Title

Freight-Truck-Pavement Interaction,Logistics, and Economics:Final Phase 1 Report (Tasks 9–11)

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Work Conducted Under Partnered Pavement Research Program (PPRC) Strategic Plan
Element 4.44: Pilot Study Investigating the Interaction and Effects for State Highway Pavements,
Trucks, Freight, and Logistics

PREPARED FOR:

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Authors: W.J.vdM Steyn, and L. du Plessis

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Abstract:

The intention of the study is to demonstrate the potential economic effects of delayed road maintenance and management, leading to deteriorated riding quality and subsequent increased vehicle operating costs, vehicle damage, and freight damage.

The overall objectives of this project are to enable Caltrans to better manage the risks of decisions regarding freight and the management and preservation of the pavement network, as the potential effects of such decisions (i.e., to resurface and improve riding quality earlier or delay such a decision for a specific pavement) will be quantifiable in economic terms. This objective will be reached through applying the principles of vehicle-pavement interaction (V-PI) and state-of-the-practice tools to simulate and measure peak loads and vertical acceleration of trucks and their freight on a selected range of typical pavement surface profiles on the State Highway System (SHS) for a specific region or Caltrans district.

The objectives of this report are to provide information on Tasks 9 to 11.

Conclusions

The following conclusions are drawn based on the information provided and discussed in this report:

- Road roughness data can be used in conjunction with appropriate models and relationships to evaluate the economic effect of road use by logistics companies through evaluation of vehicle operating costs (VOCs) and potential damage to vehicles and freight.
- As road roughness generally deteriorates with road use, road owners can evaluate the economic changes in the VOCs of road users over time, and determine optimum times for maintenance and rehabilitation of existing transportation infrastructure.
- Road users can use relationships between road roughness and various parameters (VOCs, freight damage, etc.) to select optimal routes where VOCs and damage are minimized and also objectively calculate the effect of these road conditions on their income.
- Road owners can evaluate the effect of different levels of construction and maintenance quality control on the outcome of these actions and the general transportation costs and deterioration rates of the infrastructure as affected by riding quality/road roughness.

Recommendations

The following recommendations are made based on the information provided and discussed in this report:

- The models and relationships in the report should be evaluated for incorporation into the appropriate Caltrans economic models, to enable modeling of the effects of riding quality and deterioration of riding quality over time on economic models.
- Analysis of the effect of construction and maintenance quality control using local maintenance options and their effects on the riding quality of roads should be evaluated to enable appropriate control levels to be determined.
- The effects of riding quality bonus-penalty schemes, and the effect of initial riding quality on the long-term performance of local roads, should be incorporated into an overall transportation infrastructure model.
- Further studies on the damage determination of transported agricultural produce at a range of frequencies caused by various riding quality truck combinations using laboratory-based bulk density measurements should be conducted (similar to the tomato tests discussed in this report).

- The pilot study should be expanded to cover more districts or corridors with a complete coverage of the potential VOCs, freight damage, and environmental effects for at least a full additional district. This may include expansion of freight damage to other types of freight and more detailed freight damage relationships, and incorporation of pavement construction and maintenance quality control implications—effects of maintenance to specific levels of riding quality on larger economic outcomes.
- The effect of recent technology advances such as the use of lower rolling resistance tires in the VOC and freight damage equations should be investigated.
- A more detailed analysis of environmental/emissions effects such as these are only very briefly touched on in the pilot study.

Keywords: Vehicle-Pavement Interaction, Freight transport industry sustainability and competitiveness, Pavement roughness, Economic evaluation, Cal-B/C, Logistics

Proposals for Implementation:

This final report will be studied by the Caltrans and implementation decisions taken.

Related Documents:

- W.J.vdM. Steyn, N. Viljoen, L. Popescu, and L. du Plessis . 2012. Freight-Truck-Pavement Interaction, Logistics, and Economics: Final Phase 1 Report (Tasks 1–6). Research Report prepared for Caltrans Division of Transportation Planning. (UCPRC-RR-2012-06)
- W.J.vdM. Steyn. 2013. Freight-Truck-Pavement Interaction, Logistics, and Economics: Final Phase 1 Report (Tasks 7–8). Research Report prepared for Caltrans Division of Transportation Planning. (UCPRC-RR-2013-08)
- W.J.vdM. Steyn, L. du Plessis, N. Viljoen, Q. van Heerden, L. Mashoko, E. van Dyk, and L. Popescu. 2014. Freight-Truck-Pavement Interaction, Logistics, & Economics: Final Executive Summary Report. Summary Report prepared for Caltrans Division of Transportation Planning. (UCPRC-SR-2014-01)
- N. Viljoen, Q. van Heerden, L. Popescu, L. Mashoko, E. van Dyk, and W. Bean. Logistics Augmentation to the Freight-Truck-Pavement Interaction Pilot Study: Final Report 2014. Research Report prepared for Caltrans Division of Transportation Planning.(UCPRC-RR-2014-02)

Signatures

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DISCLAIMER STATEMENT

ACKNOWLEDGMENTS

The inputs and comments of all organizations contacted for information in this project are acknowledged. Specifically, the inputs of the following persons are acknowledged:

- Caltrans technical advisors to the project team: Al Arana (DOTP Office of System Planning), Joanne McDermott (DOTP Office of Freight Planning)
- DOTP Economic Analysis Branch staff: Rose Agacer, Barry Padilla, and Austin Hicks
- DRISI Office of Materials and Infrastructure: Joe Holland and Bill Nokes

PROJECT OBJECTIVES

The overall objectives of this project is to enable Caltrans to manage the risks of decisions regarding freight and the management and preservation of the pavement network in an improved way, as the potential effects of such decisions (i.e., to resurface and improve riding quality earlier or delay such a decision for a specific pavement) will be quantifiable in economic terms. This objective will be reached through applying the principles of vehicle-pavement interaction (V-PI) and state-of-the-practice tools to simulate and measure peak loads and vertical acceleration of trucks and their freight on a selected range of typical pavement surface profiles on the State Highway System (SHS) for a specific region or Caltrans district.

The objectives of this report are to provide information on Tasks 9 to 11.

Note: This document reports information that was developed and provided incrementally by the research team as the pilot study proceeded. For consistency with the incremental nature of the work and the reporting on it, this final report retains the same grammatical tense referring to remaining tasks (as yet to be done), although all tasks and the pilot study have been completed.

EXECUTIVE SUMMARY

Introduction

This pilot study applies the principles of vehicle-pavement interaction (V-PI) and state-of-the-practice tools to simulate and measure tire loads and vertical acceleration of trucks and their freight on a selected range of typical pavement surface profiles on the State Highway System (SHS) for a specific region or Caltrans district. The pilot study does not focus on the detailed economic analysis of the situation; however, the outputs from the pilot study are expected to be used as input or insights by others towards planning and economic models to enable an improved evaluation of the freight flows and costs in the selected region/district. It is anticipated that use of findings from this study as input by others into planning and economic models will enable calculating the direct effects of riding quality (and therefore road maintenance and management efforts) on the regional and state economy.

The final product of this pilot study consists of data and information resulting from (1) simulations and measurements, (2) tracking truck/freight logistics (and costs if available), and (3) input for economic evaluation based on V-PI and freight logistics investigation. Potential links of the data and information to available and published environmental emissions models (e.g., greenhouse gas [GHG], particulate matter), pavement construction specifications, agricultural freight damage, and roadway maintenance/preservation are examined.

The intention of the pilot study is to enable economic evaluation (using tools such as Caltrans' Cal-B/C model) of the potential economic effects of delayed road maintenance and management, leading to deteriorated riding quality and subsequent increased vehicle operating costs, vehicle damage, and freight damage. The study was conducted as a pilot study in two regions where the probability of collecting the maximum data regarding road quality, vehicle population, and operational conditions was high, and where the outcomes of the study might be incorporated into economic and planning models. The final selection of the regions was done in conjunction with Caltrans and based on initial data in Tasks 3 to 5 [*1*] and availability of two companies that were willing to cooperate in the study. This focused pilot study enables developing and refining the approach in a contained region, where ample access may be available to required data, information, and models. After the pilot study is completed and the approach is accepted and has been shown to provide benefits to Caltrans and stakeholders, it can be expanded to other regions as required.

The overall objectives of this project are to enable Caltrans to better manage the risks of decisions regarding freight and the management and preservation of the pavement network, as the potential effects of such decisions (i.e., to resurface and improve riding quality earlier or delay such a decision for a specific pavement) will be quantifiable in economic terms. This objective will be reached through applying the principles of vehicle-pavement interaction (V-PI) and state-of-the-practice tools to simulate and measure peak loads and vertical acceleration of trucks and their freight on a selected range of typical pavement surface profiles on the SHS for a specific region or Caltrans district.

The objectives of this report are to provide information on Tasks 9 to 11.

Report Issues

The purpose of this pilot study is to provide data and information that will provide input supporting Caltrans' freight program plans and legislation-mandated requirements with findings potentially contributing to economic evaluations; identification of challenges to stakeholders; and identification of problems, operational concerns, and strategies that "go beyond the pavement"—including costs to the economy and the transportation network (delay, packaging, environment, etc.). Findings could lead to improved pavement policies and practices, such as strategic recommendations that link pavement surface profile, design, construction, and preservation with V-PI. These findings should also provide information for evaluating the relationship between pavement ride quality (stemming from the pavement's condition), vehicle operating costs, freight damage, and logistics.

Task 9 – Maps

Various maps were developed as layers in Google Earth^{TM}. These maps are based on the models and data collected and developed in Tasks 3 to 11 of the project, and they cover road conditions, tire loads and vehicle vertical accelerations, fuel consumption, tire wear and repair and maintenance costs, and greenhouse gas (GHG) emissions. The map data are provided as separate .kmz files that can be linked to the Caltrans Earth application as additional layers of data.

Task 10 – Relationships

Various relationships were developed between the road roughness data and the tire loads and vehicle vertical accelerations, fuel consumption, tire wear and repair and maintenance costs, and GHG emissions for use in this project. Some of the relationships were developed entirely based on data collected in this study, while others are partly based on published data and models. All the relationships were evaluated and compared to published data to ensure that they provide realistic outputs.

Task 11 – Environmental

Environmental models were developed based on available relationships between fuel consumption and road roughness. The focus in the report is on GHG emissions, although various other emissions that are relevant in climate change studies can also be expressed in terms of similar relationships.

Applications and Implications

The report contains a number of typical applications of the relationships and data to demonstrate potential practical use, implications, and outcomes of the relationships for Caltrans and its stakeholders. Specific examples evaluate the effects of road conditions on agricultural freight damage and losses to the agricultural producers due to road condition effects, route selection by road users based on road conditions, and evaluation of the benefit/cost ratios of road improvement projects by the road owner.

From the Caltrans (public agency) 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 catering for changes in the 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.

For private companies using the roads in California for transportation of goods, 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 damage due to road roughness, alternative routes may be evaluated and smoother routes selected where available.
- Evaluation of the potential losses and additional costs due to transportation of agricultural produce (specifically tomatoes) over roads with less-than-desirable road roughness levels.

LIST OF ABBREVIATIONS

AC	Asphalt concrete
CARB	California Air Resources Board
DOTP	Division of Transportation Planning
EPA	Environmental Protection Agency
FC	Fuel consumption
FHWA	Federal Highway Administration
GCM	Gross combination mass
GHG	Greenhouse gas
GMAP	Goods Movement Action Plan
GPS	Global Positioning System
HOV	High Occupancy Vehicle
IRI	International Roughness Index
LRR	Low Rolling Resistance
LTL	Less than truckload
MnDOT	Minnesota Department of Transportation
NCHRP	National Cooperative Highway Research Program
NWS	National Weather Service
PIARC	World Road Association
PMS	Pavement Management System
PPRC	Partnered Pavement Research Center
PSD	Power Spectral Density
SCAG	Southern California Association of Governments
SHS	State Highway System
SJV	San Joaquin Valley
SJVIGMP	San Joaquin Valley Interregional Goods Movement Plan
STAA	Surface Transportation Assistance Act
St. Dev.	Standard deviation
TL	Truckload
TRB	Transportation Research Board
UCPRC	University of California Pavement Research Center
VOC	Vehicle operating costs
WIM	Weigh-in-motion
V-PI	Vehicle-pavement interaction

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in.	inches	25.4	Millimeters	mm
ft	feet	0.305	Meters	m
yd	yards	0.914	Meters	m
mi	miles	1.61	Kilometers	Km
		AREA		
in^2	square inches	645.2	Square millimeters	mm^2
ft^2	square feet	0.093	Square meters	m^2
yd^2	square yard	0.836	Square meters	m^2
ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	Square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	Grams	g
lb	pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
Fc	foot-candles	10.76	Lux	lx
Fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	Kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	Inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	Hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	Milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	Ounces	oz
kg	kilograms	2.202	Pounds	lb
mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	Poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380 (Revised March 2003).

1 INTRODUCTION

1.1 Introduction

This pilot study (entitled *Pilot Study Investigating the Interaction and Effects for State Highway Pavements, Trucks, Freight, and Logistics*) will apply the principles of vehicle-pavement interaction (V-PI) and state-of-the-practice tools to simulate and measure peak loads and vertical acceleration of trucks and their freight on a selected range of typical pavement surface profiles on the State Highway System (SHS) for a specific region or Caltrans district. Successfully measuring loads and accelerations requires access to trucks and freight, so this activity is contingent on the extent of private sector collaboration as specified in the project proposal. For a given segment of pavement, quantification of loads will enable predicting potential damaging effects of these loads on pavement service life. Likewise, quantifying vertical accelerations will enable investigating the relationship between these accelerations and damage to trucks as well as to their freight. Investigating the damage caused by and imposed on each component in the pavement-truck-freight system enables understanding of small-scale (project-level) effects and also is expected to provide insights about larger-scale (network-level) impacts on freight logistics. The outputs of this pilot study may be used in planning and economic evaluation of the potential effects of deteriorated riding quality and freight in California. Results from this pilot study are intended for evaluation on the SHS statewide. Data and information about the pavement-vehicle-freight system components are expected to be applicable to regional and local evaluations, including metropolitan transportation planning.

V-PI Simulations and Measurements: Simulations will apply state-of-the-practice computer models to generate expected applied tire loads and accelerations from standard trucks based on indicators of ride quality from pavement profile survey data from California. Measurements will include instrumentation of a sample of vehicles with standalone acceleration sensors and Global Positioning System (GPS) to obtain data. Successfully measuring loads and accelerations requires access to trucks that operate on dedicated routes. It is proposed that this access will be through one or more private sector partners, operating a range of trucks on dedicated routes, *or* through use of a Caltrans vehicle, *or* through use of a rental truck. It is anticipated that one typical truck will be selected in any of the approaches. A final selection on an appropriate route covering a range of riding qualities and speeds within the selected region/district will be taken during Task 5. Measurements will provide validation of simulations and information for potentially analyzing effects of V-PI on various types of freight, as well as the pavement network through dynamically generated tire loads. Different types of freight are impacted differently by the vertical accelerations caused by V-PI; therefore it is warranted to observe more than one type of freight for, e.g., mineral resources, agricultural products (fruit, vegetables, and grains), sensitive manufactured goods (electronics), and other manufactured goods. The focus of the pilot project will be roadway segments on selected routes in a selected region/district, to enable the approach to be adopted for application towards Caltrans-specific requirements (e.g., region/district definitions, traffic volumes, riding quality levels, etc.). In this regard, the focus will probably be on segments on one major highway with a range of riding qualities, and one minor road in the same region/district with a range of riding qualities. Typically, major highways on the State Highway System will have different ranges of riding quality levels than lower volume segments of the SHS due to differences in traffic volumes, pavement design, and construction practices.

Freight Logistics Impacts: In this pilot study, *freight logistics* refers to the processes involved in moving freight from a supplier to a receiver via a route that includes the segments of road identified for this pilot study. V-PI has ramifications for freight logistics processes beyond the actual road transport, and to investigate these effects holistically requires access to selected operational information. Investigating the direct impacts of V-PI on the freight transported requires access to truck fleet operational information (e.g., a combination of routes and vertical accelerations measured on the vehicles). This data will be acquired from either collaboration with private sector partners who communicate their operations and then allow GPS tracking of their trucks and field measurements of truck/freight accelerations while traveling on California pavements, *or* from published data available through the South African State of Logistics studies or the U.S. State of Logistics studies. The private sector data would be preferable. In addition, access to operational data regarding packaging practices, loading practices, cost data, and insurance coverage would be valuable to develop a more holistic understanding. Selected data sources and potential data collection methodologies will be reported in Tasks 5 and 6.

Economic Implications: The pilot study is not focusing on detailed economic analysis of the situation; however, the outputs from the pilot study are expected to be used as input or insights by others towards planning and economic models to enable an improved evaluation of the freight flows and costs in the selected region/district. Such planning models may include the Caltrans Statewide Freight Model (in development), or the Heavy-Duty Truck Model (used by the Southern California Association of Governments [SCAG]). Input from and interaction with Caltrans will be needed during the pilot study. It is anticipated that use of findings from this pilot study as input by others into planning and economic models will enable the direct effects of riding quality (and therefore road maintenance and management efforts) on the regional and state economy to be calculated.

The final product of this pilot study will consist of data and information resulting from (1) simulations and measurements, (2) tracking truck/freight logistics (and costs if available), and (3) input for economic evaluation based on V-PI and freight logistics investigation. Potential links of the data and information to available and published environmental emissions models (e.g., greenhouse gas [GHG], particulate matter), pavement construction specifications, and roadway maintenance/preservation will be examined.

Stakeholders (Caltrans if not indicated otherwise) identified to date are: (1) Division of Transportation Planning including Office of State Planning (Economic Analysis Branch, State Planning Branch, and Team for California Interregional Blueprint/Transportation Plan [CIB/CTP]) and Office of System and Freight Planning; (2) Division of Transportation System Information including Office of Travel Forecasting and Analysis (Freight Modeling/Data Branch, Statewide Modeling Branch, and Strategic and Operational Project Planning Coordinator);

(3) Division of Traffic Operations Office of Truck Services; (4) Division of Maintenance Office of Pavement and Performance; (5) Project Delivery: Divisions of Construction, Design, and Engineering Services; and (6) private sector partner(s).

1.2 Background

Freight transport is crucial to California, the home of this country's largest container port complex and the world's fifth largest port. Freight transported by trucks on California's roadways is crucial. Planning and making informed decisions about freight transported by trucks on the SHS requires reliance on data and information that represent pavement, truck, and freight interactions under conditions as they exist in California. Data, information, and the understanding of V-PI physical effects, logistics, and economic implications within a coherent framework are lacking. This occurs at a time when a national freight policy is expected in the next federal transportation reauthorization bill, and Caltrans already has several freight initiatives in progress including a scoping study for the California Freight Mobility Plan (which is an updated and enhanced version of the Goods Movement Action Plan [GMAP]), and planning for the Statewide Freight Model (which support the California Interregional Blueprint [CIB]). These along with other plans will support the California Transportation Plan that will be updated by December 2015. Data and information identified in this study also are expected to be needed for evaluations, plans, and decisions to help meet requirements of legislation including AB 32, SB 375, and SB 391.

