SELECTED ROAD CONDITION, VEHICLE AND FREIGHT CONSIDERATIONS IN PAVEMENT LIFE CYCLE ASSESSMENT

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ABSTRACT

Road condition affects the operations and costs of vehicles using the infrastructure, as well as the rate at which the road deteriorates during use. Therefore, active and timely management of the road condition can be used as a tool to extend the service life of a road. One of the objectives of pavement Life-Cycle Assessment (LCA) is to evaluate the consequences of changes to a system on the entire life cycle and thus all relevant issues that may affect the operation of the system. It provides a comprehensive approach to evaluating the total environmental burden of a road, examining all the inputs and outputs, including material production, road construction, road use, maintenance and rehabilitation and end-of-life phases for road infrastructure. This paper focuses on issues that are directly affected by the road riding quality, and how this can potentially be utilized in LCA.

The paper is mainly based on a pilot study conducted for the California Department of Transportation (Caltrans) where actual road condition data from two corridors were collected and analyzed to determine the effect of the current road condition and potential changes in these road conditions on the economic and environmental impacts of the situation. Existing Vehicle Operating Cost (VOC) and environmental models were used for the analyses, and new relationships developed for potential freight damage. The objective of the paper is to demonstrate the importance of incorporating the active management of road condition as an aspect of LCA.

INTRODUCTION

Numerous studies have shown that the availability and condition of transportation infrastructure directly affects the cost of operating vehicles on the infrastructure, and subsequently the cost of freight being transported on such a network *(1-5)*. Road condition directly affects vehicle operations and costs, as well as the rate at which infrastructure deteriorates during use. The road condition is typically expressed in terms of the riding quality of the road. Subsequently, active and timely management of the road riding quality can be used as a tool to extend the service life of a road and the economic and environmental effects of vehicles using the specific road. Pavement Life-Cycle Assessment (LCA) partly evaluates the consequences of changes to the Vehicle-Pavement Interaction (V-PI) system and thus the entire road life cycle. The objective of this paper is to demonstrate, using data from two routes in California, how the riding quality of the road affects Vehicle Operating Costs (VOCs) and vehicle emissions. This would form part of the Maintenance and Rehabilitation Phase of a typical pavement LCA *(6)*.

The paper is based on a pilot study conducted for the California Department of Transportation (Caltrans). Principles of V-PI and state-of-the-art tools were used to simulate and measure loads and accelerations of trucks, trailers and their freight on a selected range of typical pavement surface profiles on the Interstate and State Highway System (SHS). Actual road condition data were collected from two road corridors and analyzed to determine the effect of the current road condition, and potential changes in these road conditions on the economic and environmental impacts of the situation *(7,8)*. Existing VOC and environmental models were used for the analyses, and new relationships developed for potential freight damage *(9,10)*. The project focused on determining economic effects of road conditions. The overall objective of the project was to enable Caltrans to better understand transportation planning, economic analysis and managing the risks of decisions regarding freight *(11)*.

STUDY BACKGROUND

Freight transport, and specifically truck transport is crucial to California, the home of the US's largest container port complex and the world's fifth largest port. Truck-based transportation dominates the freight transportation scene in California with 82 % of the freight tons shipped from California utilizing trucks *(10)*. Two companies voluntarily participated in a pilot study, after being selected based on contacts made with private industry to obtain interested parties that were willing to cooperate with Caltrans in this project. In order to protect the confidentiality of the information, anonymous designations (Company A and Company B) are used for all company sensitive information presented *(7,8)*. The overall scope of the pilot project entailed an inventory of current California riding quality data and vehicle population, a review of available information resources and related efforts focusing on V-PI, logistics and transportation economy, a simulation of typical trucks on selected roads using calibrated V-PI simulation software, measurement of accelerations and damage on selected locations of trucks on specific roads, development of simple relationships between riding quality, V-PI and damage and exploration of potential links regarding the environmental impacts and construction riding quality specifications *(11)*.

