performance model with different formats and inputs. For asphalt overlay, IRI is a function of initial IRI, ESAL, climate region and

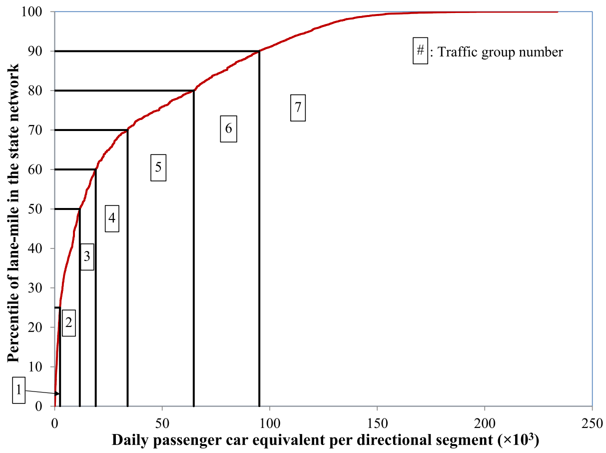

Figure 2. Cumulative distribution plot of daily PCE per directional segment and traffic group.

pavement age, whereas MPD is a determined by a number of variables such as asphalt mix type and truck traffic. For concrete pavement, IRI after diamond grinding with slab replacement is a function of initial IRI and cumulative ESAL, whereas MPD is a function of pavement age and climate region. These performance models are detailed in section S.2 in the supplementary material (available at stacks.iop.org/ERL/9/034007/mmedia). During the characterization the network, the performance of each segment is modeled using the applicable pavement, truck traffic and climate region properties of this segment that can affect the performance. If a property also contributes to other parts of the life cycle modeling, such as total vehicle traffic, it is then listed separately as a characteristic in table 1.

2.2. Life cycle assessment

This study performs life cycle GHG calculations on each pavement segment and sums the results within each traffic group. The GHGs tracked in this study include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) and they are normalized to CO_2-e using the IPCC's 100-year global warming potentials [16]. The scope of the analysis includes material production, construction, and use phases. Only the transport of materials removed during the treatments is modeled for the EOL phase. This study mainly focuses on repeated treatments with relatively short design lives, so a 10-year analysis period (2012–2021) is adopted to cover approximately 1.5 times the design lives.

In the life cycle modeling, each directional segment in the network is evaluated through two scenarios: (1) the *M&R* scenario and (2) the *Do Nothing* scenario. Then, the results are compared to current and historical Caltrans policies for IRI triggers. Caltrans historically used an IRI trigger of 3.54 m km^{-1} (224 in $mile^{-1}$) for asphalt pavement and 3.36 m km^{-1} (213 in $mile^{-1}$) for concrete pavement [23]. Recently, Caltrans has changed to a trigger of 2.86 m km^{-1} (170 in $mile^{-1}$) for all pavements. These policies are, in practice, constrained by budget limitations, meaning that pavement roughness often exceeds trigger values until funding is sufficient.

In the *M&R* scenario, when the IRI of a segment reaches the trigger, a treatment is performed, bringing down the IRI based on historical Caltrans data. The emissions and cost from the material production and construction of the treatment are calculated based on the material quantity and construction activity. The use phase CO_2-e is calculated based on the pavement surface characteristics and traffic composition and volume. The well-to-wheel (WTW) emissions of fuels are always used when there is fuel consumption.

In the *Do Nothing* scenario, the pavement is maintained at approximately its current roughness and macrotexture using repairs by local Caltrans forces. Emissions from material production and construction for these localized repairs are not calculated due to uncertainty in the particular activities and materials that might be used, and the fact that only small quantities of material are likely to be used. The use phase emissions for the *Do Nothing* scenario are calculated similarly to the *M&R* scenario. It should be noted that the state would never implement a *Do Nothing* strategy on the entire network, and would only implement a *Do Nothing* strategy on those sections where they do not have sufficient funding, with the constrained funding resulting in a de facto implementation of a *Do Nothing* strategy.