1.3 Scope

The overall scope of this project entails the tasks shown in Table 1.1. Task descriptions, deliverables, and timeframes are shown for all 12 tasks. Figure 1.1 contains a schematic layout of the tasks and linkages between tasks for this pilot study.

The intention of the pilot study is to demonstrate the potential economic effects of delayed road maintenance and management, leading to deteriorated riding quality and subsequent increased vehicle operating costs, vehicle damage, and freight damage. The study is conducted as a pilot study in a region/Caltrans district where the probability of collecting the maximum data regarding road quality, vehicle population, and operational conditions will be the highest, and where the outcomes of the pilot study may be incorporated into economic and planning models. The final selection of the region/district was done based on information collected during Tasks 3 to 5 (see Section 6). This focused pilot study enables developing and refining the approach in a contained region/district, where ample access may be available to required data, information, and models. After the pilot study is completed and the approach is accepted and has been shown to provide benefits to Caltrans and stakeholders, it can be expanded to other regions/districts as required.

Table 1.1: Task Description for Project

Task Description	Deliverable/Outcome	Time Frame
Task 1:		
Finalize and Execute Contract	Executed Contract	Oct 2011/February 2012
Task 2: Kickoff Meeting with Caltrans	Meeting and Project Materials	February 2012
(1 week travel)		
Task 3:		
Inventory of current California ride quality/road profiles Identify existing data available within Caltrans.	Map/table with current riding quality (IRI) for a selected region or district—only on truck outside-lanes for road segments on selected routes	February/April 2012
Task 4:		
Inventory of current California vehicle population—only on truck outside-lanes for road segments on selected routes Identify existing data available within Caltrans.	Table of current vehicle population per standard FHWA vehicle classifications	February/April 2012
Task 5:		
Research/review available information resources (from Tasks 3 and 4 as well as additional material) and related efforts (e.g., Pavement Condition Survey and new Pavement Mgt Sys [PMS] in progress). Data sources include State of Logistics (both USA and South Africa studies), MIRIAM project (Models for rolling resistance in Road Infrastructure Asset Management systems) (UC Pavement Research Center [UCPRC] is involved in current research), as well as related US/California studies into V-PI and riding quality.	Detailed understanding and input to progress report on the available data sources and required analyses for the project. Inclusive of indications of the potential links between the outputs from this project and the inputs for the various economic and planning models (e.g., Statewide Freight Model, Heavy-Duty Truck Model [SCAG], etc.). Final selection on an appropriate route covering a range of riding qualities and speeds within the selected region/district for potential truck measurements, as agreed on by Caltrans after evaluation of all relevant information.	March/May 2012
Task 6:		
Progress/Planning Meeting and Progress report on Tasks 3 to 5.	Progress report on pilot study containing (i) updated tasks for identifying additional required information and provisional outcomes of study; (ii) decision regarding selected region/district for pilot study; and (iii) recommendations for next tasks.	June 2012

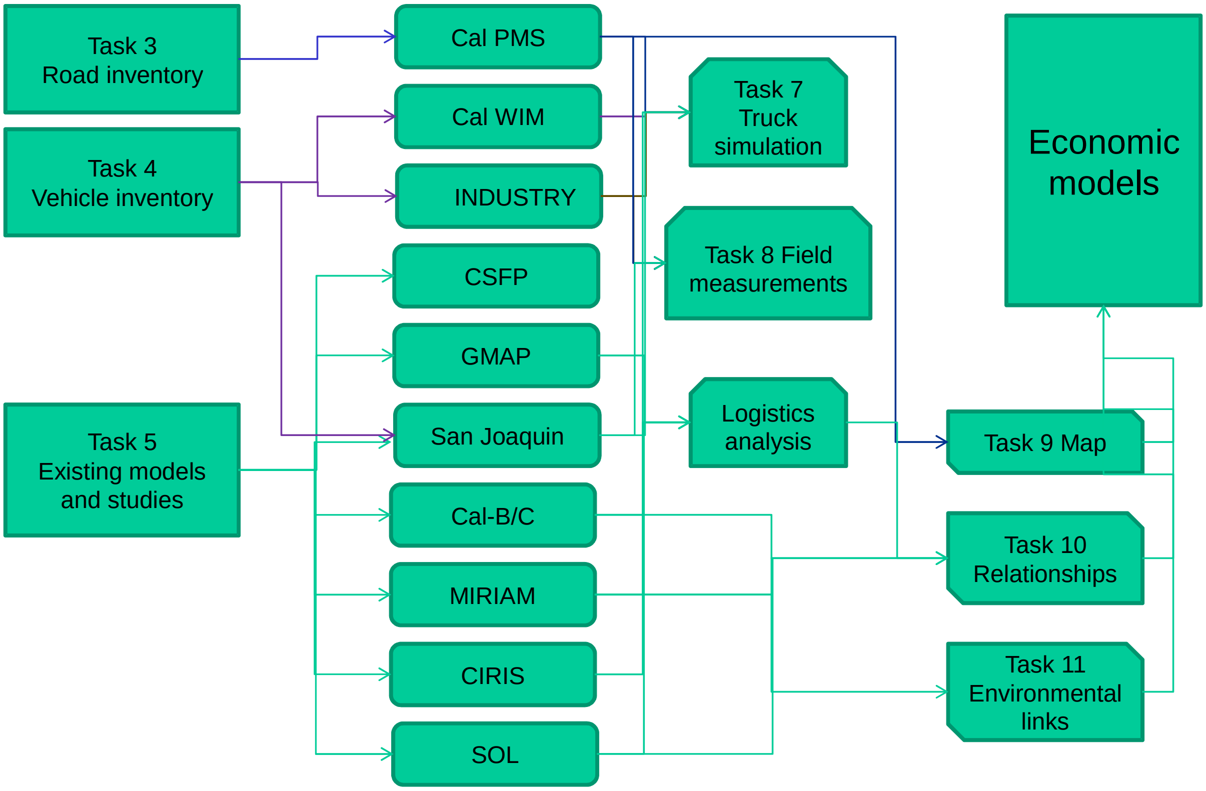


Figure 1.1: Schematic layout and linkages between project tasks.

The detailed scope of this report is:

- Summary of the project background
- Reporting on Tasks 9 to 11

The purpose of this study is to provide data and information that will provide input that supports Caltrans' freight program plans and the legislation mentioned above. Findings will contribute to economic evaluations, identify challenges to stakeholders, and identify problems, operational concerns, and strategies that "go beyond the pavement," including costs to the economy and the transportation network (delay, packaging, environment, etc.). Findings could lead to improved pavement policies and practices such as strategic recommendations that link pavement surface profile, design, construction, and preservation with V-PI. These findings also should provide information for evaluating the relationship between pavement ride quality (stemming from the pavement's condition), vehicle operating costs, freight damage, and logistics. Better understanding this relationship could provide input for development of construction ride quality specifications and pavement management strategies that maintain or reduce the costs of freight transport and pavements.

Better understanding the pavement-vehicle-freight system can help improve California's economy only if it helps those manufacturers/producers and shippers/handlers (focusing on shipping, cargo handling, logistics management, and associated private firms) who work in a highly competitive landscape. The freight shipping industry, consisting of about 17,000 companies nationally and faced with fierce international competition, is highly fragmented, with the top 50 companies accounting for 45 percent of total industry revenue. Profitability of an individual firm depends on its experience and relationships but also on efficient operations, which include transporting freight over public highways that—unlike its truck fleet—the individual firm does not own, operate, or maintain, but on which its business survival depends. Not performing this pilot study will prevent development of data and information needed for statewide planning, policy, legislative, and associated activities intended to improve the efficiency of freight transport and the economy in California.

Considering the broader economic impact on shipping firms in California, "through-traffic" in the pilot district may also be important, as the origin or destination of the freight may not be in the district or even the state, although the shipper who is earning revenue from the transport is in California, and thus operational efficiency affects its success and revenue (which in turn affects tax income for the state).

1.4 Objectives

The overall objectives of this project are to enable Caltrans to better manage the risks of decisions regarding freight and the management and preservation of the pavement network, as the potential effects of such decisions (i.e., to resurface and improve riding quality earlier or delay such a decision for a specific pavement) will be quantifiable in economic terms. This objective will be reached through applying the principles of vehicle-pavement interaction (V-PI) and state-of-the-practice tools to simulate and measure peak loads and vertical acceleration of trucks and their freight on a selected range of typical pavement surface profiles on the SHS for a specific region or Caltrans district.

The objectives of this report are to provide information on Tasks 9 to 11. The specific objectives of these tasks are:

- Task 9 Maps: Develop map of road conditions and freight corridors and indications of where what can and should be transported
- Task 10 Relationships: Develop a simple relationship between the riding quality and the additional loads on the pavement/expected freight damage/expected additional vehicle operating costs
- Task 11 Environmental: Explore potential links regarding the environmental impacts and construction riding quality specifications

An additional task was added late in the project to evaluate the potential effects of road conditions on damage to tomatoes being transported on these roads. This was approached using a laboratory study, which is described in this report.

1.5 Companies Used

Two companies were selected for the Task 7 and Task 8 studies. They are designated Company A and Company B in this and all related reports. Companies A and B were selected based on contacts made with private industry to obtain interested parties that were willing to cooperate with Caltrans in this project. For confidentiality, the companies are only identified as Companies A and B. Company A's primary business is the production of a range of bulk agricultural products. Company B is an asset-based motor carrier that focuses exclusively on Less than truckload (LTL) shipments between the United States and Canada, domestic U.S. LTL shipments and Truckload (TL) shipments from Canada to the United States.

In order to protect the confidentiality of the information, anonymous designations are used for the routes for Company A, and no maps with routes are shown. The routes are all located in the San Joaquin Valley. As the identity of Company B cannot be determined based on the location of the analyzed routes, maps and actual road section numbers analyzed are shown in the report.

1.6 San Joaquin Valley Interregional Goods Movement Plan (SJVIGMP)

The San Joaquin Valley (SJV) consists of eight counties (Kern, Kings, Tulare, Fresno, Madera, Merced, Stanislaus, and San Joaquin). The SJV has traditionally been California's geographic and agricultural center as well as its main source of exports, and more recently, also became the Californian region with the fastest growing population and is playing an increasing role in the burgeoning logistics and distribution sector. Since the initiation of this pilot project, a new SJVIGMP was developed [*2*] that contains 49 prioritized projects that emanated from in-depth research regarding SJV's current and future goods movement demands, and extensive interaction with private stakeholders. The 49 prioritized projects are grouped into seven categories:

- Regional North-South highway capacity (13 projects)
- East-West connectors (14 projects)
- Local "Last-Mile" connectors (3 projects)
- Modal capacity for expected flows (5 projects)
- Contingent economic development opportunities (6 projects)
- Inland ports (2 projects)
- Strategic programs (6 projects)

Twenty-one of the 49 projects entail the widening of sections of highways, while six propose the construction of new highway segments or upgrade of existing segments. Evaluation of the SJVIGMP indicates that the following of these projects directly relate to the V-PI portion affecting the two companies involved in this pilot project:

- Highway corridor capacity on I-5 and SR-99
- "Last Mile" connectivity (especially in rural areas and relating to the agricultural industry)
- Pavement wear and tear
- Surface Transportation Assistance Act (STAA) routing issues (restricting trucks from certain critical routes)
- Seasonality concerns (especially in the agricultural sector)
- Environmental regulation uncertainty

The 21 projects relating to the widening of highway sections and the six relating to the construction of new highway sections or upgrades of certain sections will all increase capacity and connectivity of the highway network and improve riding quality, and subsequently cause lower operational costs and damage to the vehicle fleet and transport infrastructure. Further, the following priority projects will directly affect operations and impacts on the transport infrastructure and vehicle of Companies A and B:

- Project #4 – Oversize/Overweight Truck Pilot Program/Research
- Project #5 – Reexamine STAA Designated Routes
- Project #6 – I-580 Truck Climbing Lanes
- Project #37 – CCT Lodi Branch Upgrade
- Project #61 – Improve Speeds on SR 166 from Cuyama Grade to SR 33
- Project #104 – West Coast Green Highway Initiative (LNG Truck Fueling Stops)

It is proposed that the developments around the SJVIGMP and the proposed priority projects be followed by Caltrans, and that the companies involved determine over time what the ultimate effects on operations and costs will be. This will obviously depend largely on the actual implementation program of the various projects.

1.7 Units

Use is made of dual units (both metric and U.S. customary) where possible in the report. Typically, metric units are shown with U.S. customary units in brackets. Some of the road data were provided in metric units (i.e., Pavement Management System [PMS] and road profile data), and these were kept in metric units. Where graphs and figures come directly from these data, in some cases only the metric units are shown. Where data were originally in U.S. customary units, these units are often used, e.g., mpg for miles per gallon instead of km per liter.

2 TASK 9 - MAPS

2.1 Introduction

This section provides information on the work conducted on Task 9. Task 9 focuses on the development of a map of road conditions and freight corridors and indications of where what can and should be transported, for selected region/district routes and outside lanes on multi-lane routes. The outcome of the task is a map showing at minimum current roughness indications with traffic volumes and major commodities for selected region/district routes, linked to potential (from simulations) tire load distributions, and acceleration levels for routes.

Essentially, the data for Tasks 9 have been sourced from the outputs of Tasks 4 (pavement conditions), 7 (V-PI simulations), 8 (field measurements), 10 (summary of relationships between road condition and various parameters), and 11 (environmental relationships).

The section introduces the approach taken in the development of the maps in terms of layers in Google Earth^{TM}, and the motivation and format for these layers, followed by a summary of the data obtained from the various tasks, in the format to be used in the mapping layers.

Examples of the mapping layer application are provided in the section; however, because this is a dynamic output that depends on the selection of parameters by the user, all possible options cannot be shown. The actual Google Earth^{TM} files are supplied to Caltrans for further use and application. In the current set of maps, the data for one lane of the various routes are highlighted in accordance with the original proposal. Also, due to the confidentiality and privacy issues, no maps of the routes around Company A are shown (in the report), because the company may be identified based on the routes around their location.

2.2 Maps Background

2.2.1 Introduction

The researchers decided to operate the pilot study version of the map on Google Earth^{TM}, as it is freely available, the basic routes are visible, and it provides a format that can easily be used and demonstrated to affected and interested parties.

Google Earth^{TM} provides maps of the majority of routes in California. For the macro-scale indication of the location of road sections, it provides high enough resolution and locations of routes and lanes. This is currently achieved through the use of standard .kmz files that can be used on any system that has a Google Earth^{TM} application loaded. Further, a Google Earth^{TM} application with layers of information already exists for Caltrans (Caltrans Earth, available at *www.dot.ca.gov/hq/tsip/gis/caltrans_earth/globe_content.php),* and the outcomes of this pilot study should fit into the current structure of Caltrans Earth as additional layers. In Table 2.1, the current listing of layers in Caltrans Earth are provided. In a possible follow-up and expansion of the task to a wider area of California, a more dedicated GIS-based system may be used for this task if required.

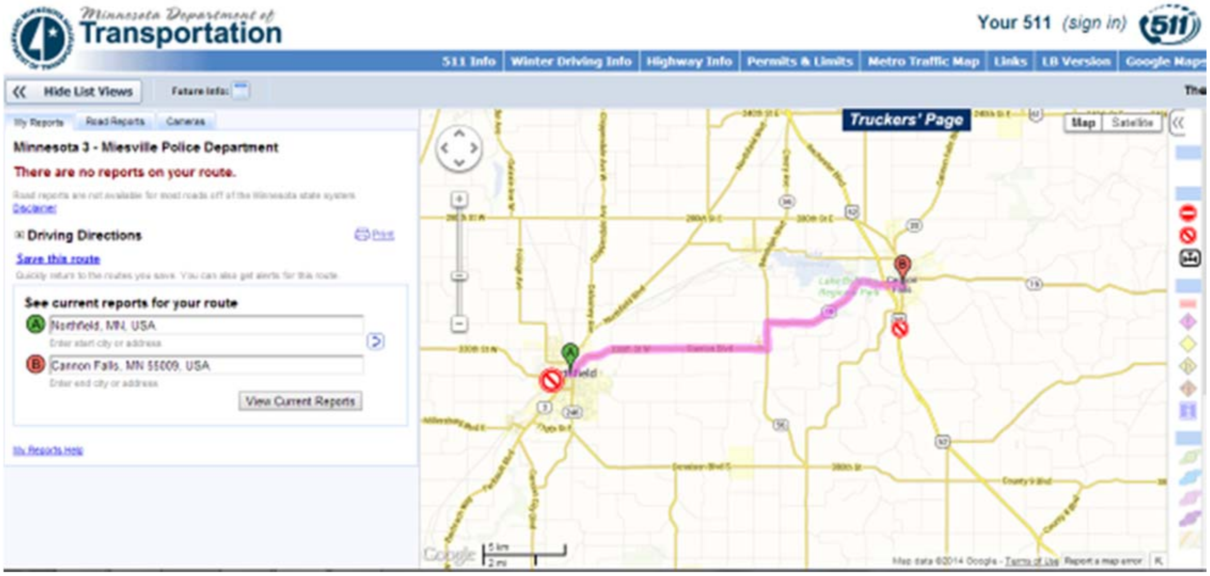
Table 2.1: Listing of Current Caltrans Earth Layers

Public Heading	Layer	Data Providers
Highways	Roads	Caltrans TSI/GIS Data Branch
	CRS Grid	
	State Highway Post Miles	
	Highway Exit Signs	Caltrans HQ Traffic Ops/District 4 System Planning
	High Occupancy Vehicle (HOV) Lanes	Caltrans Traffic Operations
	Express Lanes	
	Interregional Road System	Caltrans Office of System and Freight Planning
	High Emphasis Routes	
	Focus Routes	
	Corridor System Management Plan (CSMP)	
Traveler Information	Live Traffic	Google
	Traffic Cameras	Quickmap
	Changeable Message Signs	
	Lane Closures	
	CHP Incidents	
	Chain Control	
	National Weather Service (NWS) Warnings	NOAA
	Earthquakes	USGS
	Active Fires	
	Summits	Caltrans TSI/GIS Data Branch
Passenger Rail	Amtrak Stations	Caltrans Division of Rail
	Amtrak - Capital Corridor	
	Amtrak - Pacific Surfliner	
	Amtrak - San Joaquin	
	Amtrak Bus Routes	
Commuter Rail	ACE Train	Caltrans Division of Rail
	BART	BART
	CalTrain	TIMI/511.org
	Coaster	North County Transit District
	Metrolink	Metrolink
Aviation	Airports	Aeronautics
	Military	
	Heliports	
Goods Movement	Rail Lines	Caltrans Rail Division
	Commercial Vehicle Weigh Stations	Caltrans Asset Management Inventory
	Agricultural Inspection Stations	
	Truck Network	Caltrans Traffic Operations
	Public and Private Ports	Caltrans Office of System and Freight Planning
	Point of Entry	
	Goods Movement Routes	
	Goods Movement Railroad Routes	

Public Heading	Layer	Data Providers
CIB (Planned Projects)	HOV Lanes	Caltrans Traffic Operations
	Express Lanes	
	Commuter Rail	Caltrans Office of State Planning
	Goods Movement Projects	
	Intercity Rail Extensions	
Amtrak Service Increases	Capital Corridor	Caltrans Office of System and Freight Planning
	Pacific Surfliner	
	San Joaquin	
Boundaries	Caltrans Districts	Caltrans TSI/GIS Data Branch
	City Boundaries	League of California Cities/CALAFCO/California Cities by Incorp date
	County Boundaries	CalFire
	Urban Areas	TSI/HSE
	Regional Transportation Planning Areas	Caltrans TSI/GIS Data Branch
	Metropolitan Planning Organizations	
	Air Basins	Air Resources Board
	Air Districts	
	Military Facilities	www.data.gov/DOD
Caltrans Facilities	Park & Ride Lots	Caltrans Asset Management Inventory
	Roadside Rest Areas	
	Toll Booths	
	Traffic Management Centers	
	Vista Points	
	Caltrans Offices	
	Equipment Shops	
Bridges	State Highway Bridges	Caltrans TSI/GIS Data Branch
	Local Road Bridges	
Hydrography	Rivers	Teale Data Center
	Lakes & Reservoirs	California Department of Fish and Game

From a user's viewpoint, the use of the Google Earth^{TM} type of application is practical because it already is in use in various transportation settings in the U.S.. One example is the Minnesota Department of Transportation (MnDOT) app for truckers to assist in planning routes, which is available on the MnDOT website and various mobile app stores [*3*]. The app provides truckers with information and alerts about possible road restrictions along their routes, including roundabouts, weight and height restrictions on bridges, road works etc. (Figure 2.1). Planned stops can be added to routes.