The riding quality of a road is traditionally used as the primary indication of the quality of a road - mainly due to findings that most of the deterioration in the road structure ultimately translates into deterioration in the riding quality *(12)*. Various studies about the effect of the riding quality of roads on the vibrations and responses in vehicles concluded that deterioration in the riding quality of a road is a major cause of increased vibrations and subsequent structural damage to vehicles and cargo *(13-16)*.

These increased vibrations and structural damage to vehicles can potentially have negative effects on the transportation cost of companies and the broader economy *(17)*. Comparing the estimated annual road maintenance costs per kilometer with the potential savings in VOC shows significant benefits that can be realized when keeping the road in a good condition *(1)*. Other parameters such as the engine and vehicle properties, environmental properties and other pavement properties such as grade, texture depth and pavement type also affect these relationships to an extent *(17)*. However, for this analysis and paper the focus was on the riding quality as one of the major parameters.

The current Caltrans Pavement Management System (PMS) provides an indication of the riding quality (in terms of International Roughness Index (IRI)) of the majority of the California Interstate and State Highway route network. In Table 1 a selection of the data for the roads used in the analysis are shown, including minimum, 20th percentile, average, 90th percentile and maximum of riding quality.

Table 1: Summary of State Highway System and Interstate Route Pavement Data *(8)*

State Highway System Route Data								
District	**Road #**	**Riding Quality (IRI) [In/Mi]***						
		Min	**20th Perc**	**Avg**	**90th Perc**	**Max**	**Stdev**	**Dist. [Mile]**
SJV	1 Inbound	13	33	56	85	648	43	5
	1 Outbound	10	40	69	104	1578	74	
	D road Inbound	17	48	80	125	593	50	3
	D Road O/bound	19	51	85	137	729	56	
	HM Road I/bound	19	63	115	196	1466	82	9
	HM Road O/bound	17	58	107	183	1058	75	
	L Road Inbound	39	107	225	463	1131	165	1.5
	L Road Outbound	37	91	187	354	1051	140	
Interstate Route Data								
District	**County**	**RIDING QUALITY (IRI) [In/Mi]***						**DIST. [Mile]**
		Min	**20th Perc**	**Avg**	**90th Perc**	**Max**	**Stdev**	
4	NAP	21	34	54	81	275	27	4.2
4	NAP	19	33	58	91	301	32	4.2
4	SOL	19	28	59	109	477	53	2.0
4	NAP	29	41	60	86	161	18	1.2
4	SOL	21	34	66	100	524	52	4.3
3	SAC	44	97	152	211	624	54	0.5
3	SAC	35	73	158	260	733	86	18.0
4	ALA	49	81	160	269	727	93	2.9
3	NEV	58	98	169	251	686	80	1.2
4	SF	125	141	210	277	381	53	0.3
3	NEV	63	99	244	452	974	147	4.1

* IRI [m/km] = IRI [in/mi]/64

VEHICLE-PAVEMENT INTERACTION, VEHICLE OPERATING COST, AND ENVIRONMENTAL RELATIONSHIPS

Simple relationships were developed between the road riding quality and a range of response parameters. These relationships are not developed for load compliance or enforcement. They may be used as an initial version of relationships to be used for generating data for use of planning and economic models. These relationships were developed between the riding quality and:

- Tire loads;
- Vertical acceleration of selected locations on the vehicle and freight;
- Fuel consumption;
- Tire wear, and
- Repair and maintenance costs.

Vehicle-Pavement Interaction (V-PI) Relationships

The tire load data originated from *TruckSIM™* simulations. Tire load models were developed for the steer, drive and trail axle tires (both separately and as a group) of the two types of vehicles (Table 2). Based on the procedure to develop a probability distribution of the expected tire loads for each of these axles or axle groups, Equations 1 to 4 were developed to determine the average and standard deviation of the normal probability distribution curves for the three axles of Company A trucks, while Equations 5 to 8 are applicable to Company B trucks. As the various axles' loads are normally not known in the field, the average is expressed in terms of the Gross Combination Mass (GCM) of the vehicle and the total number of tires on the vehicle.