The difference in CO_2-e emissions between these two scenarios is calculated over the analysis period. This procedure is repeated for all segments in the network and the difference from each segment is summed for the final result over the analysis period. Ten IRI triggers, evenly distributed from 0.4 to 4.4 m km^{-1} (38–279 in $mile^{-1}$) are assessed for each traffic group and the value that leads to the highest CO_2-e reduction is considered optimal. The selection of the IRI triggers is intended to cover the common range of IRI values on modern paved highways in the US. It should be emphasized that the 'optimal triggers' developed in this study only apply to the CO_2-e emission reduction on the modeled highway using the selected maintenance treatments. Other social benefits such as increased safety, and social disbenefits such as diversion of funding for other purposes, are not included in the analysis and the results may not be optimal considering a broader range of objectives or a larger system definition.

2.3. Cost-effectiveness

Cost-effectiveness describes the cost of abatement per unit of pollution (here metric tons of CO_2-e emission, or tCO_2-e). A lower cost-effectiveness value indicates less money is needed to achieve the same level of CO_2-e reduction. This study assesses two types of costs: *agency cost* and *modified total cost*. *Agency cost* reflects the total contracted expenditures of the transportation agency, while the *modified total cost* is the *agency cost* subtracting the cost of saved fuel for the road users. A negative modified total cost indicates that this measure in the long term can reduce CO_2-e as well as save money for the two stakeholders considered (agency and road users) and is therefore a 'no-regret' strategy. A *total cost* calculation would consider additional costs of rougher pavement due to vehicle maintenance, vehicle life, accidents, etc. However, high-quality data for these costs are not readily available, which is why a modified total cost is used.

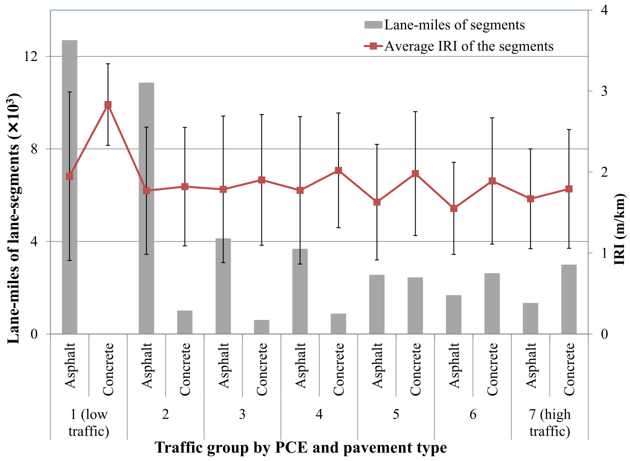

Figure 3. IRI and lane-miles on each traffic group and pavement type[5,6].

3. Input data

3.1. State pavement network

Figure 3 shows some descriptive statistics of the highway network based on the traffic groupings. Pavement type and IRI data are from the 2011 Caltrans Automated Pavement Condition Survey, and used as the initial state for the analysis in this study. Overall, asphalt surfaced pavement accounts for about 76% of the total lane-miles, mostly the segments in Groups 1–4.

3.2. LCA model

3.2.1. Material and construction phases. The modeling of emissions from the material production and construction phases is described in the project-level study that this network-level study builds on [12]. When applied to the network, the modeling of these phases is calculated based on the materials quantities and total lane-miles of each treatment.

For cost analysis, the agency cost of each treatment is acquired from the Caltrans PMS [17]. The fuel price for the saved energy consumption is acquired from the US Annual Energy Outlook [18]. A discount rate of 4% is used in accordance with Caltrans' practice for life cycle cost analysis [19]. Detailed life cycle emissions data and cost information are included in section S.3 of the supplementary material (available at stacks.iop.org/ERL/9/034007/mmedia).

The selection and timing of treatments roughly follow Caltrans guidelines [13] and the decision tree in the Caltrans PMS for the treatments modeled in this study [17], with the assumption that pavement surface type (asphalt or concrete) does not change. Detailed design of these treatments can be found in section S.1 of the supplementary material (available at stacks.iop.org/ERL/9/034007/mmedia).