Application of the information currently available from this pilot project should enable Caltrans to develop a similar app for use by all road users, enabling a better understanding of not only those features covered in the MnDOT app, but also pavement roughness conditions and related expected relative vehicle operations cost on alternative routes, and also expected damage to vehicle and freight indications based on the developed relationships.



Minnesota 3 - Miesville Police Department

There are no reports on your route.

Road reports are not available for most roads off of the Minnesota state system.

Driving Directions

Quickly return to the routes you save. You can also get alerts for this route.

See current reports for your route

A: Northfield, MN, USA

B: Cannon Falls, MN 55009, USA

Figure 2.1: Example of MnDOT app guidance to road user.

2.2.2 *Methodology*

The process followed for this task essentially consists of calculation of the various parameters for the specific road section (i.e., roughness, fuel consumption, expected damage, etc.), based on published relationships and the data published in the report for Tasks 4 (pavement conditions), 7 (V-PI simulations), 8 (field measurements), 10 (summary of relationships between road condition and various parameters), and 11 (environmental relationships), highlighting the road sections in Google Earth™ using standard line segments, coloring the line segments indicating the severity of the parameter, adding the relevant statistics to the description, and saving the .kmz file.

2.3 Pavement Data (Task 3)

The current California Pavement Management System (PMS) provides an indication of the riding quality of the majority of the California Interstate and State Highway route network. Data are collected on a regular basis using a survey vehicle. This data include the riding quality of the route at 100 m intervals. In Task 3 of this project, the available pavement data for various corridors in California were evaluated to support the selection for a specific corridor for use in the remainder of the project. The availability of these data, together with the availability of truck companies for inclusion into the surveys (Task 8) and the routes they serve, lead to the selection of the I-80 corridor between Newark and Reno, as well as a portion of the routes in the San Joaquin Valley, to be selected as the regions where the focus falls for this pilot study.

The pavement riding quality data for the I-80 corridor routes were obtained from the PMS data, while an additional survey was conducted on the San Joaquin Valley routes to obtain these data. The data were reported in the report on Tasks 3 and 4 [*1*], and only a summary is provided in this section of the specific data.

Data were collected at 10 m intervals; however, for Task 9 these data are summarized for the whole road section. In Table 2.2, a selection of the data the I-80 corridor are provided, while Table 2.3 provides the summary for the San Joaquin Valley routes (data in Table 2.3 without actual locations and county due to confidentiality and privacy issues [refer to Section 1.5]). The pavement data used to designate the condition of the various sections include:

- Minimum, 20th percentile, average, 90th percentile and maximum of riding quality (in terms of International Roughness Index).

In the Google Earth™ layers, the statistical data for the specific section are summarized, while the layer color is dependent on the average value only. In the maps, these data are provided in the Roughness layer. Based on the earlier analysis of the riding quality data, the data are shown on the Google Earth™ maps in the colors indicated in Table 2.4.

These data also form the basis of the analysis for the vehicle data and economic data, as the relationships developed in Tasks 8, 10, and 11 are all related to the road through the pavement roughness.

Table 2.2: Summary of San Joaquin Valley Route Pavement Data

DISTRICT	ROAD #	RIDING QUALITY (IRI) (in./mi)*					
		MIN	20th PERC	AVG	90th PERC	MAX	STDEV
SJV	1 Outbound	10	40	69	104	1578	74
	1 Inbound	13	33	56	85	648	43
	D Road Inbound	17	48	80	125	593	50
	D Road Outbound	19	51	85	137	729	56
	HM Road Inbound	19	63	115	196	1466	82
	HM Road Outbound	17	58	107	183	1058	75
	L Road Inbound	39	107	225	463	1131	165
	L Road Outbound	37	91	187	354	1051	140

* IRI shown in in./mi due to space restrictions. IRI (m/km) = IRI (in./mi)/64.

Table 2.3: Summary of I-80 Corridor Pavement Data

DISTRICT	COUNTY	ROAD#	START		END		RIDING QUALITY (IRI) (in./mi)*						DISTANCE [mile]	DIRECTION
			LONGITUDE	LATITUDE	LONGITUDE	LATITUDE	MIN	20th PERC	AVG	90th PERC	MAX	STDEV		
4	NAP	80	38.16868086	-122.2014615	38.16874104	-122.2013762	21.0	34.0	54.3	81.0	275.0	26.9	4.2	WB
4	NAP	80	38.1685949	-122.2013977	38.16866746	-122.201295	19.0	33.0	57.9	91.3	301.0	32.0	4.2	WB
4	SOL	80	38.37576305	-121.9507511	38.39589397	-121.9242536	19.0	28.1	58.6	109.1	477.0	52.6	2.0	WB
4	NAP	80	38.16751547	-122.2029204	38.1552528	-122.2146755	29.0	41.0	59.7	86.0	161.0	18.2	1.2	WB
4	ALA	80	37.82647092	-122.3005519	37.82505236	-122.3104443	-1.0	-1.0	62.2	160.3	504.0	85.2	0.5	WB
4	SOL	80	38.2500222	-122.0696089	38.21756947	-122.136761	21.0	34.0	66.1	100.0	524.0	52.4	4.3	WB
3	SAC	80	38.72002571	-121.2959692	38.66097402	-121.360425	44.0	97.1	152.2	211.0	624.0	53.7	0.5	WB
4	SF	80	37.8137405	-122.3601939	37.80807714	-122.367212	-1.0	61.0	152.6	271.0	732.0	88.7	0.5	WB
4	ALA	80	37.87372674	-122.3062325	37.84652487	-122.2985365	-1.0	-1.0	153.6	276.0	575.0	101.2	1.6	WB
3	SAC	80	38.7216405	-121.2940622	38.59832579	-121.5481428	35.0	73.0	158.0	259.9	733.0	86.1	18.0	WB
4	ALA	80	37.8916678	-122.3077392	37.84652357	-122.2984963	49.0	81.0	159.9	269.0	727.0	93.0	2.9	WB
3	PLA	80	39.31631915	-120.436705	39.31603346	-120.5560691	-1.0	87.0	163.4	300.0	781.0	98.0	7.0	WB
3	NEV	80	39.37280425	-120.1121905	39.36131563	-120.1324798	58.0	98.3	169.1	251.0	686.0	80.0	1.2	WB
4	SF	80	37.77046693	-122.4059222	37.7693444	-122.4104063	125.0	141.9	209.8	277.3	381.0	52.6	0.3	WB
3	NEV	80	39.31611518	-120.5562	39.31540277	-120.6250019	63.0	99.0	244.2	452.0	974.0	147.4	4.1	WB
4	SF	80	37.81384718	-122.3601909	37.8081457	-122.3672932	-1.0	182.3	265.5	377.9	872.0	92.4	0.7	WB
4	SF	80	37.81376043	-122.3602324	37.78034994	-122.3991233	-1.0	273.0	373.5	504.0	773.0	97.5	0.6	WB

* IRI shown in in./mi due to space restrictions. IRI (m/km) = IRI (in./mi)/64.

Table 2.4: Colors and Limits for Riding Quality Data in Roughness Layer

Average roughness data	Color
< 96 in./mi	Blue
96 – 122.0 in./mi	Green
122.1 – 173.0 in./mi	Orange
>173.1 in./mi	Red

2.4 Vehicle Data (Tasks 4, 8, 10 and 11)

2.4.1 Introduction

Vehicle data were initially collected to identify the basic vehicles that are used on each of the routes and corridors (Task 4). This data were supplemented by the actual vehicle data from Companies A and B. In Task 7, models of the vehicles were used in a simulation exercise together with the route conditions to enable a mathematical model to be developed for the response of the vehicles to road conditions. In Task 8, the vehicles were instrumented using accelerometers and the vertical accelerations generated on the vehicles as they traveled over the route sections measured. These data (together with similar data from related studies and similar vehicles) were used to generate a basic relationship between the expected vertical accelerations on the vehicle and the route conditions (mainly through the riding quality of the route). These relationships were presented in the report on Tasks 7 and 8 [*4*] as well as Section 3 of this report, and are used in this analysis to generate a macro version of the expected vertical accelerations on the vehicle. Also, the expected distribution of tire loads for the various vehicles on route sections are evaluated through a statistical distribution approach.

2.4.2 Task 4 Data

The data from Task 4 were used to identify the types of vehicles that are prevalent on the specific routes. Therefore, the data do not directly provide input for Task 9, but served as basis for the Task 7 simulations and the Task 8 measurements. For clarity, these data are repeated in Table 2.5, with the vehicle designations shown in Table 2.6 and Figure 2.2 and Figure 2.3.

Table 2.5: Summarized Analysis of Truck Count Data per District [5]

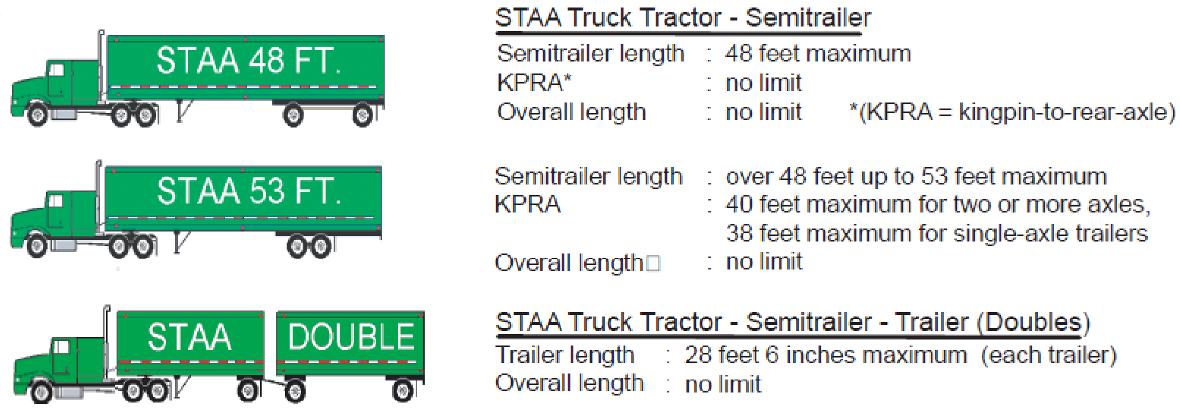
District	AADT Total	Total Trucks	Total Truck %	2 Axle/Class 5		3 Axle/Class 6		4 Axle/Classes 7 and 8		5 Axle/Classes 9 and 11	
				Volume	Percent	Volume	Percent	Volume	Percent	Volume	Percent
1	1,135,860	101,876	9%	46,237	45%	14,475	14%	5,603	5%	35,207	35%
2	3,662,370	540,168	15%	52,913	10%	33,515	6%	13,907	3%	416,907	77%
3	12,481,183	980,516	8%	334,299	34%	93,000	9%	45,644	5%	504,006	51%
4	43,707,890	1,925,535	4%	850,496	44%	222,646	12%	72,584	4%	850,374	44%
5	6,270,340	478,600	8%	201,503	42%	46,750	10%	21,406	4%	195,688	41%
6	8,250,955	1,417,304	17%	423,796	30%	94,751	7%	52,977	4%	816,238	58%
7	56,002,040	3,283,835	6%	1,301,599	40%	360,991	11%	125,496	4%	1,428,555	44%
8	21,450,950	2,351,222	11%	819,266	35%	182,365	8%	78,184	3%	1,271,394	54%
9	201,825	18,334	9%	5,886	32%	1,778	10%	917	5%	9,752	53%
10	6,412,135	944,602	15%	194,754	21%	87,701	9%	30,713	3%	619,819	66%
11	17,715,618	940,633	5%	498,081	53%	95,452	10%	36,021	4%	304,845	32%
12	19,297,800	1,057,294	5%	526,137	50%	102,220	10%	49,109	5%	342,897	32%
TOTAL	196,588,966	14,039,919	7%	5,254,967	37%	1,335,644	10%	532,561	4%	6,795,682	48%

Table 2.6: FHWA Vehicle Classes with Definitions

Class	Description	Definitions
1	Motorcycles (Optional)	All two- or three-wheeled motorized vehicles. Typical vehicles in this category have saddle-type seats and are steered by handlebars rather than steering wheels. This category includes motorcycles, motor scooters, mopeds, motor-powered bicycles, and three-wheel motorcycles. This vehicle type may be reported at the option of the State.
2	Passenger Cars	All sedans, coupes, and station wagons manufactured primarily for the purpose of carrying passengers and including those passenger cars pulling recreational or other light trailers.
3	Other Two Axle, Four Tire Single Unit Vehicles	All two axle, four tire, vehicles, other than passenger cars. Included in this classification are pickups, panels, vans, and other vehicles such as campers, motor homes, ambulances, hearses, carryalls, and minibuses. Other two axle, four tire single unit vehicles pulling recreational or other light trailers are included in this classification. Because automatic vehicle classifiers have difficulty distinguishing class 3 from class 2, these two classes may be combined into class 2.
4	Buses	All vehicles manufactured as traditional passenger-carrying buses with two axles and six tires or three or more axles. This category includes only traditional buses (including school buses) functioning as passenger-carrying vehicles. Modified buses should be considered to be trucks and should be appropriately classified.
5	Two Axle, Six Tire, Single Unit Trucks	All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with two axles and dual rear wheels.
6	Three Axle Single Unit Trucks	All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with three axles.
7	Four or More Axle Single Unit Trucks	All trucks on a single frame with four or more axles.
8	Four or Fewer Axle Single Trailer Trucks	All vehicles with four or fewer axles consisting of two units, one of which is a tractor or straight truck power unit.
9	Five Axle Single Trailer Trucks	All five axle vehicles consisting of two units, one of which is a tractor or straight truck power unit.
10	Six or More Axle Single Trailer Trucks	All vehicles with six or more axles consisting of two units, one of which is a tractor or straight truck power unit.
11	Five or Fewer Axle Multi-Trailer Trucks	All vehicles with five or fewer axles consisting of three or more units, one of which is a tractor or straight truck power unit.
12	Six Axle Multi-Trailer Trucks	All six axle vehicles consisting of three or more units, one of which is a tractor or straight truck power unit.
13	Seven or More Axle Multi-Trailer Trucks	All vehicles with seven or more axles consisting of three or more units, one of which is a tractor or straight truck power unit.

NOTE: In reporting information on trucks, the following criteria should be used:

- Truck tractor units traveling without a trailer will be considered single-unit trucks.
- A truck tractor unit pulling other such units in a "saddle mount" configuration will be considered one single-unit truck and will be defined only by the axles on the pulling unit.
- Vehicles are defined by the number of axles in contact with the road. Therefore, "floating" axles are counted only when in the down position.
- The term "trailer" includes both semi- and full trailers.



STAA Truck Tractor - Semitrailer

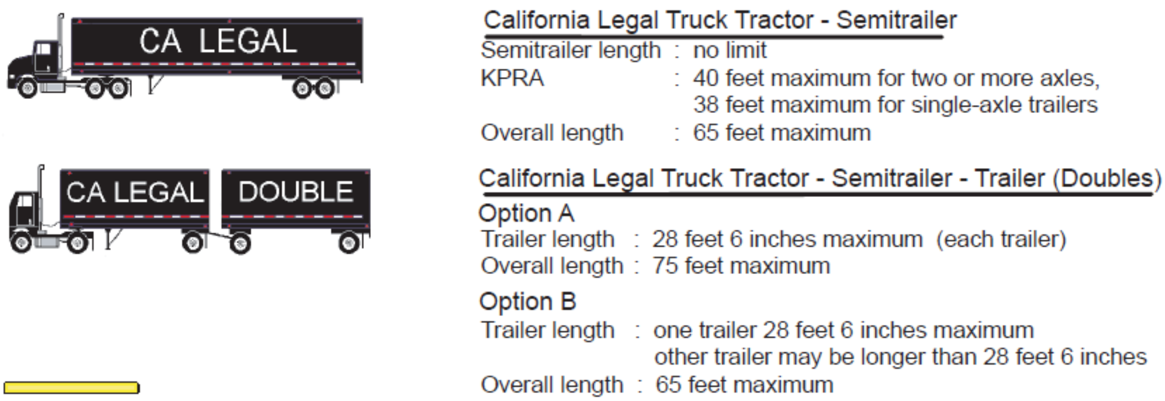
Semitrailer length : 48 feet maximum
KPRA* : no limit
Overall length : no limit *(KPRA = kingpin-to-rear-axle)

Semitrailer length : over 48 feet up to 53 feet maximum
KPRA : 40 feet maximum for two or more axles, 38 feet maximum for single-axle trailers
Overall length□ : no limit

STAA Truck Tractor - Semitrailer - Trailer (Doubles)

Trailer length : 28 feet 6 inches maximum (each trailer)
Overall length : no limit

Figure 2.2: California Truck Map legend for STAA routes (Caltrans, 2012)[*6*].



California Legal Truck Tractor - Semitrailer

Semitrailer length : no limit
KPRA : 40 feet maximum for two or more axles, 38 feet maximum for single-axle trailers
Overall length : 65 feet maximum

California Legal Truck Tractor - Semitrailer - Trailer (Doubles)

Option A
Trailer length : 28 feet 6 inches maximum (each trailer)
Overall length : 75 feet maximum

Option B
Trailer length : one trailer 28 feet 6 inches maximum, other trailer may be longer than 28 feet 6 inches
Overall length : 65 feet maximum

Figure 2.3: California Truck Map legend for California Legal Routes (Caltrans, 2012) [*6*].