The relationships were compared to existing work in South Africa where similar relationships were developed for typical South African vehicles and pavement conditions, and found to be relatively similar *(1)*. It was found that the average of the probability distribution of the tire loads for the axles are related mainly to the GCM of the vehicle, while the Standard Deviation of the probability distribution were mainly related to the roughness of the road. Current studies in South Africa also evaluate the use of alternative distributions (such as log-Normal and Weibull distributions) for describing these data.

Table 2: Equations for Calculating Distributions of Various Axle Load Distributions

Equation #	Axles	Company A	Company B
1	All*	AVG = GCM / # Total tires	
2	Steer**	STDEVstr = 0.0305*IRI + 1.6679	
3	Drive**	STDEVdrv = 0.0125*IRI + 1.7667	
4	Trail**	STDEVtr = 0.0276*IRI + 1.2376	
5	All*		AVG = GCM / # Total tires
6	Steer**		STDEVstr = $5.9665e^{(0.0043IRI)}$
7	Drive**		STDEVdrv = $24.223e^{(0.002IRI)}$
8	Trail**		STDEVtr = $19.168e^{(0.0023IRI)}$

* GCM [kN]   ** IRI [in/mi]

The vertical acceleration data were one of the standard outputs of the field measurements on both vehicles and freight during trips undertaken on a range of selected routes. Vertical acceleration data models were developed for the most critical (highest accelerations) vehicle and freight locations (highest point at back of front and rear trailers) on each of the vehicles. The models were used to determine the average and standard deviation of a distribution of vertical acceleration data as obtained from the vehicle simulation. It was found that the average of the probability distributions is not dependent on the speed, riding quality or GCM of the vehicle, and equal to 1 (gravity) (AVGall = 1.00 g), while the standard deviations depended mainly on the road riding quality. The equations for the standard deviation of the probability distributions are provided in Table 3.

Table 3: Equations for Calculating Vertical Acceleration Relationship Probability Distributions

Equation #	Location	Company A*	Company B*
9	Top front**	STDEV (top front) = 0.001*IRI + 0.021	
10	Top rear**	STDEV (top rear) = 0.002*IRI + 0.248	
11	Top front**		STDEV (top front) = 0.022*IRI + 0.023
12	Top rear**		STDEV (top rear) = 0.170*IRI + 0.139

* IRI [in/mi]   **STDEV (top front); (top rear) – Standard Deviation of vertical acceleration data at highest point at back of front; rear trailers

Vehicle Operating Costs (VOC) Relationships

New fuel consumption, tire wear, and vehicle repair and maintenance models could not be developed due to the lack of input data from the two companies. However, recently calibrated vehicle cost models using US vehicles and roads *(17)* were used as the basis of these relationships as they contain current evaluation of vehicles similar to those operational in California. The models for fuel consumption (Equation 13), tire wear (Equation 14) and repair and maintenance (Equation 15) were obtained from this data, simplified for the available data in the study and applied. The repair and maintenance models were previously compared to a separate set of South African vehicles and found to be reliable in terms of the predicted outputs when compared to actual data *(1)*.

$$Fuel\ Consumption = ((((2e^{-10}*speed^{2})-(2e^{-8}*speed)+8e^{-7})*IRI^{2})+(((-5e^{-8}*speed^{2})+(5e^{-6}*speed)-2e^{-4})*IRI)+(0.0495*e^{(0.0247*speed)}))^{-1} \quad (13)$$

$$Tire\ wear\ [\%/mile] = ((20e\text{-}10)*(speed^{1.7408}))*IRI) + (0.0007*e^{(0.0115*speed)}) \quad (14)$$

$$Repair\ and\ Maintenance\ [\$/mile] = ((0.0007*speed) + 0.0128)*e(0.0032*IRI) \quad (15)$$

Where:
Speed [mph] and IRI [in/mi]

In Table 4 an indication of the sensitivity of these outputs to the range of riding quality data for a specific route is provided, with examples of roads with a relatively low and relatively high variability (based on statistical analysis) in riding quality, as well as a road with localized low riding quality (short good section of road). These routes all originate from the sample obtained from the Company A and B routes. A speed of 55 mph was selected based on an analysis of truck traffic in California using Weigh-In-Motion (WIM) indicating 55 mph as the average speed of trucks on the selected population of Interstate routes *(18)*.