[5] The error bar shown with the average IRI value is the standard deviation of the IRI in each group.

[6] There are only 0.9 lane-miles of concrete pavement observed in Group 1, so the average IRI value for that group is much higher than others and may not be considered representative.

The effect from work zone traffic, either through additional fuel use and traffic delay cost from congestion, or fuel savings caused by vehicles operating at slightly slower speeds in the work zone, is not considered in this study because construction of the modeled treatments on high traffic segments will generally be performed at night, causing almost no traffic delay and therefore minimal impacts. On the other hand, major rehabilitation or reconstruction treatments, although not modeled in this study, often occur during the daytime and can cause substantial traffic congestion. The cost and emission from their work zone congestion should be included in the modeling.

3.2.2. Use phase. The use phase of the pavement life cycle considered in this study includes the additional CO_2-e from vehicle operation due to pavement deterioration. Because CO_2 contributes over 99.8% of the vehicle tailpipe CO_2-e emissions, other tailpipe GHG emissions are not included. The well-to-pump (WTP) CO_2-e emissions for fuel are included based on vehicle fuel consumption using the GREET model [20].

To conduct the network-level analysis, vehicle tailpipe CO_2 emission factors are developed as a function of selected pavement segment characteristics, as shown in table 2. Sensitivity analyses were performed to evaluate whether additional characteristics were needed to represent the network's heterogeneity. The characteristics include the effects of congestion on urban restricted-access roads and different road vertical gradients on mountainous roads. Both had very small impacts on the relationship between pavement roughness and fuel consumption, and therefore were omitted.

The vehicle tailpipe CO_2 emission factors were developed as a continuous function of MPD and IRI for each combination of the categorical variables. A series of IRI and MPD values under each combination of the categorical variables were modeled using *MOVES* to calculate the tailpipe CO_2 emission [21], and then linear regression was used on the results to develop the function. The R-squared of the regression is above 0.99 in all cases, indicating that the vehicle tailpipe CO_2 emission factor is highly linearly correlated with IRI and MPD for each combination of the categorical variables. Section S.5 of the supplementary material (available at stacks.iop.org/ERL/9/034007/mmedia) provides additional details on these calculations.

Because pavement surface characteristics are inputs in the use phase and they change every year, the performance models for IRI and MPD developed by Tseng [22], Lu *et al* [23] and Rao *et al* [24] are used. These models are mainly functions of truck traffic level and climate, detailed in section S.2 of the supplementary material (available at stacks.iop.org/ERL/9/034007/mmedia).

4. Results and discussion

4.1. Comparison of M&R with Do Nothing

Figure 4 shows the annualized CO_2-e reduction when the modeled treatments are performed using different IRI triggers.

Table 2. Factorial variables used to develop vehicle tailpipe CO_2 emission factors.

Pavement type	Road type	Road-access type	Vehicle type mix	Pavement surface characteristics
Asphalt pavement; Concrete pavement	Urban roads; Rural roads	Restricted-access road; Unrestricted-access road	Passenger cars; 2-axle truck; 3-axle truck; 4-axle truck; 5 or more axle truck, including fuel efficiency improvement from 2012 to 2021	IRI performance; MPD performance
Categorical variable	Categorical variable	Categorical variable	Categorical variable	Continuous variable

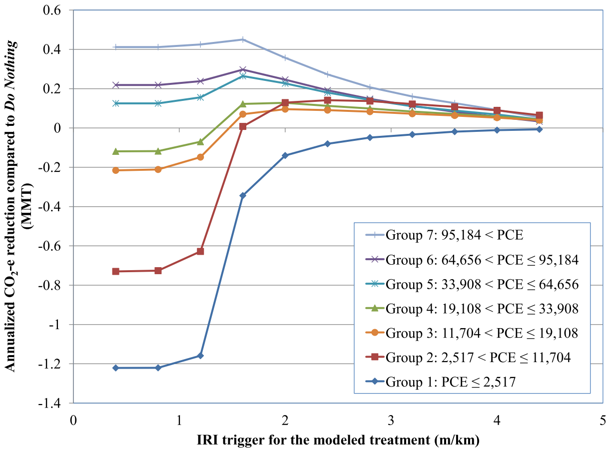

Figure 4. Annualized CO_2-e reductions versus IRI trigger for different traffic level over the 10-year analysis period for entire state network compared to *Do Nothing*.