2.4.3 Task 7 Data

Task 7 focused on the generation of vehicle response data based on the application of the TruckSIM^{TM} program using the vehicles used in the field study (Task 8) and the actual route pavement conditions. This analysis provided various insights into the interaction between the pavement condition and the vehicle response, and focused on demonstrating the availability of a tool that can be used to analyze conditions not measured during the field testing (i.e., changing loads, speeds, etc. of the vehicles), and also conducting similar analyses on routes not originally included in the field measurements. Because the outcome of the Task 7 analysis was that similar data were obtained from the field measurements and the simulation exercise, only one of the two data sets are used in the generation of the maps for Task 9.

The outcome of the Task 7 simulation analysis is summarized in this section. The actual simulations focused on a selection of road sections traveled on by Company A (mostly State Routes) and Company B (Interstate Highway System) with a range of riding qualities on both. The intention was to select representative sections based on riding quality data on the routes that the trucks traveled on, and conduct the analysis on these routes to enable comparison with the data collected in Task 8. The outcome of Task 7 is data (graphs and tables) indicating the relationships between pavements with a range of typical California riding quality values and tire loads, as well as accelerations at selected locations on the two vehicles used.

These data were used in Task 10 (Section 3.2 of this report) to develop relationships between the road riding quality and the tire loads for the various vehicles, together with similar data for similar vehicle types. The relationships that were used in the development of the maps are shown in Equations 5 to 12 (Section 3.2.2).

In the maps, the focus of the tire loads is the standard deviation data, since these are mainly affected by the road roughness. The .kmz file contains a layer termed LOADS that can be switched on to see the different values. Because there are no specific limits for the standard deviation data, the values are not colored according to a scale. However, to provide an indication of the differences, the colors are designated for standard deviation data less than the average of all the standard deviations, between the average and the 90th percentile and higher than the 90th percentile. These limits are shown in Table 2.7.

Table 2.7: Limiting Values and Colors for Tire Load Data on Google Earth Maps

Tire load STDEV data [Company A; Company B]				**Color**
	Steer	**Drive**	**Trail**	
Minimum to 50th percentile	1.99 to 5.19; 5.9 to 9.9	1.90 to 3.21; 24.1 to 30.5	1.53 to 4.42; 19.1 to 25.0	Blue
50th to 90th percentile	5.19 to 7.95; 9.9 to 14.0	3.21 to 4.34; 30.5 to 35.3	4.42 to 6.92; 25.0 to 29.7	Green
90th percentile to maximum	7.95 to 49.78; 14.0 to 414	4.34 to 21.49; 35.3 to 174	6.92 to 44.78; 29.7 to 185.1	Red

The vertical acceleration data from the TruckSIM simulations were similar to the Task 8 field data and are discussed in detail in Steyn [*4*] and Section 2.4.4. For the vertical acceleration data, because no adequate and uniformly-accepted limits could be found indicating levels of severity, the vertical acceleration data were classified as lower than 50th percentile (green in the maps), between 50th and 90th percentile (orange in the maps), and between 90th percentile and maximum (red in the maps). These limits are shown in Table 2.8. While no universally accepted levels of damage to tomatoes are available (Section 5.3.5), this classification should enable the various routes to at least be classified in terms of their perceived severity of causing potential damage to the vehicles and freight due to vertical acceleration generated on the route.

Table 2.8: Limiting Values and Colors for Vertical Acceleration Data on Google Earth Maps

Vertical acceleration data (Company A; Company B)			Color
	Location 1 (Drive axle)	**Location 5 (Back trail axle)**	
Minimum to 50th percentile	0.03 to 0.14; .001 to 2.5	0.27 to 0.48; -0.03 to 19.3	Blue
50th to 90th percentile	0.14 to 0.23; 2.5 to 4.0	0.48 to 0.66; 19.3 to 31.1	Green
90th percentile to maximum	0.23 to 1.60; 4.0 to 21.7	0.66 to 3.40; 31.1 to 168	Red

2.4.4 Task 8 Data

The outcome of the Task 8 analysis is summarized in this section. Task 8 focused on measurements of accelerations on selected locations of selected California vehicles on specific routes. The objective of Task 8 was to measure typical vehicle response data from typical routes in California to be used in a comparison with the simulation data generated in Task 7. The task consisted of instrumenting two trucks (one per company) for Companies A and B at various locations on the bodies, and collecting acceleration data from the vehicle body and cargo during trips over standard routes followed by these vehicles. The specific tasks and objectives of Task 8 were to:

- Compare vertical accelerations measured on different locations of the same vehicle
- Compare accelerations measured on the same vehicle but different road sections
- Compare damage potential to vehicle and freight due to travel over a specific road section
- Evaluate whether the effect of concrete slab lengths (Route 1) is affecting the vertical acceleration data
- Evaluate the effect of riding quality on the speeds at which vehicles travel on different routes
- Show linkages between the information collected in Task 8 and Tasks 9 to 11

Task 8 data analysis indicated that in general, vertical accelerations and severity of acceleration increased with increasing roughness on all roads. The location of the freight on the trailer also affected the magnitude of the acceleration and severity, with those locations furthest from the center of gravity of the trailer typically showing the worst conditions. Four equations based on the field measured data are used in Task 9 (Section 3.2.3, Equations 13 to 16).

For the vertical acceleration data, as no adequate and universally accepted limits could be found indicating levels of severity, the vertical acceleration data were classified as lower than 50th percentile (green in the maps), between 50th and 90th percentile (orange in the maps) and between 90th percentile and maximum (red in the maps). While no universally accepted levels of damage to tomatoes are available (Section 5.3.5), this classification should enable the various routes to at least be classified in terms of their perceived severity of causing potential damage to the vehicles and freight due to vertical acceleration generated on the route. The .kmz file contains a layer termed ACCELERATIONS that can be switched on to see the different values.

For Company A, a significant relationship could be observed between the speed attained on the various routes and the roughness of the routes, with rougher routes leading to slower speeds (Equation 1) ($n = 12$, $R^2 = 0.86$). The same relationships could not be observed on the Company B routes, probably due to generally better riding quality on these routes, and the result that the speed is governed more by traffic flow conditions than road condition.

Speed [mph] = –0.1254 (IRI [inch/mile]) + 55.55 Equation 1

2.4.5 Task 10 Data

The Task 10 data are discussed and analyzed in Section 3 of this report. As the data are required to generate the maps for Task 9, it is summarized in this section for clarity. The relationships developed based on the Tasks 7 and 8 measurements have already been discussed in Section 2.4.3 and 2.4.4. The additional relationships, developed from published data, are as follows:

- Fuel consumption based on vehicle details and riding quality (Equations 2 [Company A and Company B])
- Tire wear based on vehicle details and riding quality (Equation 3 [Company A and Company B])
- Average repair and maintenance cost due to riding quality based on vehicle details and riding quality (Equation 4 [Company A and Company B]) (constant for IRI <192).

Fuel Consumption (FC) [mpg]

FC (for IRI>100) = ((((2e-10*speed2)-(2e-8*speed)+8e-7)*IRI2)+(((-5e-8*speed2)+
(5e-6*speed)-2e-4)*IRI)+ (0.0495*e(0.0247*speed)))-1 Equation 2a

FC (for IRI≤100) = ((((2e-6*speed2)-(2e-4*speed)+8e-3))+(((-5e-6*speed2)+
(5e-4*speed)-2e-2))+ (0.0495*e(0.0247*speed)))-1 Equation 2b

Tire wear [%/mile] = ((20e-10)*(speed1.7408))*IRI) + (0.0007*e(0.0115*speed)) Equation 3

Repair and Maintenance [$/mile] = ((0.0007*speed) + 0.0128)*e(0.0032*IRI) Equation 4

* speed (mph)
* IRI (in./mi)

The calculated parameters for the average riding quality condition and a speed of 88 km/h (55 mph) are shown for the Company A (Table 2.9) and a selection of the Company B (Table 2.10) routes. The speed of 55 mph was selected as an analysis of truck traffic in California using Weigh-In-Motion (WIM), indicated 55 mph as the average speed of trucks on the selected population of routes [*7*]. In Table 2.11, an indication of the sensitivity of these outputs to the range of riding quality data for a specific route is provided, with an example of a relatively constant riding quality route and a route with a high variability in riding quality. It is clear that the various parameters differ significantly for these two examples.

Table 2.9: Calculated Fuel Consumption, Tire Wear, and Average Repair and Maintenance Costs for Company A Routes

ROAD	Fuel consumption (mpg)	Tire use (%/mile)	Additional damage ($/mile)
1 Outbound	5.319	0.0013	0.095
1 Inbound	5.319	0.0013	0.095
D road Inbound	5.319	0.0013	0.095
D Road Outbound	5.319	0.0013	0.095
HM Road Inbound	5.324	0.0013	0.095
HM Road Outbound	5.322	0.0013	0.095
L Road Inbound	5.240	0.0014	0.105
L Road Outbound	5.292	0.0014	0.095
1 Outbound	5.319	0.0013	0.095
1 Inbound	5.319	0.0013	0.095

Table 2.10: Calculated Fuel Consumption, Tire Wear, and Average Repair and Maintenance Costs for Company B Routes

DISTRICT	COUNTY	ROAD	Fuel consumption (mpg)	Tire use (%/mile)	Additional damage ($/mile)
4	NAP	80	5.319	0.0013	0.095
4	NAP	80	5.319	0.0013	0.095
4	SOL	80	5.319	0.0013	0.095
4	NAP	80	5.319	0.0013	0.095
4	ALA	80	5.319	0.0013	0.095
4	SOL	80	5.319	0.0013	0.095
3	SAC	80	5.318	0.0014	0.095
4	SF	80	5.318	0.0014	0.095
4	ALA	80	5.318	0.0014	0.095
3	SAC	80	5.315	0.0014	0.095
4	ALA	80	5.314	0.0014	0.095
3	PLA	80	5.312	0.0014	0.095
3	NEV	80	5.308	0.0014	0.095
4	SF	80	5.263	0.0014	0.100
3	NEV	80	5.205	0.0014	0.112
4	SF	80	5.159	0.0014	0.120
4	SF	80	4.839	0.0014	0.167

Table 2.11: Examples of Relatively Low Variability, Relatively High Variability, and Localized Bad Section Routes' Calculated Fuel Consumption, Tire Wear, and Average Repair and Maintenance Costs

	Minimum	20th %	Average	90th %	Maximum	Standard Deviation	Coefficient of Variation [%]
Riding quality (IRI) (in./mi)							
Low variability	125	142	210	277	381	53	25%
High variability	39	107	225	463	1131	165	73%
Localized bad sections	10	40	69	104	1578	74	108%
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		

In the maps, the focus of the fuel consumption, tire wear, and repair and maintenance cost data is the 50th and 90th percentile data as well as the maximum VOC, since there are no universally accepted levels of acceptable and unacceptable costs. The COSTS FC, COSTS TW, and COSTS RM layers contain the data for the different values. The colors are designated green for values smaller than the 50th percentile, orange for values between the 50th and 90th percentile, and red for values between the 90th percentile and the maximum for the specific parameter, as indicated in Table 2.12.

Table 2.12: Limiting Values and Colors for Fuel Cost, Tire Wear, and Repair and Maintenance Cost Data on Google Earth Maps

Cost Data (Company A; Company B)				Color
	Fuel Consumption (mpg)	Tire Wear (%/mi)	Repair and Maintenance ($/mi)	
Minimum to 50th percentile	5.31 to 5.32 ; 5.315 to 5.32	0.00132 to 0.00134 ; 0.00132 to 0.00134	0.09 to 0.10; 0.095 to 0.096	Blue
50th to 90th percentile	5.16 to 5.31; 5.31 to 5.315	0.00134 to 0.00136; 0.00134 to 0.0014	0.10 to 0.12; 0.096 to 0.104	Green
90th percentile to maximum	3.93 to 5.16; 2.42 to 5.31	0.00136 to 0.00166; 0.0014 to 0.0015	0.12 to 7.99; 0.104 to 1.203	Red

2.4.6 *Task 11 Data*

The Task 11 data are discussed and analyzed in Section 4 of this report. As the data are required to generate the maps for Task 9, they are summarized in this section for clarity.

Various available models exist for determining emissions generated by vehicles. Most of the models indicate the emissions in terms of fuel consumption, and, as it has been shown in Section 3 that the fuel consumption is related to the road roughness and vehicle speed (for a specific type of vehicle), relationships were developed between road roughness and vehicle speed, and GHG emissions (Section 4.3, Equation 17).

In the maps, the focus of the environmental emissions data again the levels in terms of values less than the 50th percentile (green), between the 50th and 90th percentile (orange), and higher than the 90th percentile (red), and the data are contained in the GHG layer (limits indicated in Table 2.13).

Table 2.13: Limiting Values and Colors for Emission (GHG) Data on Google Earth Maps

GHG Emission Data (Company A; Company B)		Color
	GHG emission (kg/mi)	
Minimum to 50th percentile	1.729 to 1.733; 1.727 to 1.731	Blue
50th to 90th percentile	1.733 to 1.789; 1.731 to 1.753	Green
90th percentile to maximum	1.189 to 7.644 ; 1.753 to 3.806	Red

2.4.7 *Summary*

The data available for the generation of the maps in Task 9 have been presented in this section. In summary, the following data are available for the maps:

- Riding quality (Minimum, 20th percentile, average, 90th percentile and maximum of riding quality, in terms of International Roughness Index) (Task 4)
- Vehicle vertical vibration summary (Tasks 7 and 8)
- Expected tire load distributions (Task 7)
- Vehicle operating costs (fuel consumption, tire usage and repair, and maintenance costs) (Task 10)
- Emission information (Task 11)

2.5 Google Earth Files

The Google Earth™ files are in a standard .kmz format that can be transported between computers that have the Google Earth™ application running. A summary of the range of .kmz files generated for this project is provided in Table 2.14. Each of these files indicates a different layer of data for each of the data sets evaluated (i.e., riding quality, operating costs, and vibrations).

Table 2.14: Summary of Google Earth .kmz files Generated for Task 9 Maps

Parameter	Layer in .kmz file
Tire load	LOADS
Fuel consumption	COSTS FC
Tire wear	COSTS TW
Repair and maintenance costs	COSTS RM
Vertical acceleration	ACCELERATIONS
GHG emissions	GHG
Road roughness	ROUGHNESS

The application of the Google Earth™ .kmz files to the maps is demonstrated in Figure 2.5 to Figure 2.10, where the application of the layers with different types of layer data is shown (road numbers are deleted in these figures to show the colored sections of road clearly). In the interest of privacy and confidentiality, no maps are shown for the San Joaquin Valley area in the report.

In Figure 4.1, a comparison is made between the various parameters for a small section of road, indicating how differences can occur on the same section of road due to different sensitivities in the various parameters.

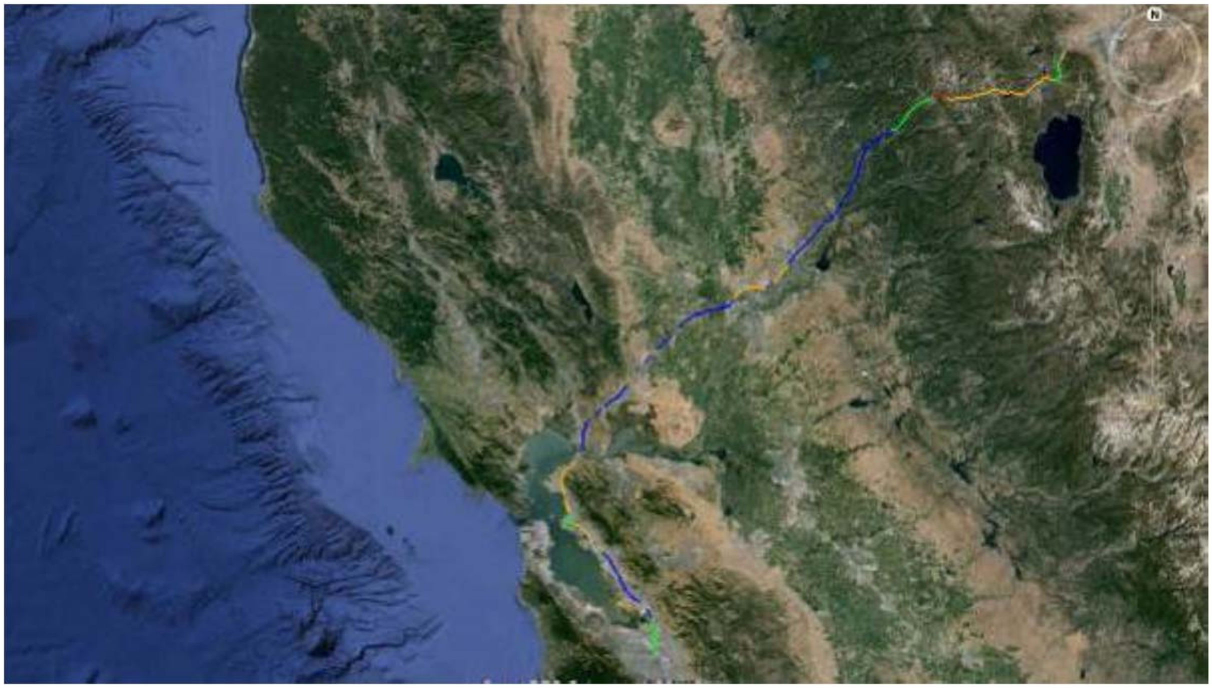


Figure 2.4: Pavement roughness data layer for I-80 corridor.

Figure 2.5: Vehicle vertical acceleration (location 1) data layer for I-80 corridor.