Environmental Impact Models and Data

The final part of the pilot project evaluated the use of existing relationships between road riding quality properties and environmental properties. The survey for existing relationships included evaluation of Transportation Research Board (TRB) and related publications (NCHRP), European publications (mainly PIARC) as well as other international sources. Numerous recent studies evaluated these relationships in light of the focus on the effect of human activities on the environment *(19-26)*. Suffice to indicate for the purposes of this paper that most of the studies agree on the various causes of climate change and the contribution made by human actions such as construction and transportation. Potential links regarding the environmental impacts (i.e. Greenhouse Gas (GHG) emission impacts and increased particulate matter) and construction riding quality specifications for the selected routes as a precursor to improved bonus penalty schemes for construction and maintenance / preservation of roads were evaluated. This analysis excludes investigating the environmental effects of pavement construction, maintenance and rehabilitation, as well as congestion. Road pavements that are constructed to a higher quality and maintained regularly are expected to provide a longer life, and thus lower construction related emissions, and a positive effect on LCA outcomes.

Table 4: Examples of Relatively Low and High Variability and Localized Bad Section Routes' Calculated Fuel Consumption, Tire Wear and Average Repair and Maintenance Costs at 55 mph

	Minimum	20^{th} %	Average	90^{th} %	Maximum
Riding quality (IRI) [in/mi]					
Low variability	125	142	210	277	381
High variability	39	107	225	463	1131
Localized bad sections	10	40	69	104	1578
Fuel consumption [mpg]					
Low variability	5.33	5.32	5.26	5.13	4.81
High variability	5.33	5.33	5.24	4.49	2.01
Localized bad sections	5.33	5.33	5.33	5.33	1.20
Tire wear [%/mile]					
Low variability	0.0013	0.0013	0.0014	0.0014	0.0014
High variability	0.0013	0.0013	0.0014	0.0014	0.0016
Localized bad sections	0.0013	0.0013	0.0013	0.0013	0.0017
Repair and maintenance cost [$/mile]					
Low variability	0.09	0.09	0.10	0.12	0.17
High variability	0.09	0.09	0.11	0.23	1.91
Localized bad sections	0.09	0.09	0.09	0.09	7.99

Rolling resistance of a pavement surfacing affects the fuel consumption, and therefore the emissions from the vehicle. Rolling resistance was not measured for this pilot project, and thus direct analysis and relationships cannot be developed. Published relationships between riding quality and rolling resistance indicate a change in rolling resistance (percentage) for a decrease in riding quality of 1 m/km (64 in/mi) per kilometer of 1.8 percent at a speed of 54 km/h (33 mph), and 6 percent at a speed of 90 km/h (56 mph) *(27,28)*. This is confirmed by studies on the life-cycle energy consumption and GHG emissions from pavement rehabilitation in California due to changes in rolling resistance *(29)*.

After evaluating the different models available (based on the conditions for which they were developed and the input parameters required to use them), a set of models was selected *(28)* for use in this project, as they provided a relatively simple relationship between the various parameters, and provided indications of the four main emission products typically evaluated (GHG, CO_2, CH_4 and N_2O). In this paper, only the GHG emissions are indicated in the relationship between riding quality, speed and emission (Equation 16). Application of Equation 16 is summarized in Table 5 and Figure 1 for three speeds and four road roughness levels.

$$\textit{GHG emission [kg/mile]} = 9.1948 / \textit{Fuel consumption [mpg]} \qquad (16)$$

Table 5: Summary of GHG Emissions as Affected by Speed and Road Roughness

IRI [in/mi]	64	128	256	512
GHG [kg/mi] (20 mph)	0.68	0.68	0.75	1.34
GHG [kg/mi] (55 mph)	1.73	1.73	1.77	2.15
GHG [kg/mi] (80 mph)	3.21	3.21	3.29	NA