The x-axis shows the IRI value that triggers the modeled treatments, and the y-axis shows the annualized CO_2-e emissions reduction compared to *Do Nothing* over the 10-year analysis period under different triggers. A positive value means there is a net reduction of CO_2-e.

Figure 4 shows that the higher the traffic level, the lower the IRI trigger that results in the maximum life cycle CO_2-e emissions reduction. Table 3 shows the maximum emission reductions in each group, the corresponding IRI triggers, and the modified total cost-effectiveness. Detailed cost-effectiveness results are in table S7 of the supplementary material (available at stacks.iop.org/ERL/9/034007/mmedia).

The ten percent of the network with the highest traffic (Group 7) yields nearly 35% of the CO_2-e emissions reductions, despite similar or lower roughness compared to the next lower traffic groups. For the segments that make up the bottom quartile of the network based on traffic volume (daily PCE lower than 2517) there is no IRI trigger that yields a reduction, indicating emissions from the material production and construction phases are always higher than reductions during the use phase.

The annualized CO_2-e emissions reduction that can be achieved if these optimal IRI triggers are implemented is 1.38 MMT over 10 years compared to *Do Nothing*. For comparison, CARB has estimated that the average annual baseline emissions from on-road vehicles is about 168.1 MMT CO_2-e between 2006 and 2020 [2]. Therefore, the potential reduction estimated from this study would contribute to about a 0.8% decrease compared to *Do Nothing*.

The IRI triggers for the maximum CO_2-e reductions are not the same as those which lead to the highest modified total cost-effectiveness (detailed results shown in table S8 of the supplementary material (available at stacks.iop.org/ERL/9/034007/mmedia)). In fact, in all traffic groups, the highest cost-effectiveness occurs at the IRI trigger of 4.4 m km^{-1}; the highest trigger assessed. This is because the relative change in cost with a higher IRI trigger is always greater than the relative change in CO_2-e emissions. In a given analysis period, a higher IRI trigger leads to fewer treatments and thus lower agency cost, but brings a relatively larger drop of IRI and thus greater reduction in emissions. As a result, as the IRI trigger increases, the cost-effectiveness increases. However, this conclusion may change if longer life treatments and total road user costs are evaluated.

The results in table 3 show that CO_2-e reductions from performing the modeled treatments on rough pavements has the potential to contribute to the statewide GHG reduction target, and that the traffic level plays an important role in determining optimal triggers. The cost-effectiveness provides a guide for prioritizing projects: the segments with a high cost-effectiveness, such as Group 7, should receive a higher priority for treatments when under a budget constraint.

4.2. Comparison with Caltrans' IRI triggers

Caltrans' PMS prioritization policies prior to 2011 used an IRI trigger of 3.54 m km^{-1} (224 in $mile^{-1}$) for asphalt pavement and 3.36 m km^{-1} (213 in $mile^{-1}$) for concrete pavement [25]. Since 2011, the trigger has been 2.86 m km^{-1} (170 in $mile^{-1}$) for all pavements. In practice, meeting these policy goals is constrained by budget, which does not permit all segments in the network to receive planned treatments.

By interpolating this study's results, the historical and current Caltrans IRI triggers lead to an annualized CO_2-e reduction of 0.57 and 0.82 MMT compared to *Do Nothing* over 10 years, with a modified total cost-effectiveness of \$355/tCO_2-e and \$520/tCO_2-e, respectively. Therefore, compared to the historical trigger, the current trigger of 2.86 m km^{-1} substantially reduces CO_2-e, although it is less cost-effective. The complete results of using these triggers are shown in table S9 and S10 of the supplementary material (available at stacks.iop.org/ERL/9/034007/mmedia). Compared to the historical and current Caltrans IRI triggers, the optimal IRI triggers can achieve an annualized marginal CO_2-e reduction of 0.82 and

Table 3. IRI trigger for the maximum CO_2-e reductions compared to *Do Nothing* over the 10-year analysis period for the entire network.