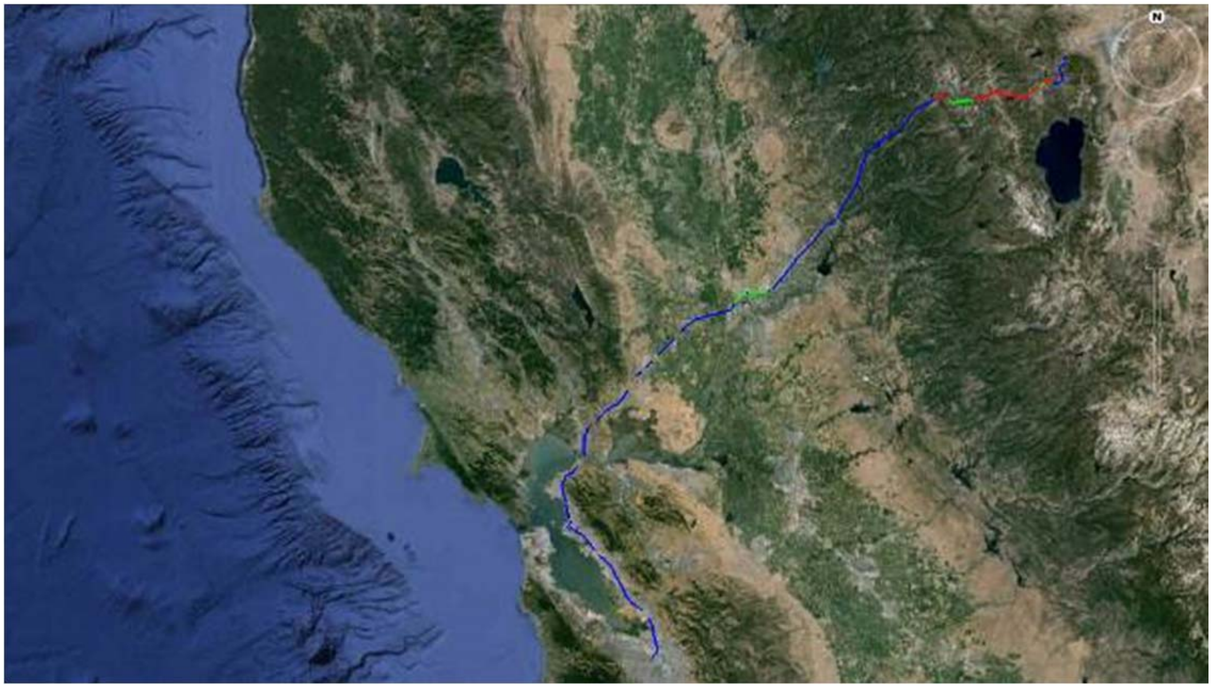


Figure 2.6: Fuel consumption data layer for I-80 corridor.

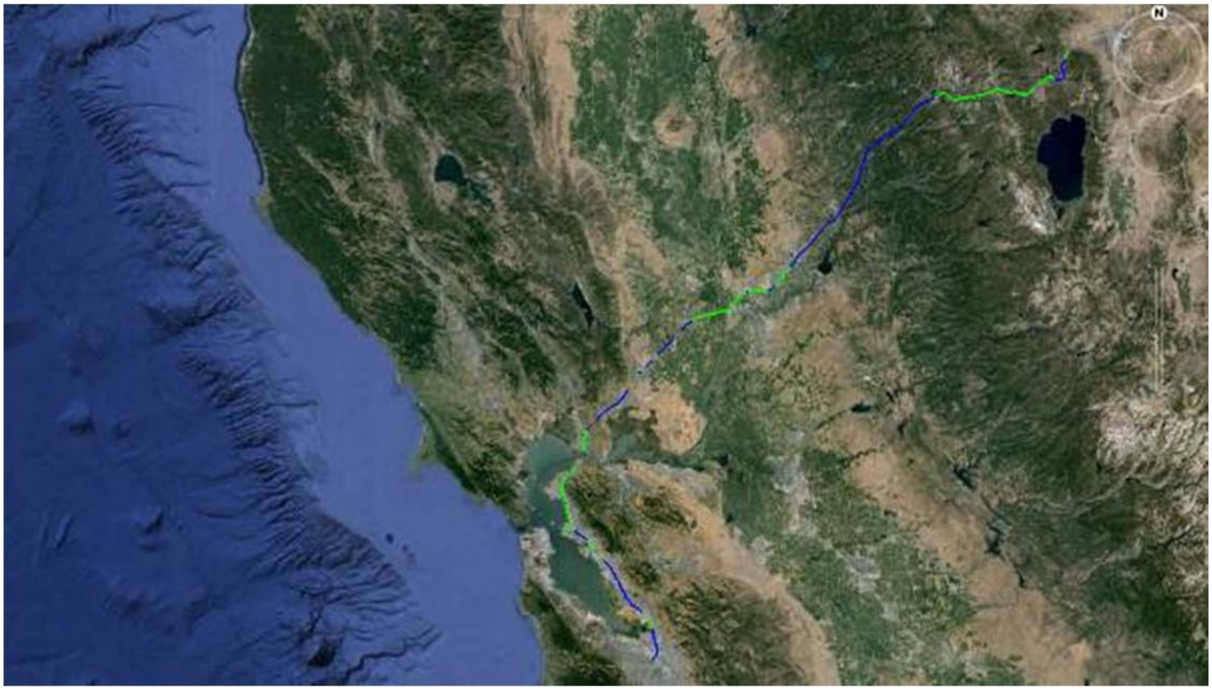


Figure 2.7: Tire wear data layer for I-80 corridor.

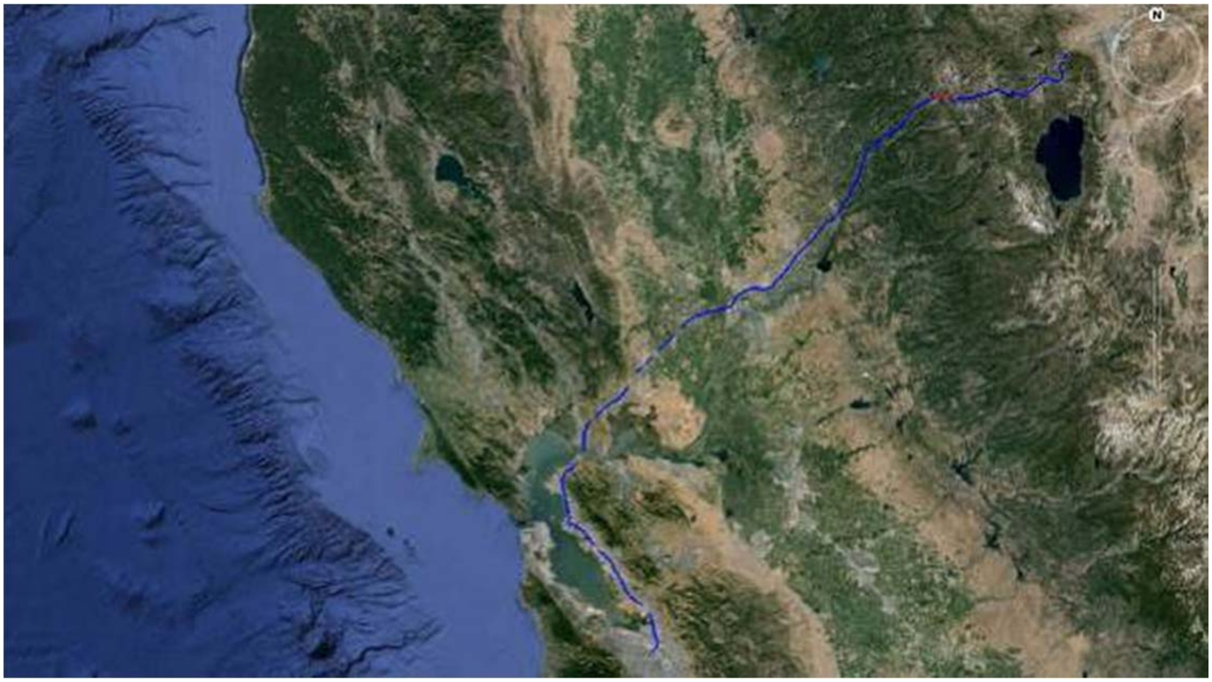


Figure 2.8: Repair and maintenance cost due to riding quality data layer for I-80 corridor.

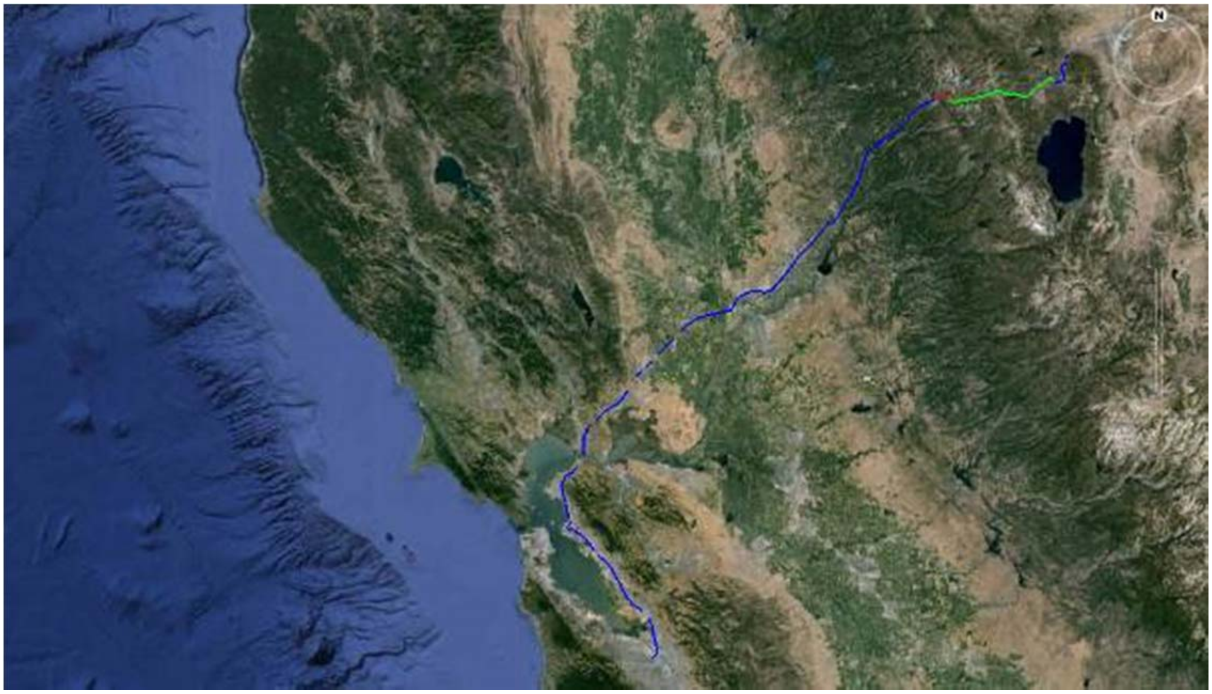


Figure 2.9: Greenhouse gas emissions due to riding quality data layer for I-80 corridor.

Roughness

Tire loads; Emissions; Vertical acceleration; Fuel consumption

Tire wear

Repair and maintenance

Figure 2.10: Comparison between parameters for section of I-80 corridor.

Analysis of the information in Figure 2.5 to Figure 2.10 demonstrates the benefit of the mapping application in developing an understanding of the ways in which the pavement condition and the vehicle-pavement interaction affect the economics of road use.

2.6 Summary

This section contains data for Task 9, which covers the mapping of the data collected, measured, and generated for the two corridors under investigation.

3 TASK 10 - RELATIONSHIPS

3.1 Introduction

This section contains information on Task 10. The objective of Task 10 is to develop a simple relationship between the riding quality and the additional loads on the pavement, the expected freight damage, and the expected additional vehicle operating costs. These relationships can be used to expand the pilot project data to other routes and corridors without a full detailed analysis of each such a route or corridor. These relationships are not developed for load compliance or enforcement. They may be used as an initial version of relationships to generate data for use of planning and economic models (activities not included in this pilot study). The output from Task 10 is essentially a set of equations showing the developed relationships, and examples of graphs and tables generated using these relationships.

3.2 Available Relationships

3.2.1 Introduction

In the preparations for the data analysis required for Task 10 activities, the basis of the investigation focused on an initial search for available relationships that can be used and, where required, adapted or calibrated using the collected data. In the development of the relationships, the focus was on the following parameters:

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

Tire Loads

The tire load data originated from Task 7, and was one of the standard outputs of the vehicle simulations conducted using TruckSIM.™ Data and relationships previously developed for similar vehicles and road conditions as part of various South African studies were incorporated to evaluate the appropriateness of the relationships. Tire load models were developed for the steer axle tires, as well as for the drive and trail axle tires combining the two types of vehicles. The models are used to determine the average and standard deviation of a distribution of axle loads, and these relationships can thus be used to develop the expected probability curves of these data.

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. Differences such as vehicle dynamics will play a role in the final relationships.

It was found that the average of the probability distribution of the tire loads for the axles is related mainly to the Gross Combination Mass (GCM) of the vehicle, while the standard deviation of the probability distribution is 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; however, further refinements are required in this area, and the development of these refinements falls outside the scope of this pilot study. It may, however, be incorporated into further detailed work in this regard.

Company A

The analyses of the tire load data for Company A was conducted with a focus on the steer, drive, and trail axles of the vehicle. Based on the procedure to develop a probability distribution of the expected tire loads for each of these axles or axle groups, Equations 5 to 8 were developed to determine the average and standard deviation of the normal probability distribution curves for the three axles.

All axles*

AVG = GCM/# Total tires Equation 5

Steer axle**

STDEVstr = 0.0305*IRI + 1.6679 Equation 6

Drive axle**

STDEVdrv = 0.0125*IRI + 1.7667 Equation 7

Trail axle**

STDEVtr = 0.0276*IRI + 1.2376 Equation 8

* GCM [kN]

** IRI [in./mi]

Company B

The analyses of the tire load data for Company B was conducted with a focus on the steer, drive, and trail axles of the vehicle. Based on the procedure to develop a probability distribution of the expected tire loads for each of these axles or axle groups, Equations 9 to 12 were developed to determine the average and standard deviation of the normal probability distribution curves for the three axles. As the various axles' loads are normally not known in the field, the average is expressed in terms of the GCM of the vehicle and the total number of tires on the vehicle.

All axles

AVG = GCM/# Total tires Equation 9

Steer axle*

STDEVstr = 5.9665e(0.0043IRI) Equation 10

Drive axle*

STDEVdrv = 24.223e(0.002IRI) Equation 11

Trail axle*

STDEVtr = 19.168e(0.0023IRI) Equation 12

* GCM [kN]

** IRI [in./mi]

3.2.2 Vertical Acceleration of Selected Locations on the Vehicle and Freight

The vertical acceleration data originated from Task 8, and was one of the standard outputs of the field measurements on both vehicles and freight during trips undertaken on a range of selected routes. Data and relationships previously developed for similar vehicles and road conditions as part of various South African studies were incorporated to evaluate the appropriateness of the relationships. Vertical acceleration data models were developed for the worse case vehicle and freight locations on each of the vehicles. The models are again 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 any of the variables, and equal to 1, while the standard deviations depended mainly on the road roughness. The equations for the standard deviation of the probability distributions are provided in Equations 13 to 16. As per the previous report on the detailed analysis of the TruckSIM data [*4*], the focus is on locations 1 and 5 (Steer axle and Trailer axle group 2).

*Company A**

AVGall = 1.00 g

$$STDEV1 = 0.001*IRI + 0.021 \qquad \text{Equation 13}$$

$$STDEV5 = 0.002*IRI + 0.248 \qquad \text{Equation 14}$$

* IRI (in./mi)

*Company B**

AVGall = 1.00 g

$$STDEV1 = 0.022*IRI + 0.023 \qquad \text{Equation 15}$$

$$STDEV5 = 0.170*IRI + 0.139 \qquad \text{Equation 16}$$

* IRI (in./mi)

3.2.3 Fuel Consumption

New fuel consumption models could not be developed due to the lack of input data from the two companies. However, Chatti and Zaabar [*8*] recently calibrated various vehicle cost models using U.S. vehicles and roads. This study was conducted as part of a National Cooperative Highway Research Program (NCHRP) study and, since it contains current evaluation of vehicles similar to those operational in California, these relationships were used as the basis for Task 10. The fuel consumption model was obtained from this data, and simplified for the available data in the study and applied (Equation 2; Section 2.4.5).

3.2.4 Tire Wear

New tire wear models could not be developed because the pilot study was too short to accurately and reliably measure tire wear. The Chatti and Zaabar [*8*] study tire wear models were simplified for the available data in the study and applied (Equation 3; Section 2.4.5).

3.2.5 Additional Repair and Maintenance Costs

New repair and maintenance cost models could not be developed because the pilot study was too short to accurately and reliably measure these costs for a fleet of vehicles. The Chatti and Zaabar [*8*] relationships for additional repair and maintenance costs were simplified for the available data in the study and applied (Equation 4; Section 2.4.5). These models were previously compared to both a separate set of South African vehicles and found to be reliable in terms of the predicted outputs, when compared to actual data [*9*].

3.3 Summary

The relationships for the tire loads, vertical acceleration, fuel consumption, tire wear, and repair and maintenance costs are based on the TruckSIM simulations (Task 7), as well as field measurement data (Task 8) and available calibrated models.

4 TASK 11 – ENVIRONMENTAL AND CONSTRUCTION CONTROL EFFECTS

4.1 Introduction

This section contains information on Task 11. The objective of Task 11 is to explore potential links regarding the environmental impacts (i.e., GHG emission impacts and increased particular matter) and construction riding quality specifications for the selected region/district routes as a precursor to improved bonus-penalty schemes for construction and maintenance/preservation of roads. Existing published relationships between truck volumes and speed have been used to generate a first version of such an outcome. The outcome of the task is information on a map (refer to Task 9, Section 2) with indication of expected/measured GHG levels for different routes as originating from published information only.

4.2 Environmental Impact Models and Data

This section excludes analysis of the environmental effects of pavement construction, maintenance, and rehabilitation, as well as congestion. However, it should be clear that road pavements that are constructed to a higher quality and maintained regularly will provide a longer life, and thus lower construction-related emissions.

Rolling resistance of a pavement surfacing is one of the major factors affecting 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. Hammarström et al. [*10*] published relationships between pavement roughness (IRI) and rolling resistance, and indicated a change in rolling resistance (percentage) for an increase in pavement roughness 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) [*11*].

Wang et al. [*12*] evaluated the life cycle energy consumption and GHG emissions from pavement rehabilitation in California due to changes in rolling resistance. Although this type of analysis falls outside of the scope of this pilot study, it is important to appreciate that, in a full life cycle analysis of a pavement's costs, the rehabilitation options and their effects on the parameters partly evaluated in this pilot project are important.

Recently, the California Air Resources Board (CARB) approved the Tractor-Trailer Greenhouse Gas regulation that requires the use of U.S. Environmental Protection Agency (EPA) SmartWay-verified aerodynamic technologies and Low Rolling Resistance (LRR) tires on vehicles operating on California highways [*13*]. These tires are defined as tires designed to improve the fuel efficiency of tractor-trailers through minimizing rolling resistance. As tire rolling resistance equates to the energy lost per unit/distance traveled as the tire rolls under load, a tire with lower rolling resistance should be more fuel efficient than a tire with greater rolling resistance. The potential effects of the use of LRR tires on V-PI, emissions, and the economy were outside the scope of this pilot study; however, it can be stated that such a move will affect the fuel consumption and emissions of the vehicle fleet. The specific effect on tire load variation and vertical accelerations has not been evaluated and should be done in a follow-up study. Such an analysis can be done both in a field study (such as Task 8) and through a simulation study (similar to Task 7).

Fuel consumption is one of the major factors affecting vehicle emission. Fuel consumption was not directly measured in this project; however, the relationships developed by Chatti and Zaabar [*8*] can be used to estimate reasonable fuel consumption rates for the various sections of road (Equation 2; Section 2.4.5).