NA – Not applicable combination for speed and roughness

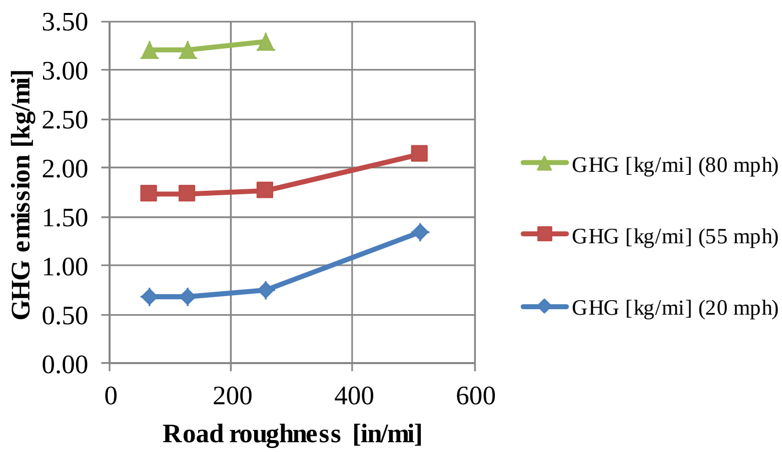

Figure 1: Summary of GHG emissions as affected by speed and road roughness.

The data available for the environmental and construction control analyses were mainly the riding quality data. For both Companies A and B, riding quality data are available for the networks that they use, and thus the typical GHG emissions could be determined on each of these general routes. For this analysis an average speed of 42 mph was used for the Company A routes, while an average speed of 55 mph was used for the Company B routes, based on that observed during the field work. The calculated GHG emissions for each of the companies are summarized in Table 6. It should be appreciated that the speed on the Company A routes was slower than on the Company B routes, although the riding quality was worse, and this had a major effect on the calculated GHG emissions. An additional line of data in Table 6 indicate the Company A data for a speed of 55 mph for comparison purposes. The analysis indicates that the speed does affect the GHG emissions significantly.

Table 6: Summarized GHG Emissions for Company A and Company B on Indicated Routes

Company	Average speed [mph]	Average riding quality [in/mi]	Nominal distance [mi]	Total GHG emissions [kg]	Average GHG emissions [kg/mi]
Company A	42	115	23	32	1.38
Company A	55	115	23	40	1.73
Company B	55	108	470	842	1.76

CONSTRUCTION QUALITY CONTROL

Construction quality control has a direct influence on the riding quality of a pavement, with improved control of density, layer thickness and attention to other details generally leading to smoother pavements. This is also true for construction control during pavement maintenance and rehabilitation. Generally, better riding quality provided by construction or maintenance will extend the life of a specific pavement for constant environmental conditions and traffic loads in contrast to a pavement with lower riding quality (higher level of roughness). The information and relationships developed in this pilot project, relating riding quality of pavements to tire loads, vertical acceleration, environmental emissions and costs, can be utilized to evaluate the potential costs and effects of different levels of construction quality control on the performance of the pavement. In order to conduct such an analysis, information is required on the pre-maintenance riding quality of the pavement, as well as the quality control guidelines and limits for the specific type of project. This may include the use of bonus-penalty schemes on the specific project.

Road Maintenance Analysis

As an example of the potential application of the relationships developed in the analysis of construction quality control effects on VPI and VOC, the following example was developed. It is assumed that the roads incorporated in the Company A analysis are to be maintained. The planned maintenance action (typically an Asphalt Concrete (AC) overlay), have the ability to improve the riding quality of the existing road. Equation 17 (n = 46; R^2 = 0.989; IRI converted to in/mi for this paper) *(31)* was used to predict the percentage improvement in riding quality (based on the IRI before mill and overlay) of a road overlaid with a 40 mm (1.6 in) AC overlay (the study focused on a typical South African highway and overlay thickness) under ideal conditions in terms of quality control and construction procedures.