Traffic group	Daily PCE	Total lane-miles	Percentile of lane-miles	Optimal IRI trigger in m km^{-1} [a]	Annualized CO_2-e reductions (MMT)	Modified total cost-effectiveness[b] ($/t$CO_2$-e)
1	<2517	12 068	0–25	—	0	N/A
2	2517–11 704	12 068	25–50	2.4 (152)	0.141	1169
3	11 704–19 108	4 827	50–60	2.0 (127)	0.096	857
4	19 108–33 908	4 827	60–70	2.0 (127)	0.128	503
5	33 908–64 656	4 827	70–80	1.6 (101)	0.264	516
6	64 656–95 184	4 827	80–90	1.6 (101)	0.297	259
7	>95 184	4 827	90–100	1.6 (101)	0.45	104
Total					**1.38**	**416**

[a] inch $mile^{-1}$ is in the parentheses. 'Optimal' here only applies to CO_2-e reductions and does not include other social benefits.
[b] N/A = not applicable since no net CO_2-e reduction. 'Modified total cost' is the agency cost subtracting the cost of saved fuel for the road users. Agency cost, while not shown here, is the total contracted expenditures of the transportation agency. Detailed cost-effectiveness results are in table S7 of the supplementary material (available at stacks.iop.org/ERL/9/034007/mmedia).

Table 4. Example of comparison between on-time and late triggering (10-year analysis period).

When is treatment performed	Total agency cost compared to *Do Nothing* (dollar)	Annualized CO_2-e reduction compared to *Do Nothing* (metric ton)	Agency cost ratio (compared to on-time treatment)	CO_2-e reduction ratio (compared to on-time treatment)
On time	8.72×10^4	6.22×10^4	1.00	1.00
1 year later	7.90×10^4	5.85×10^4	0.91	0.94
2 years later	7.16×10^4	5.39×10^4	0.82	0.87
3 years later	7.04×10^4	5.08×10^4	0.81	0.82

0.57 MMT, with a marginal modified total cost-effectiveness of $457/t$CO_2$-e and $266/t$CO_2$-e, respectively. The current Caltrans IRI trigger is much closer to the optimal IRI triggers than the historical triggers, and this leads to a very small marginal cost change and an improved cost-effectiveness. The complete results of the comparison are in table S11 and S12 of the supplementary material (available at stacks.iop.org/ERL/9/034007/mmedia).

In practice, even if the IRI of a segment has reached its designated trigger, a treatment may not occur until 1–3 years later because of project development and delivery time, or longer if there are budget constraints. Therefore, the actual CO_2-e reductions and the cost in the analysis period are likely to be reduced.

Table 4 shows how the CO_2-e reduction and cost can change if the M&R activity is delayed. For a two-lane (per direction) 1-mile rural freeway with a one-direction annual average daily traffic of 12 000 and 10% trucks (PCE of 12 600), the treatment should be triggered at 2 m km^{-1} (127 in $mile^{-1}$). If the treatment is performed 1, 2, or 3 years after the IRI reaches the trigger, the CO_2-e reductions can drop by approximately 6%, 13%, and 18%, respectively, compared to on-time treatment. Also evident is that the cost drops faster than the CO_2-e reductions. Although the delay can lead to better cost-effectiveness, in part because fewer treatments are triggered in the analysis period, it reduces the potential CO_2-e reductions.

4.3. Comparison with alternative GHG mitigation measures

Lutsey examined GHG mitigation strategies for the transportation sector and their cost-effectiveness [26]. The cost-effectiveness of the pavement management treatments in this study are considerably lower than many alternative measures Lutsey identified, which were as low as $60/t$CO_2$-e or less, as shown in table 5 [26].