4.3 Available Relationships

4.3.1 Introduction

The planning for Task 11 focused on the use of existing relationships between pavement properties and environmental properties. The survey for existing relationships included evaluation of Transportation Research Board (TRB) and related publications (NCHRP), European publications (mainly the World Road Association [PIARC]), and other international sources. Numerous recent studies evaluated these relationships in the light of the focus on the effect of human activities on the environment [*14, 15, 16, 17, 18, 19, 20, 21*]. The detailed evaluation of these and similar studies falls outside the scope of this pilot project. Suffice to indicate 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. For this pilot study, specific relationships that are deemed representative of the available relationships are used to indicate the potential effect of road roughness on emissions.

4.3.2 Selected Relationships

After evaluating the different models available, the one presented by Nielsen and Skibsted [*11*] was selected for use in this project, as it is relatively simple in the relationship between the various parameters, and it provides indications of the four main emission products typically evaluated (GHG, CO_2, CH_4, and N_2O). The relationships between the emission of the four emission products and fuel consumption are shown in Table 4.1. For simplicity in this pilot project, only the GHG emissions are indicated in the relationship between road roughness, speed, and emission in Equation 17. Application of Equation 17 is summarized in Table 4.2 and Figure 4.2 for three speeds and four road roughness levels.

Table 4.1: Relationships Between Fuel Consumption and Emissions [*11*]

Emission product	Emission (kg/liter fuel)
CO_2	2.409
CH_4	0.000132
N_2O	0.0000561
GHG	2.429

GHG emission (kg/mile) = 9.1948/Fuel consumption (mpg) (Equation 6) Equation 17

Table 4.2: Summary of GHG Emission 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

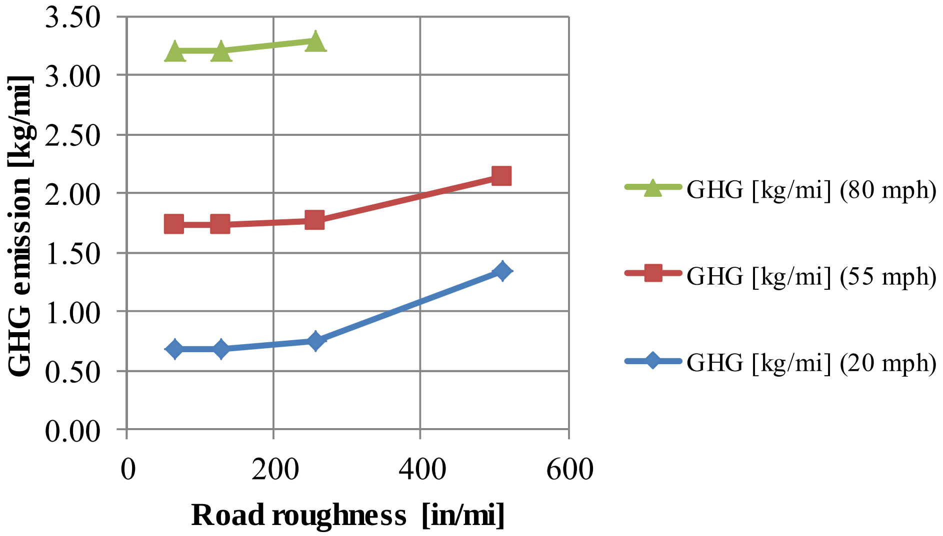


Figure 4.1: Summary of GHG emission as affected by speed and road roughness.

4.4 Data

The data available for the environmental and construction control analyses were mainly the pavement roughness data. As indicated in various sources, pavement roughness is a basic parameter indicating the condition of the pavement, and also directly affects the response of vehicles using the specific route.

For both Companies A and B, road roughness 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 in Task 8. The calculated GHG emissions for each of the companies are summarized in Table 4.3.

It should be appreciated that the speed on the Company A routes was lower 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 4.3 indicates that the Company A data has a speed of 55 mph. The analysis indicates that the speed does affect the GHG emissions significantly.

Table 4.3: Summarized GHG emissions for Company A and Company B on indicated routes

	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

4.5 Construction Quality Control Issues

4.5.1 Introduction

Construction quality control has a direct influence on the riding quality of a pavement, with improved control of density, layer thickness, and general attention to detail generally leading to smoother pavements. This is also true for construction control during pavement maintenance and rehabilitation [*22*]. Generally, better riding quality after construction or maintenance will extend the life of a specific pavement for constant environmental conditions and traffic loads as compared 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.

4.5.2 Application Procedure

As an example of the potential application of the relationships developed in the analysis of construction quality control effects on V-PI 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 actions (typically an Asphalt Concrete [AC] overlay), have the ability to improve the riding quality of the existing road. An unpublished dissertation [*23*] developed Equation 18 (converted to IRI in in./mi here) 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) ($n = 46$; $R^2 = 0.989$).

Percentage improvement = 56.029 * (ln[IRI])–239.57 Equation 18

Using this relationship and the Company A initial 90th percentile riding quality data, two scenarios are evaluated. In the first, Equation 18 is used with the initial data. In the second scenario, it is assumed that the quality control is not conducted optimally, and for the example, a 20 percent worse end condition in terms of riding quality assumed (20 percent variation may, for instance, indicate a variance of only 8 mm or 0.3 in in the 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 4.4.

Analysis of the data in Table 4.4 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 4.3 and Figure 5.1 the probability distributions are shown, and the higher percentage of increased tire loads is visible in Figure 5.1.

4.5.3 Summary

The example shown in this section focuses on one potential aspect of the effect of construction control on riding quality and subsequent V-PI and VOC effects. It is recommended that Caltrans conduct further analysis of local conditions, incorporating local maintenance options and their effects on the riding quality of roads. Further, the effects of riding quality bonus-penalty schemes, and the effect of initial riding quality on the long-term performance of local roads should be incorporated into an overall model.

4.6 Summary

This section evaluated the environmental and construction control-related effects of road riding quality. Existing relationships were sourced, and it was indicated that the road riding quality does have a direct influence on these parameters, although the level of influence is not linear.

The outcomes of the analyses indicate that further investigations into local (Californian) conditions are required in a follow-up study to ensure that the available models are calibrated for local conditions in terms of vehicles, road conditions, operating conditions, and applicable laws and regulations.

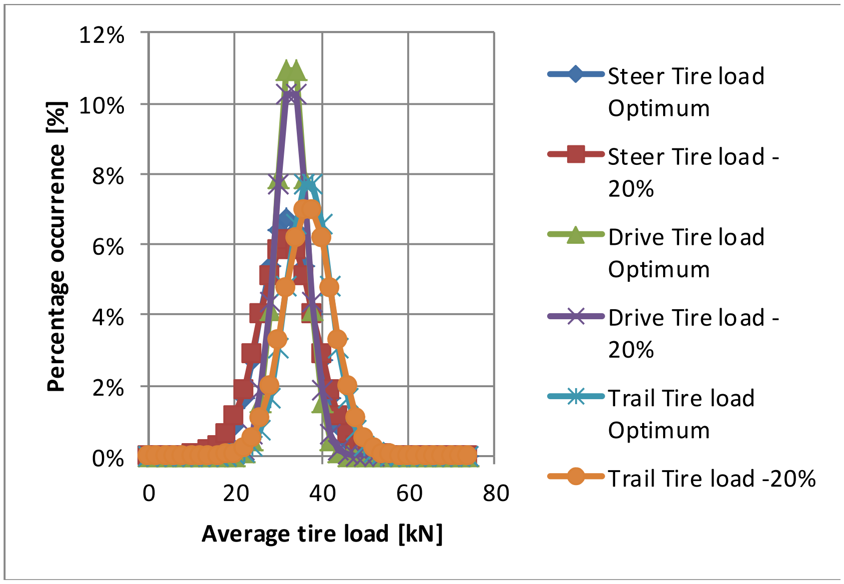


Figure 4.2: Expected probability distribution for optimum and 20% less-than-optimum maintenance of Company A routes.

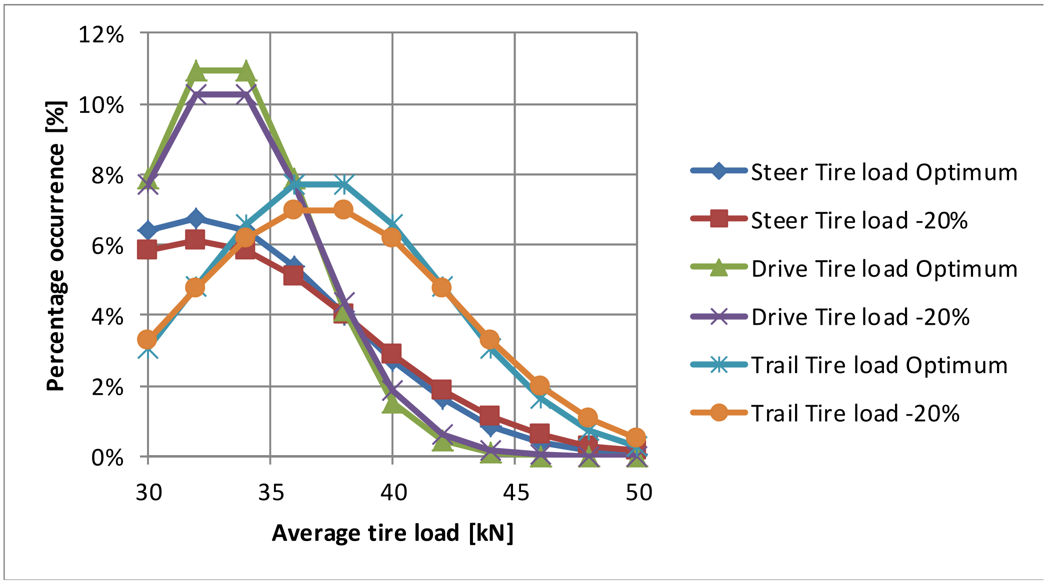


Figure 4.3: Detail of expected probability distribution for optimum and 20% less-than-optimum maintenance of Company A routes.

Table 4.4: Comparison Between Two Scenarios for Optimal and Less-Than-Optimal Quality Control During Road Maintenance

	% Improvement (optimum)		Average IRI After		Fuel Consumption (mpg)		GHG Emission (kg/mi)		Tire Use (%/mile]		Additional Damage ($/mile)	
Average IRI before	Optimum	-20%	Optimum	-20%	Optimum	-20%	Optimum	-20%	Optimum	-20%	Optimum	-20%
225	49	29	139	159	7.454	7.389	1.300	1.305	0.00117	0.00117	0.0873	0.0886

	% Improvement (optimum)		Average IRI After		Tire Load STDEV Steer		Tire Load STDEV Drive		Tire load STDEV Trail		Vertical Acceleration	
Average IRI before	Optimum	-20%	Optimum	-20%	Optimum	-20%	Optimum	-20%	Optimum	-20%	Optimum	-20%
225	49	29	139	159	5.911	6.516	3.506	3.753	5.077	5.624	0.160	0.180

5 DISCUSSION

5.1 Introduction

This section focuses on a general discussion of the information and data presented in this report, as well as the potential effects that these relationships and their application may have for both Caltrans and private companies in California. An additional section has been added where the outcome of the limited tomato damage laboratory study and its implications for the remainder of the project is discussed.

5.2 Relationships and Maps

5.2.1 Introduction

This project focuses on the vehicle-pavement interaction (V-PI) occurring when trucks are operated on typical roads in California. From a 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 catering for changes in the 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.

For private companies using the roads in California for transportation of goods, 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 damage due to road roughness, alternative routes may be evaluated and smoother routes selected where available.

Selected examples of such applications are discussed in the remainder of this section. Various assumptions were made in these provisional applications, and they serve only as examples of potential applications.

5.3 Example Application of Information

5.3.1 Introduction

In this section, some selected examples of application of the information and relationships presented in this report are discussed. Where examples were already discussed in the body of the report, reference is made only to such examples and sections in the report.

5.3.2 Empty Tin Analysis

Company A indicated that it experiences damage of up to 10 percent of transported empty tins when transporting these tins between the tin factory and the tomato processing plant. As a potential indication of the application of the relationships in this pilot study to private companies, an analysis was conducted on the riding quality of the different routes that the company may follow, and the application of the relationships to attempt in identifying the most optimum route for the company. While application of the relationships may be beneficial to private companies, it also provides practical insight to Caltrans and others about how the transportation infrastructure can affect operational and cost considerations of immediate concern to private companies and, therefore, relevant to the state's economic interests. In this analysis, the vertical acceleration relationships and the VOC relationships are used. In terms of the confidentiality clauses in the project (Section 1.5), no maps of the various routes are shown.

The analysis was based on riding quality data that were collected for the three potential routes identified by the company for transport of the empty tins. The riding quality information for the three routes is summarized in Table 5.1 and shown in Figure 5.2.

Table 5.1: Riding Quality Data for Three Potential Empty Tin Routes

	Riding Quality (in./mi)		
	Route 1	**Route 2**	**Route 3**
Minimum	52	52	55
Average	108	118	93
90th percentile	135	179	115
Maximum	1176	1119	952

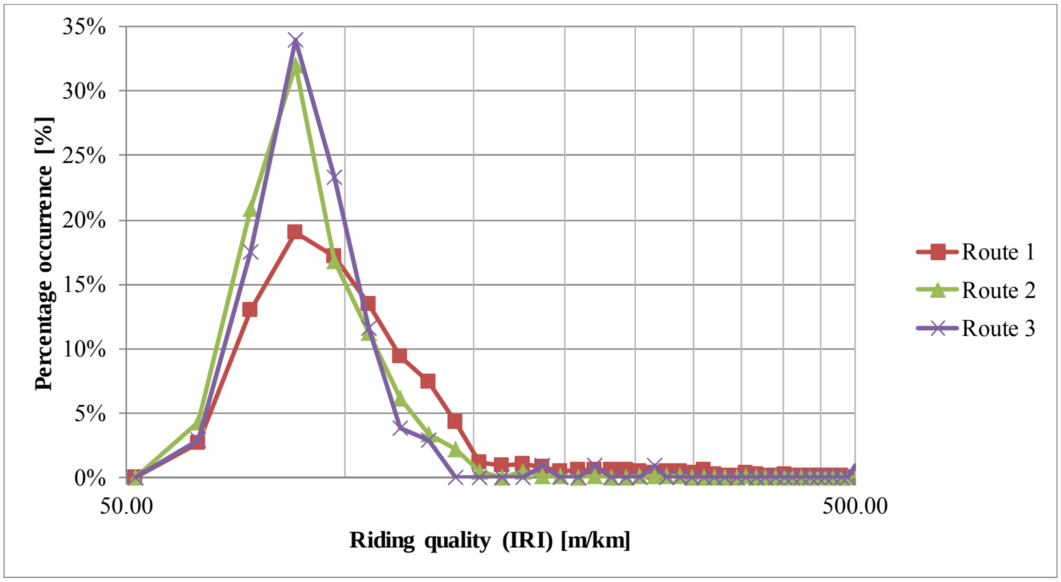


Figure 5.1: Distribution of riding qualities for three potential empty tin routes.

Calculation of the VOC parameters and vertical acceleration parameters for the three options indicate the outcome summarized in Table 5.2. Analysis of this data indicate that Route 3 is the optimum for Company A, since it provides the lowest cost and the least vertical acceleration variation during transport.

Table 5.2: Summary of Company A Route Selection

Parameter	Route	Value
Fuel consumption (mpg)	Route 1	6.613
	Route 2	6.633
	Route 3	6.728
GHG emission (kg/mi)	Route 1	1.717
	Route 2	1.668
	Route 3	1.536
Tire use (%/mile)	Route 1	0.00117
	Route 2	0.00117
	Route 3	0.00116
Additional damage ($/mile)	Route 1	0.353
	Route 2	0.308
	Route 3	0.214
Vertical acceleration	Route 1	0.279
	Route 2	0.282
	Route 3	0.237

5.3.3 *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 a route. The focus is on both the tire load relationships and the VOC relationships.

The roads traveled on by Company A 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. In Steyn et al. [*1*] 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.

The process consisted of identification of the riding quality of the various routes (already covered in Section 2.3), calculating the various costs and parameters for these conditions, and then reanalyzing the data as though 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 5.3 the outcome is summarized for all the parameters. As the total length of the roads is relatively short, the differences in vehicle-related parameters are not major; however, the difference in the standard deviation of the various tire loads and the vertical acceleration is significant. In Figure 5.3 and Figure 5.4, the distributions of tire loads are shown. The detailed view in Figure 5.4 clearly indicates the decrease in overloaded conditions for the maintained routes.

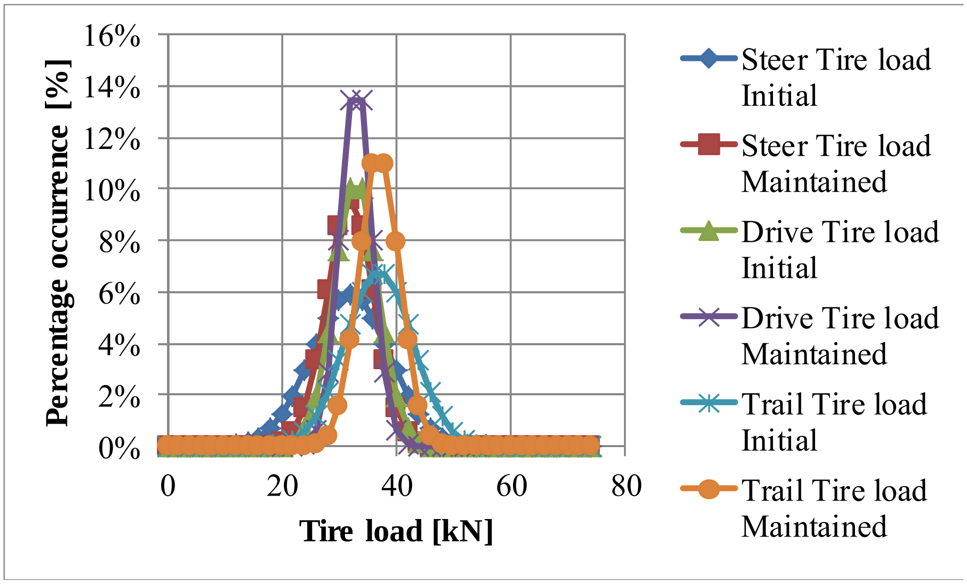


Figure 5.2: Expected probability distribution for initial and after maintenance conditions of Company A routes.