$$\text{Percentage riding quality improvement} = 56.029 * (\ln(IRI)) - 239.57 \quad (17)$$

Using this relationship and the Company A initial 90th percentile riding quality data, two scenarios are evaluated. In the first scenario Equation 17 (indicating optimal improvement due to maintenance) is used with the current actual condition data and the riding quality for the improved condition calculated (Table 7). In the second scenario, it is assumed that the quality control was not conducted well during the maintenance, and, for the example, a 20 % worse end condition than for the optimum maintenance scenario obtained (20 % variation may for instance indicate a variance of only 8 mm or 0.3 in of the AC layer thickness). The tire load distribution, vertical acceleration distribution, fuel consumption, tire wear and repair and maintenance cost differences between the two outcomes are compared in Table 7.

Table 7: Comparison Between two Scenarios for Optimum Maintenance and Less-than-Optimum Quality Control during Road Maintenance

	% Improvement (from actual current)		**Average IRI After**		**Fuel Consumption [mpg]**		**GHG Emission [kg/mi]**		**Tire Use [%/mile]**		**Additional Damage [$/mile]**	
Average IRI before	**Opt***	**-20%****	**Opt***	**-20%****	**Opt***	**-20%****	**Opt***	**-20%****	**Opt***	**-20%****	**Opt***	**-20%****
225	49	29	139	159	7.454	7.389	1.300	1.305	0.00117	0.00117	0.0873	0.0886
			Average IRI after		**Tire load STDEV Steer**		**Tire load STDEV Drive**		**Tire load STDEV Trail**		**Vertical acceleration**	
			Opt*	**-20%****	**Opt***	**-20%****	**Opt***	**-20%****	**Opt***	**-20%****	**Opt***	**-20%****
			139	159	5.911	6.516	3.506	3.753	5.077	5.624	0.160	0.180

* Opt – Optimum maintenance scenario
**-20% - 20 % less-than-optimum maintenance scenario

Analysis of the data in Table 7 indicates limited differences between most of the cost items between the two maintenance outcomes. However, the changes in standard deviation of the probability distributions of the tire loads and the vertical accelerations indicate that the road will deteriorate at a quicker pace if not maintained optimally. In Figure 2 the probability distributions are shown, and the higher percentage of increased tire loads is visible in the expanded view on the right of Figure 2.