This result for pavement occurs because the construction of civil infrastructure is expensive, and more importantly, the costs evaluated in this study only include the agency and fuel cost, and exclude other road user costs. Because the main functionality of pavement is to maintain the mobility of goods and people using vehicles, one of the primary purposes for pavement management is to ensure the safety and efficiency for transportation, which is what a road user cares most about. Therefore, a more comprehensive benefit analysis would include other social benefits such as vehicle life, safety, tire consumption, goods damage, vehicle maintenance, driver comfort, and the value of time. From this point of view, the CO_2-e reduction can be considered a 'co-benefit' from pavement management when used as a GHG mitigation measure, and will be more cost-effective if all road user costs are included.

A preliminary study showed that while the fuel consumption (and therefore fuel cost) exhibits a linear relationship with roughness, the total road user cost can increase exponentially with the pavement roughness [27]. The ratio between total road user cost and fuel cost ranges from 6 to 10, depending on the vehicle type, driving speed and pavement condition [27]. A first-order estimate shows that the total cost-effectiveness can range from −$710/t$CO_2$-e to −$1610/tCO_2-e (compared to the $416/t$CO_2$-e as shown in table 3) if all road user costs are included. This result indicates that pavement management,

Table 5. Comparison of cost-effectiveness between pavement and some alternative measures in the transportation sector [26].

Measure	Annual CO_2-e emission reduction[a]	Total life cycle cost-effectiveness (\$2008/tCO_2-e)[b]
Light duty vehicle: incremental efficiency	20% tailpipe reduction	−75
Light duty vehicle: advanced hybrid vehicle	38% tailpipe reduction on new vehicles	42
Commercial trucks: class 2b efficiency	25% tailpipe reduction	−108
Alternative refrigerant	Replacement of HFC-134a with R-744a (CO_2)	67
Ethanol fuel substitution	Increase mix of cellulosic ethanol to 13% by volume	31
Biodiesel fuel substitution	Increase mix of biodiesel to 5% by volume	51
Aircraft efficiency	35% reduction in energy intensity	−9
Strategic pavement roughness triggers (this study)	1.38 MMT	390

[a] The first seven measures show the value of CO_2-e emission reduction in 2025. The value from 'strategic pavement roughness triggers (this study)' is an annualized life cycle value between 2012 and 2021.
[b] The result from table 3 is in 2012 dollars and is converted to 2008 dollars in this table using consumer price index (CPI).

when properly programmed like in this study, can potentially be a cost-competitive measure to reduce GHG emissions if total road user cost is considered. Once the total cost models as a function of pavement roughness for California are fully developed, the comparison with other transportation strategies should be performed again.

4.4. Uncertainty and sensitivity analyses

The main input data for this study include the traffic count and IRI on the state pavement network, the emission factors from the *MOVES* model, maintenance cost and IRI performance.

The traffic count used in this study is extracted from the traffic database used by the Caltrans PMS. It incorporates the high-quality data from Caltrans Performance Measurement System (PeMS) and Weigh-In-Motion stations. The IRI on the network was collected in the 2011 Caltrans Automated Pavement Condition Survey. Because of their wide use within Caltrans, these two sources of data have gone through a number of quality control and quality assurance studies to ensure their accuracy and should have minimal uncertainty. For emission factors, because *MOVES* itself does not provide an uncertainty analysis module, it is very difficult to perform any uncertainty analyses outside this complex model. Further, because this study is focused on the emission difference between scenarios, the uncertainty of emission factors can be expected to play a less important role. For maintenance cost, although it is averaged from historical Caltrans construction projects and there are some uncertainties associated with it, it can be predicted that the impact on the result is completely linear because this study does not include cost in the optimization procedure.

Therefore, sensitivity analyses are performed on two variables to assess their impacts on the results: constructed smoothness and analysis period. Complete results can be found in table S13 and S14 of the supplementary material (available at stacks.iop.org/ERL/9/034007/mmedia).