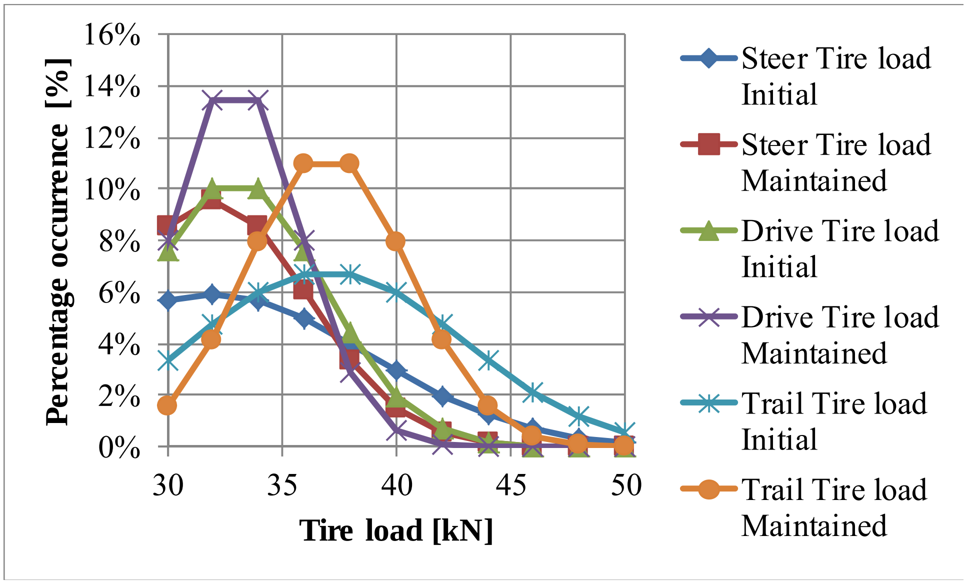


Figure 5.3: Detail of expected probability distribution for initial and after maintenance conditions of Company A routes.

5.3.4 Construction quality improvement analysis

Section 4.5.2 provides an indication of the process to evaluate the potential effect of construction quality control differences on the outcome of the V-PI analyses as well as the VOCs. It was indicated that for the example evaluated, the main effect was on the distribution of tire loads and vertical accelerations. Depending on the length of the roads investigated, the speeds attained by vehicles on the roads and the initial riding quality condition of the roads, the outcome of such an analysis will differ.

Table 5.3: 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 Maintenance**	**Initial**	**After Maintenance**	**Initial**	**After Maintenance**	**Initial**	**After Maintenance**
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**	
Average IRI before	**Average IRI after Maintenance**	**Initial**	**After Maintenance**	**Initial**	**After Maintenance**	**Initial**	**After Maintenance**	**Initial**	**After Maintenance**
167	82	6.760	4.162	3.853	2.789	5.845	3.495	0.188	0.103

5.3.5 Freight damage analysis

One of the potential outcomes of the data collection, analysis, and development of relationships between riding quality and vertical acceleration of the freight in the vehicles is the option to evaluate the probability of damage that may occur to freight during transport, caused by the unevenness or roughness of the route.

O'Brien et al. [*24*] indicated that various types of fruit can be damaged when vibrated at frequencies ranging from 9 to 54 Hz, with specific bands of frequencies for different types of fruit. The frequency range of sensitivity for tomatoes is between 5 and 13 Hz with a mode of 10. These frequencies fall in the range of the axle hop frequencies (high frequency vibrations mainly experienced by the truck's axles and tires) of the truck, which are between 5 Hz and 20 Hz. The axle hop frequencies are often transposed to the fruit cargo inside of the packaging, especially in the case of bad truck suspension.

De Ketelaere and Baerdemaeker [*25*] indicated that there is currently not a clear physical quality damage reference measurement scale, and developed a vibration analysis method for quality assessment. However, to use this method in the evaluation of the quality of the transported tomatoes in the field study is not practical, due to the volume of tomatoes involved. An alternative approach where the bulk tomato density changes at different frequencies are determined, and the damage to individual tomatoes at such frequencies is determined and related to the frequencies, was recommended for further evaluation by Steyn [*4*], and this may be viewed as one of the options for further research after this pilot project.

Figure 5.5 provides a visual comparison between the dominant frequencies experienced at two locations on the Company A trailers and sensitive frequencies for potential damage of transported tomatoes (shaded area). It indicates that on the front trailer the most dominant frequencies (around 3 Hz, specifically Roads HM and D) falls just lower than the sensitivity range for tomatoes, although the frequencies generated on specifically Road 1 coincides with the higher tomato sensitivities (around 10 to 13 Hz). The dominant frequencies on the back trailer (bottom graph) are around an order of magnitude smaller at these sensitive frequencies.

Based on the outcome of this comparison, the potential for fruit damage on these routes with these vehicles and masses should be relatively low. Changes in the vehicle dynamics (suspension properties, tire inflation pressures, vehicle loads) may change this situation.

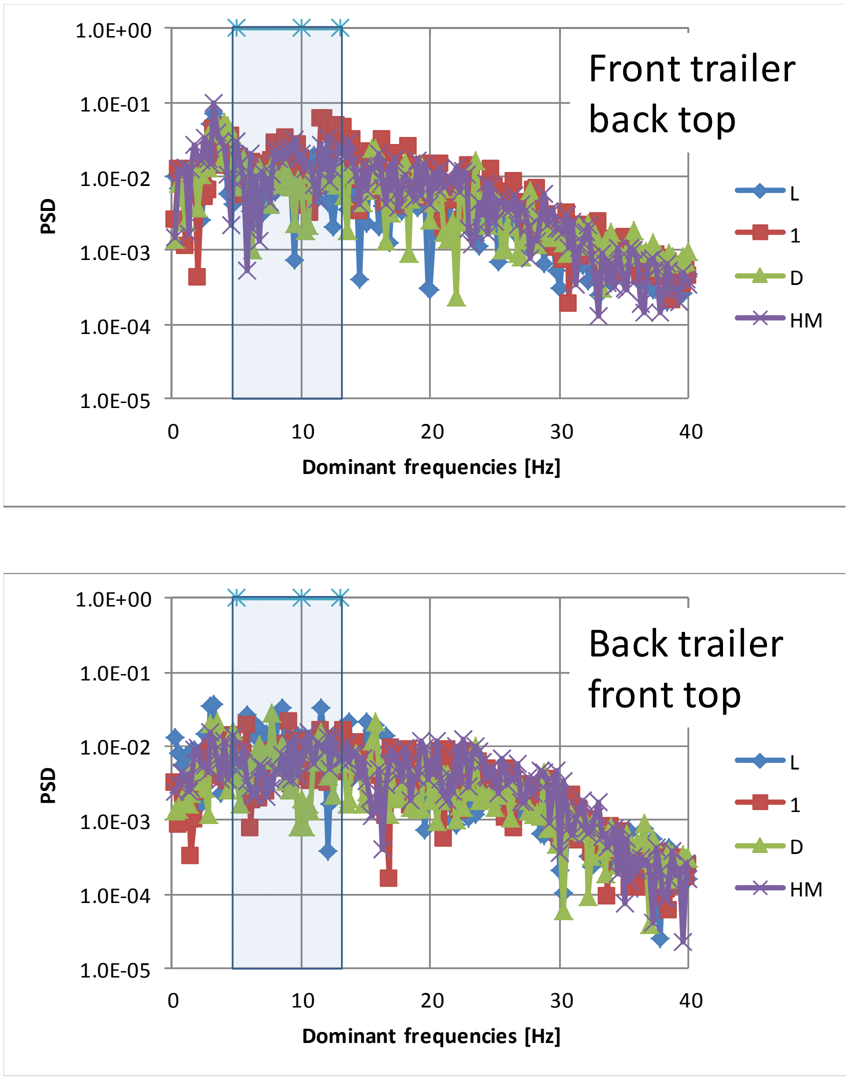


Figure 5.4: Comparison between dominant frequencies at two locations on trailers and tomato sensitivity frequencies that may result in fruit damage.

5.4 Tomato Damage Laboratory Study

5.4.1 Introduction

Based on the field and literature study conducted in this project, it was decided to conduct a limited laboratory study to determine the potential damage that may be caused to transported tomatoes on the routes traveled by Company A, as discussed in this and previous reports. For this study, a laboratory experiment has been developed at the University of Pretoria (South Africa), in which the accelerations as experienced on the Company A vehicle were applied to a sample of tomatoes, while the contact stresses between the tomatoes are being measured. These data were analyzed and, together with recent fresh produce market prices from the Johannesburg Fresh Produce Market, used to estimate potential economic damage due to the condition of the routes on which Company A transports their tomatoes.

It should be appreciated that this is a very limited study, and that the objective was mainly to determine whether or not it is possible to obtain such information. In order to implement the outputs from this study wider, a larger sample of different types of tomatoes and routes will be required, as well as typical California market prices for tomatoes (or other sensitive fruits and vegetables).

5.4.2 Methodology

The methodology used for the determination of the potential damage on the tomatoes during transportation is as follows:

- Accelerations were measured at various locations on the load of tomatoes during transport over a range of roads in September 2012 (Task 8 of this study). These accelerations provided an indication of the dominant frequencies (the Power Spectral Density [PSD] curves) and the PSD areas (severity of vibrations) that the tomatoes experience while being transported.
- A laboratory setup was manufactured that allowed for placing around 40 kg of tomatoes inside a container on top of a vibrating table for which the dominant frequency could be selected (Figure 5.6). Flexible pressure sensors were placed between the tomatoes to measure the pressures (contact stresses) that they exert on each other during vibration (Figure 5.7). Accelerometers were also placed to measure the accelerations during the test.
- The container of tomatoes was vibrated at a range of frequencies as obtained from the actual truck data (Task 8), while measuring the pressures and accelerations.
- The stiffness (firmness) of the tomatoes was determined using a standard load/deflection test, of which the data were converted to stress/strain (σ/ε) relationships (Figure 5.8). These data were compared to published tomato firmness data and compared well.
- The damage limit of the tomatoes was defined as the stress when the stress/strain curve diverted from a linear-elastic relationship, and the failure condition as the stress where the tomatoes failed in the stress/strain test.
- The data obtained from the pressure films inside the container of tomatoes (Figure 5.9) were analyzed and the range of contact stresses compared to the defined damage and failure conditions. A guideline was set to compare the 98th percentile contact stress with the damage and failure stresses.

Figure 5.5: Vibration table with tomatoes in container ready for testing.

Figure 5.6: Bottom layer of tomatoes showing bottom and first layer pressure sensors in place.

Figure 5.7: Measurement of stiffness of tomatoes in laboratory.

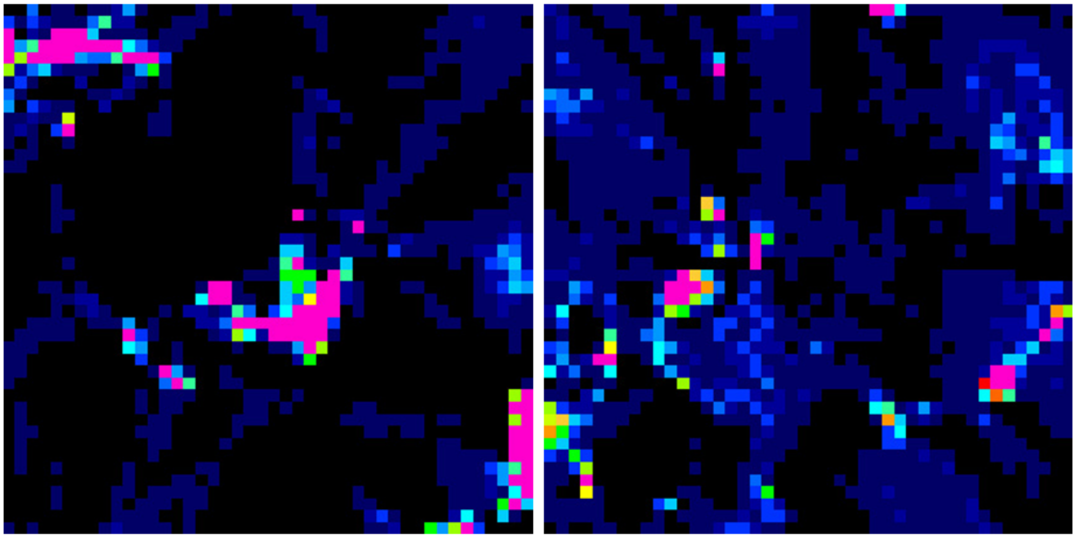


Figure 5.8: Typical contact stress measurement data as observed between tomatoes during test (pink – highest stresses, black – no stresses).

There are some limitations in the current study (type and shape of tomatoes, speed effects, duration of transport effects), that should be attended to in follow-up studies to ensure that the data are applicable to a wider range of agricultural produce and road conditions, but these can be addressed in small adaptations in the current laboratory test procedure.

5.4.3 Data

Further details on aspects of the data collected during the process are presented and discussed in this section. The major frequency bands identified from the PSD data of the accelerations on the Company A truck are shown in Figure 5.9.

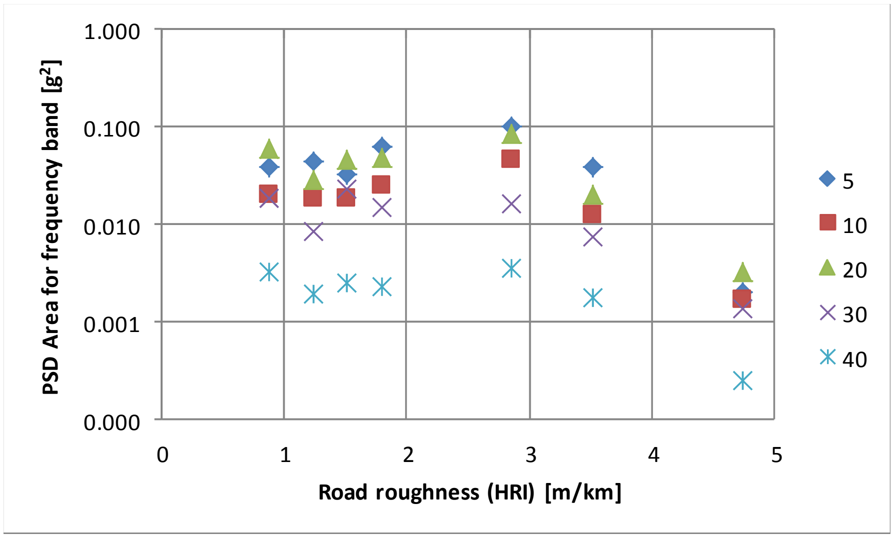


Figure 5.9: Major frequency bands for Company A truck on different routes (indicated by roughness level).

The vibrations inside the tomato container and of the vibration table were monitored during the vibration procedure to ensure that they are similar to those measured on the trucks (Figure 5.10).

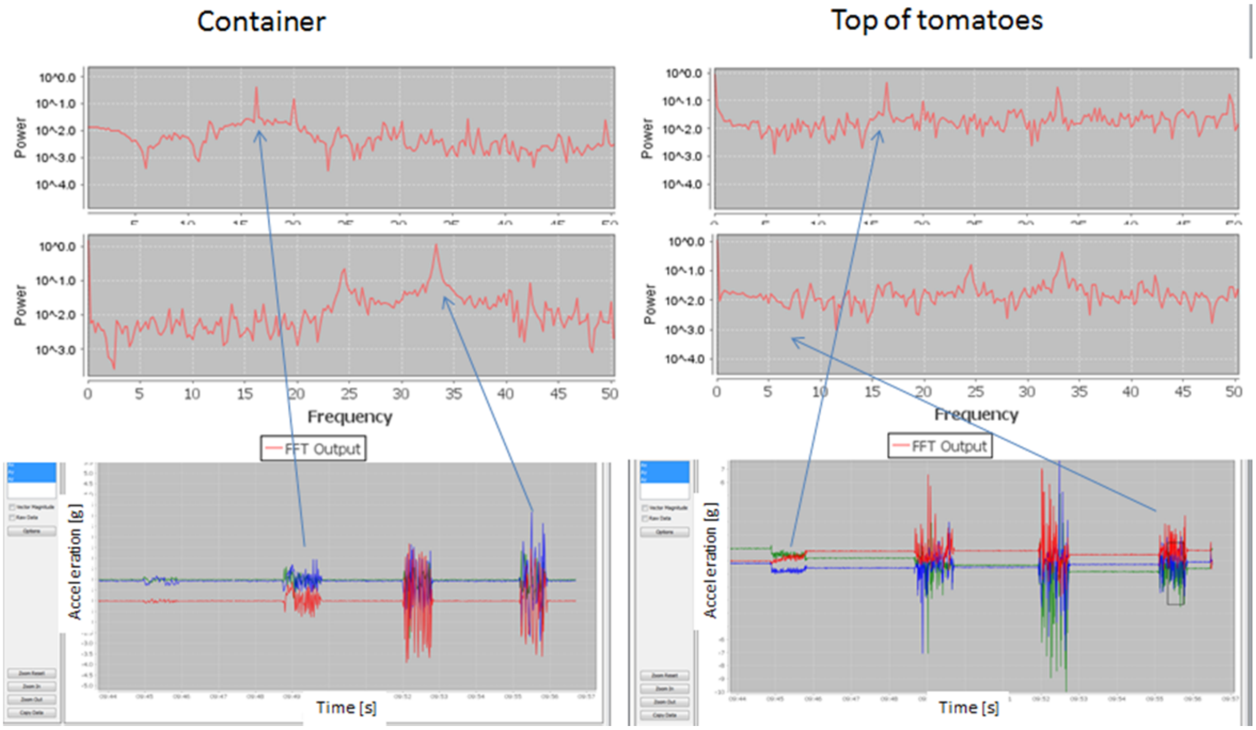


Figure 5.10: Measured vibrations of container (vibration table) and tomatoes during vibration.

The stiffness of the tomatoes was measured for both relatively green and ripe tomatoes, and also for both major configurations (loading from top and loading from side). The outcome of these tests showed clear groups of stiffness data (Figure 5.11 and Figure 5.12). Comparison of these data sets with published tomato firmness data [*26*] showed relatively good similarity (Figure 5.13).

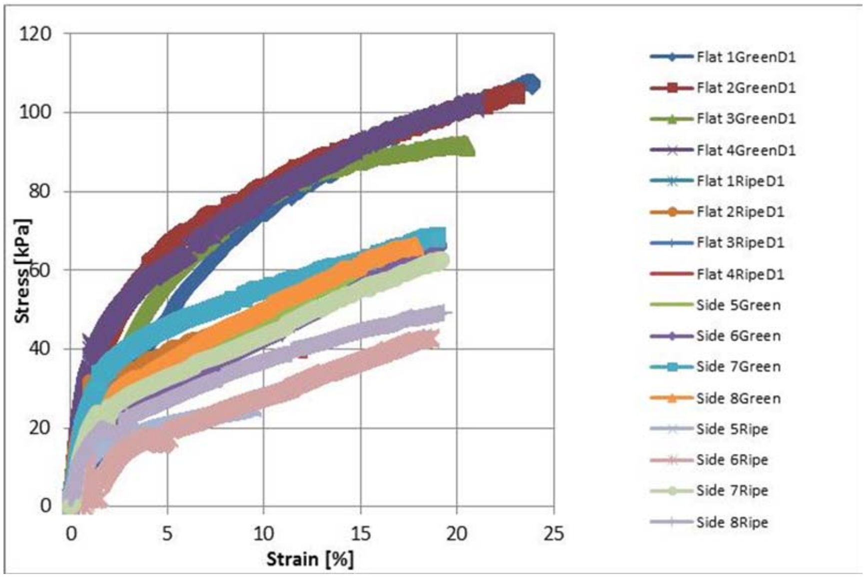


Figure 5.11: Stress/strain behavior of all sampled tomatoes.