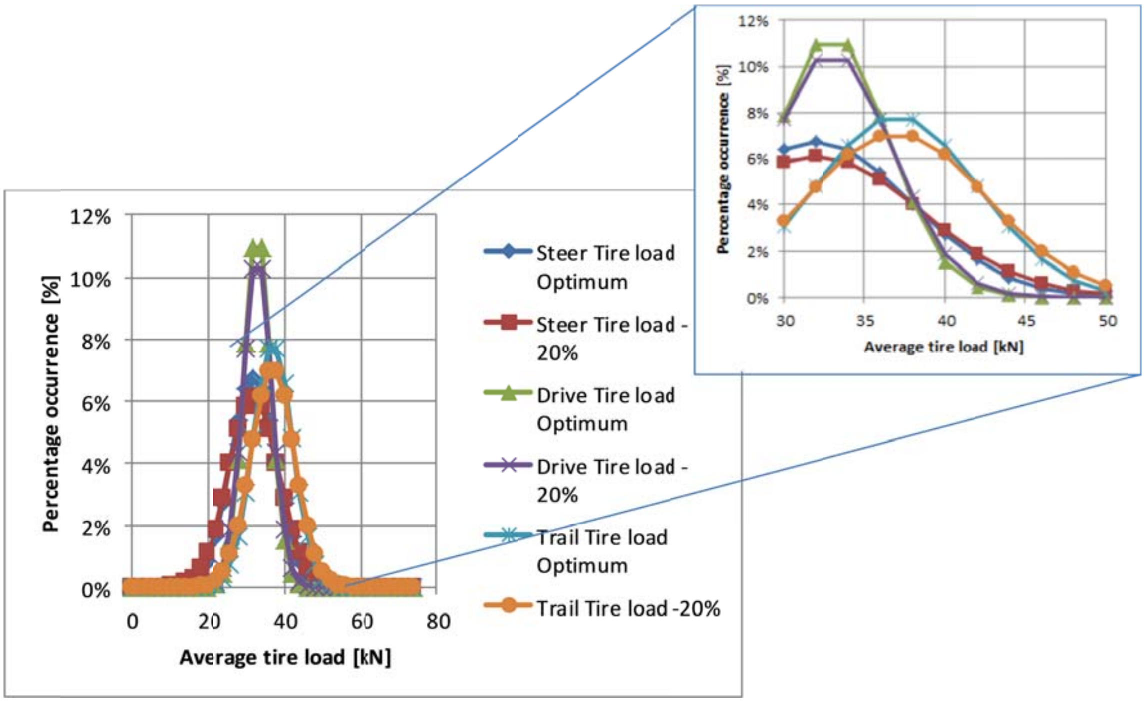

Figure 2: Expected probability distribution for optimum and 20% less-than-optimum maintenance of Company A routes (expanded detail on right).

Road Improvement Analysis

The road improvement analysis evaluates the application of the relationships to enable Caltrans to determine the potential benefits in improving the riding quality of an existing route. This differs from the previous example in that more than surface-related (AC overlay) type work would be required, and thus Equation 17 would not apply. The focus is on both the tire load relationships and the VOC relationships. The roads traveled by Company A trucks are used as data for this example, as the detailed roughness data and lengths of the roads are available, and the total distance is only 23 miles. It was shown that the average riding quality on a major sample of California routes is 109 in/mi, and this was taken as the target riding quality for the routes in this application *(8)*.

The process consisted of identifying the riding quality of the various routes, calculating the various costs and parameters for these conditions and then reanalyzing the data as if all roads that had riding qualities of worse than 109 in/mi are maintained or rehabilitated to at least 109 in/mi condition. The effects of this improvement in the road condition on all the parameters discussed in this report are evaluated. In Table 8 the outcome is summarized for all the parameters. As the total length of the roads is relatively short, the difference in vehicle related parameters is not major, however, the difference in the standard deviation of the various tire loads and the vertical acceleration is significant. In Figure 3 the distribution of tire loads are shown. The detailed view in Figure 3 (right) clearly indicates the decrease in overloaded conditions for the maintained routes.

Table 8: Comparison Between two Scenarios for Initial and Maintained Company A Routes

		Fuel consumption [mpg]		GHG emission [kg/mi]		Tire use [%/mile]		Additional damage [$/mile]	
Average IRI before	Average IRI after maintenance	Initial	After	Initial	After	Initial	After	Initial	After
167	82	6.696	6.712	1.373	1.370	0.00121	0.00120	0.095	0.095
		Tire load STDEV Steer		Tire load STDEV Drive		Tire load STDEV Trail		Vertical acceleration	
		Initial	After	Initial	After	Initial	After	Initial	After
		6.760	4.162	3.853	2.789	5.845	3.495	0.188	0.103