For constructed smoothness, three levels of initial IRI after construction are considered based on the statistical analysis described in section S.2.1 of the supplementary material (available at stacks.iop.org/ERL/9/034007/mmedia). The results show that the constructed smoothness can change the optimal triggers by as much as 0.8 m km^{-1}(51 in $mile^{-1}$). With a good construction smoothness, the benefit from the treatment can be more than doubled compared to the average construction smoothness; likewise, with poor constructed smoothness the benefits can be reduced by more than half. The constructed smoothness is primarily controlled by construction practice, quality control and the existing pavement condition, and to a lesser degree by the treatment type. Some 'Best Practices' to improve the constructed smoothness include pre-paving/grinding planning and preparation, good mix design, grade control, equipment control and good communication between personnel [28, 29]. Construction smoothness has historically not been specified in terms of IRI in California and most other states due to technical difficulties; a specification based on a moving beam has been used to identify 'bumps' which were then removed before acceptance of the completed project. However, those difficulties have recently been solved and many states are now moving to specification of construction in terms of IRI [30]. The new specifications are expected to reduce average IRIs obtained from treatment as well as variability. For example, California implemented an IRI based construction smoothness specification in July, 2013. However, data are not yet available to analyze the marginal benefit from this and other specific practices to improve smoothness.

Sensitivity analysis on the analysis period was performed to assess whether the selection of a particular time horizon substantially influences the results, using three analysis periods: 10, 15, and 20 years. The results show that different selections do not substantially change the optimal IRI triggers. One explanation for the small effect of the analysis period is that all periods selected covered the design life of most treatments, and this study amortizes the impact from material production and construction phases of the last treatment to avoid horizon effects.

5. Conclusions and future work

In this letter, a pavement LCA model is applied to the California state pavement network to evaluate the CO_2-e reduction resulting from a strategic application of selected M&R treatments. This approach and methodology can be adapted to any road network by substituting the appropriate local or regional conditions, treatments and practices, and used to support network-level pavement decision-making.

In this study, the network is broken into different groups based on their traffic level. An optimal IRI trigger leading to the highest CO_2-e reduction is developed for each group. These IRI triggers are only optimized for CO_2-e reduction for this study and may not lead to a socially optimal result. The following conclusions are drawn from this study:

- Traffic level has a substantial impact on the optimal IRI trigger. With optimal triggering, annualized CO_2-e reductions of 1.38, 0.82, and 0.57 MMT can be achieved compared to the *Do Nothing*, the historical, and the current Caltrans IRI triggers over the 10-year analysis period. The cost-effectiveness of these CO_2-e reduction strategies is worse than those reported for other transportation sector CO_2-e abatement measures when only considering fuel cost savings, but preliminary analyses indicate that pavement management can potentially be a cost-competitive measure to reduce GHG emissions if total road user cost is considered.
- Delaying M&R treatment when the IRI has reached the designated trigger can considerably reduce potential CO_2-e reduction.
- Sensitivity analyses show that the constructed smoothness has a substantial impact on the results, and the analysis period does not have a substantial impact on the optimal IRI triggers. The potential for changes in cost-effectiveness of treatment in light of recently improved construction smoothness specifications warrants future investigation.

Future implementation of this work will include the expansion of the treatment options using an approach similar to this study, such as major rehabilitation/reconstruction treatments. An upcoming study will investigate the impact on fuel consumption from pavement structure change. With this expansion of scope, it is possible to develop a more comprehensive M&R schedule and policy to reduce CO_2-e emissions over the pavement network life cycle.

Acknowledgments and disclaimer

This work is funded by the California Department of Transportation, Division of Research, Innovation and System Information, and the University of California Institute of Transportation Studies, Multi-campus Research Programs and Initiatives. The California LCA project is part of a pooled-effort program with eight European national road laboratories and the Federal Highway Administration called Models for rolling resistance In Road Infrastructure Asset Management Systems (MIRIAM).

The opinions and conclusions expressed in this letter are those of the authors and do not necessarily represent those of the California Department of Transportation, the Federal Highway Administration, the University of California, or the MIRIAM consortium.

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