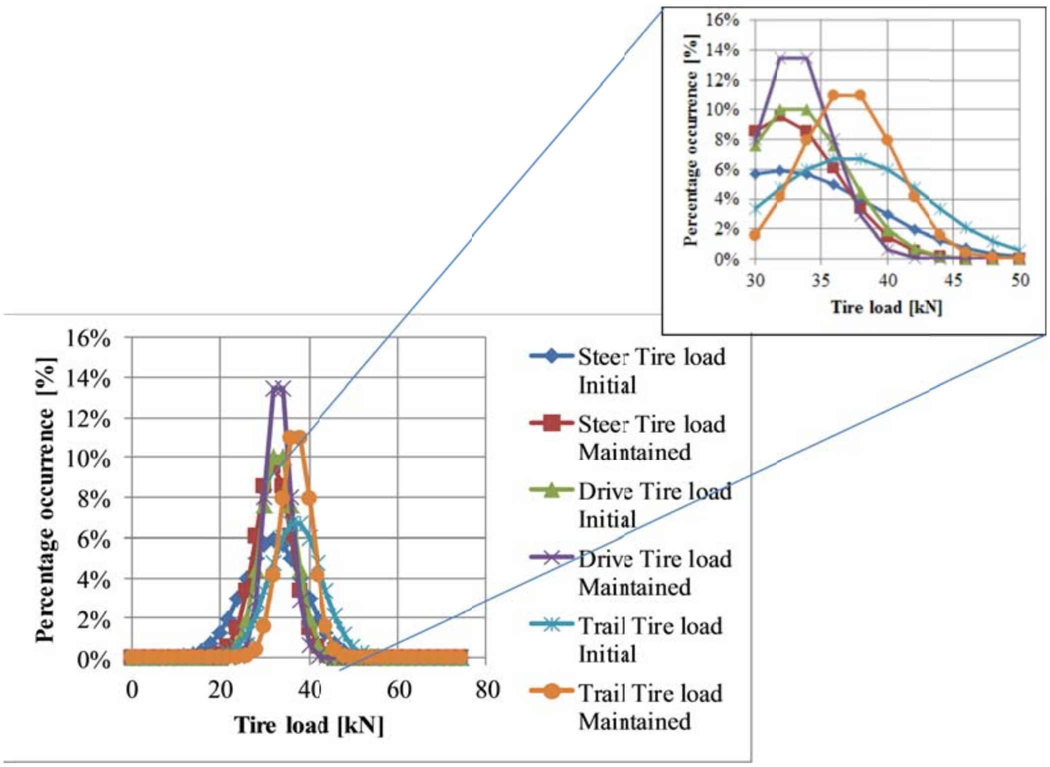

Figure 3: Expected probability distribution for initial and after maintenance conditions of Company A routes (expanded detail on right).

CONCLUSIONS

This paper reports on a pilot study for Caltrans. It is appreciated that the scope of the study and therefore the general application of findings are limited. However, as a pilot study it has proven to the client that the approach can provide valid results, and the general methodology has since been applied in a number of similar and more detailed projects where it has been shown to be applicable and robust in generating similar results on a wider scale. The results of these studies will only be published once they are completed.

The pilot project focused on V-PI for trucks operated on typical roads in California. Based on the information provided in this paper the following conclusions are drawn:

- From a public sector agency (Caltrans) viewpoint, the potential benefits of the information and models provided and discussed in this report are the following:
  - Tire loads on specific routes – tire loads generated on roads with different levels of roughness can be determined, and this information can be used as input for road pavement design, specifically focused on changes in road roughness over the life of the pavement;
  - Construction / maintenance quality control evaluation – the information can be used to determine the effects of different levels of quality control during construction and/or maintenance of the roads, as the effect of quality control on road roughness is known, and these changes can be related to expected life and user costs for the road,
  - User costs on specific routes – models are presented that can be used to calculate the user costs on roads with different roughness levels, serving as input to various economic models and calculation of benefit / cost ratios of maintenance and upgrading actions on these routes.
  - General riding quality – the sensitivity of the VOC models to riding quality indicate that a lower required riding quality of around 110 in/mi should be optimal for best VOC.
- For private sector companies using the roads in California for transportation of freight, the potential benefits of these models and data are:
  - Evaluation of potential VOCs on specific routes – the data can be used to calculate the costs of traveling specific routes, as well as in the selection of routes that may be longer in distance, but more cost effective due to lower roughness levels,
  - Route planning – based on the potential damage to sensitive freight, and the potential vehicle operating costs and damage due to road roughness, alternative routes may be evaluated and smoother routes selected where available.

This paper gives some indications of potential considerations for pavement LCA that reflect decisions and actions by the roadway infrastructure owner/operator and its roadway users. Relationships between riding quality and its influence on economic and environmental aspects of roadways described from the pilot study can advance understanding and evaluation for the Maintenance and Rehabilitation Phase of a typical pavement LCA.

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