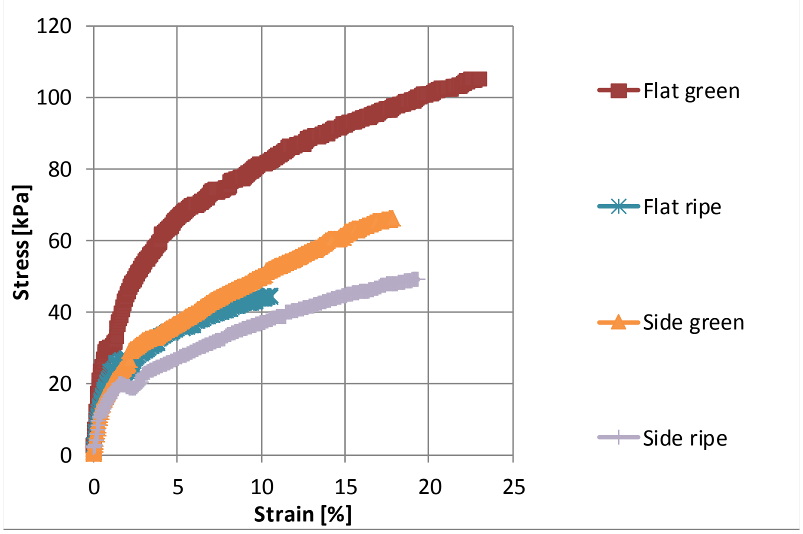


Figure 5.12: Simplified stress/strain behavior of four main groups of tomato stiffness data.

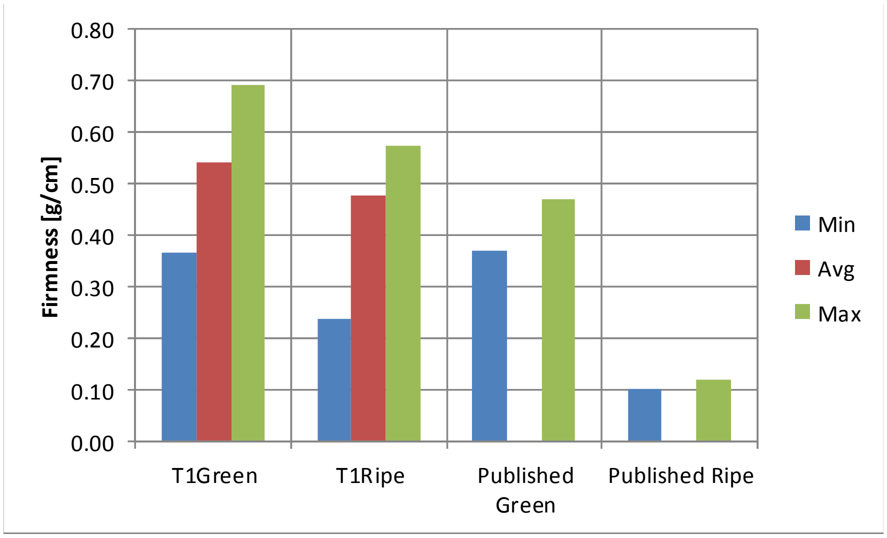


Figure 5.13: Comparison between measured and published tomato firmness data.

Using the definition of damage as the linear elastic part of the stiffness data (Figure 5.12), and the failure condition as the part of the stiffness graph where the tomatoes physically collapsed, the damage stress and failure stress for the different tomato conditions were defined as indicated in Table 5.4.

Table 5.4: Damage and Failure Stresses for Tomatoes in Experiment

Condition	Flat Green	Flat Ripe	Side Green	Side Ripe
Damage stress (kPa)	28	23	12	11
Failure stress (kPa)	104	44	65	48

Cumulative contact stresses measured between tomatoes during the tests at the various dominant frequencies are shown in Figure 5.14 (graph only shows 80 to 100 per cent cumulative distribution data for clarity). The data indicate that the majority of the measured contact stresses were less than 5 kPa. In Figure 5.15, the percentage of damage stress experienced by the tomatoes (in terms of percentage of tomatoes experiencing the specific damage levels) is illustrated, while the same data are shown in Figure 5.16 for the percentage of failure stress experienced.

Using the data in Figure 5.14 through Figure 5.16, the 98th per cent damage and failure levels were used to define the percentage tomatoes being damaged during transportation. Using this definition, the damage shown in Figure 5.17 was calculated for the tomatoes on the routes with different riding qualities.

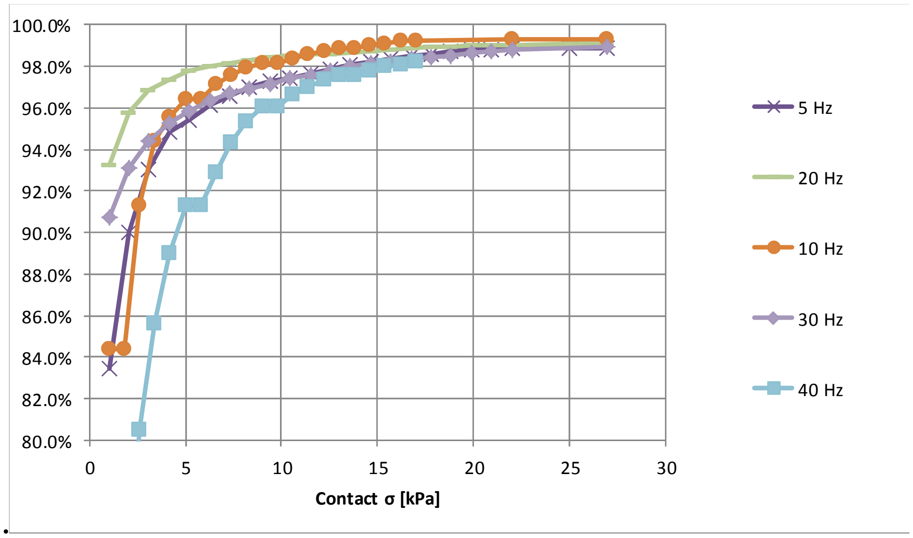


Figure 5.14: Cumulative contact stress distribution between tomatoes during tests for different dominant frequencies.

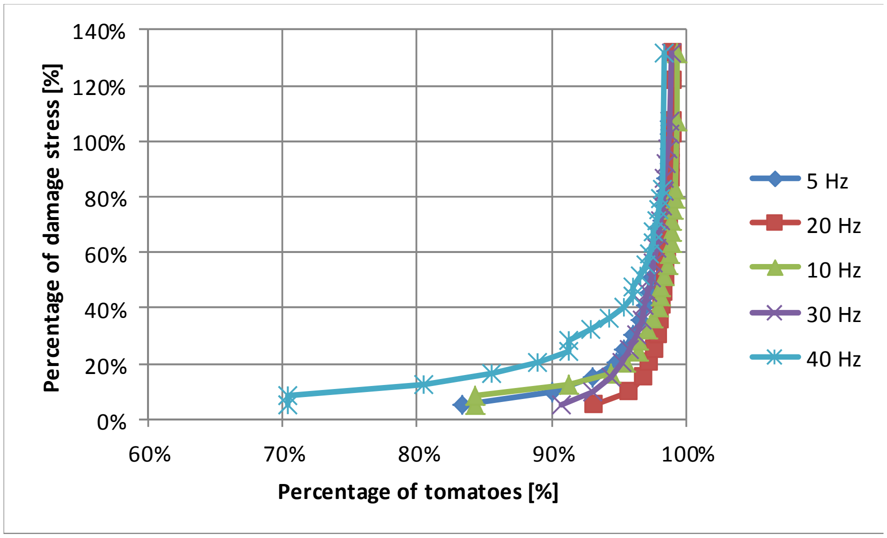


Figure 5.15: Percentage tomatoes experiencing different levels of damage stresses.

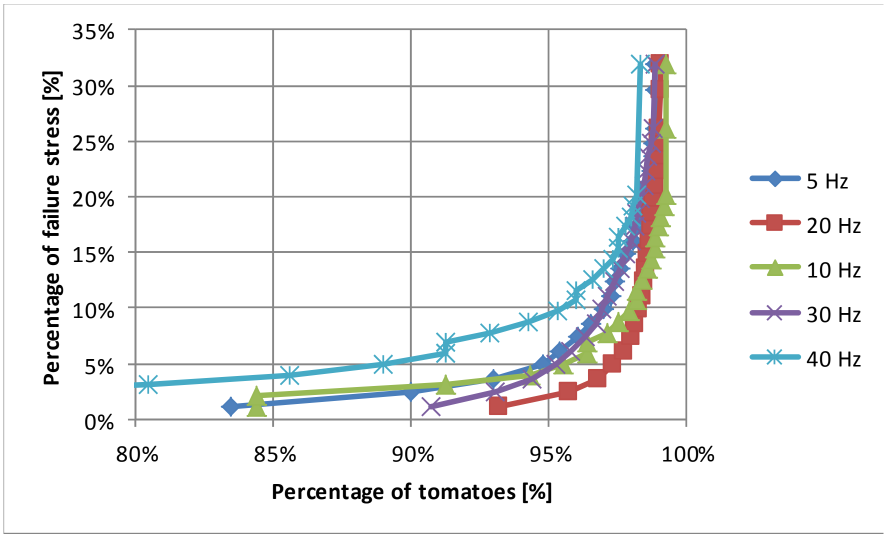


Figure 5.16: Percentage tomatoes experiencing different levels of failure stresses.

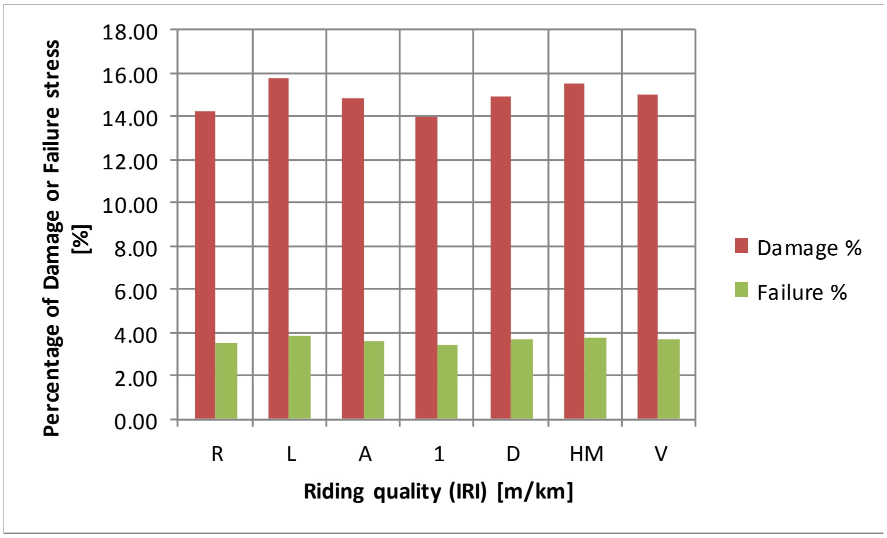


Figure 5.17: Percentage of damage and failure stress versus road riding quality (98th percent damage). (Note: Values on X-axis refer to the road identifiers for Company A routes.)

Analysis of the data in Figure 5.17, as well as the similar data for the 98^{th} percent damage levels, provided for development of a relationship between the road riding quality and the damage and failure levels for the specific truck transporting tomatoes (Figure 5.18).

This research strategy thus provides for evaluation of the expected damages that may be experienced by transported agricultural produce as trucks travel over roads of varying roughness or riding quality. Although there are a number of limitations in the current study (see Section 5.4.4), the process provides for the principles of an objective evaluation of these damages, and should be adaptable to other agricultural produce as well.

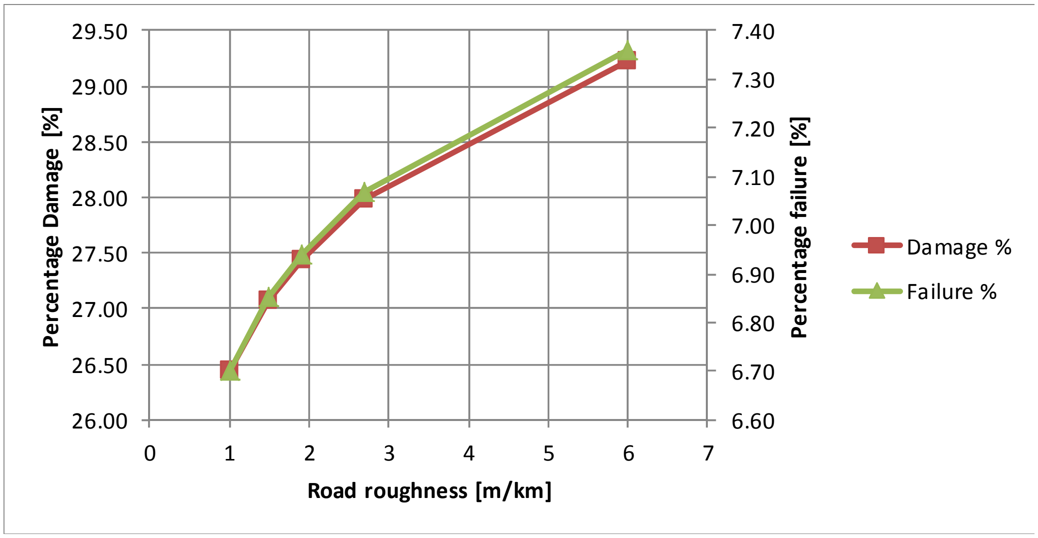


Figure 5.18: Relationship between damage and failure levels and road riding quality.

5.4.4 Implications

The process as described in Sections 5.4.1 to 5.4.3 provides for an objective evaluation of potential damage to transported agricultural produce on a range of roads. However, there are some limitations to the current process and data set (note that the current study was focused on data from farm-to-processing plant transportation versus farm-to-market transportation):

- Range of tomato types: Those tested in South Africa were not the same shape as typical California tomatoes.
- Ripeness of tomatoes: A range of ripeness conditions should be included in the study and not only one or two levels of ripeness.
- Speed variations: Tests should be conducted at acceleration levels obtained at a range of speeds.
- Long duration trips: Current laboratory tests were conducted only for 60 seconds, and the effects of shorter and longer trip durations should be evaluated.
- Scaled models: The current tests were conducted on a small sample of tomatoes; the potential effects on bulk tomatoes should be evaluated.
- Other types of fruits/vegetables: Transportation of the main types of agricultural produce should be included in the testing.
- Focus of analysis: The output focuses on damage and not the economic effects of the damage.

However, the methodology still provides for a robust evaluation of the damage levels. In order to develop a method for the incorporation of economic effects in the evaluation, a South African application of the process was conducted, as access was possible to actual market prices of tomatoes.

The process to calculate the economic impact of road conditions consisted of the following steps:

- The typical market volumes and prices of tomato sales for one market day at the Johannesburg Fresh Produce Market were obtained (578,000 kg of tomatoes).
- Prices per class of tomato were obtained. The tomatoes were classified as good, damaged, or failed corresponding to the categories in the laboratory tests. An average price per tomato class was calculated to indicate the income expected for the day's produce. A clear relationship was observed between the tomato class and price, with lower classes having lower prices. Failed tomatoes were deemed unsuitable for sale. The cost of this loss was incorporated into recalculating the average price of tomatoes for each category in the laboratory tests.
- Using this information, one day's income from the tomatoes was calculated, and compared to the potential for income if no tomatoes were damaged or failed.

The outcome of this analysis was an indication that a loss of about 8 per cent in income was generated due to tomatoes fetching lower prices (damaged) or not being sold at all (failed). It should be appreciated that tomato prices have a direct influence on this calculation, as do the volumes of tomatoes and distances for trucks to travel to and from the market or processing plant. However, the process allows for an objective calculation rather than a guess of the potential damage caused by inadequate road conditions.

In terms of the use of this type of information to Caltrans, it is suggested that such information (beyond what is possible to produce in a pilot study) could help in developing some form of freight performance measurement indicator(s). Performance measurement indicators might be a combination of the expected damage and failure of produce on the routes for a specific county or region, combined with the lower speeds that trucks typically travel on rougher routes (as shown in Section 2.4.4) to indicate the potential economic effects of a road network on which the roughness is less than optimal.

A further application of the information is to determine the potential cost/benefit of improving riding quality on roads where agricultural produce is being transported. In this regard, a limited application of the principles in a South African context (as the authors had access to broader information on truck volumes, market data, and riding quality for a whole region) indicated that improvement of road conditions from a current weighted average riding quality of 194 in/mi to a weighted average riding quality of 110 in./mi (poor to good) translates into a 47 per cent lower loss and additional costs (produce loss and additional fuel and damage costs; refer to Section 2.4.5) due to road conditions (Figure 5.19 [figure added for completeness] showing South African data). This type of information can significantly benefit the current California Benefit Cost analysis process.

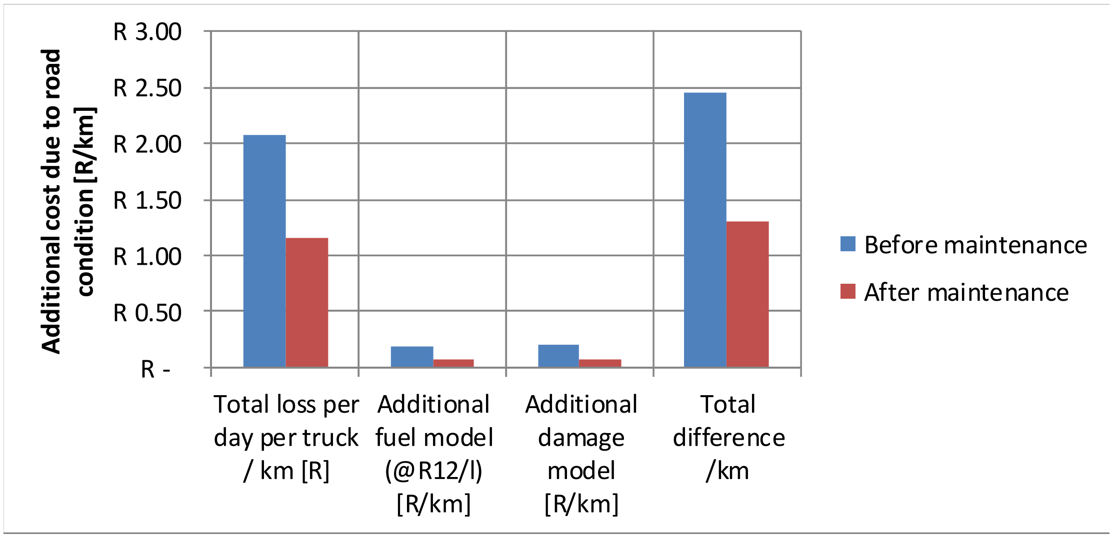


Figure 5.19: Potential savings due to improvement of road roughness (South African example). (Note: R=Rand)

5.4.5 Summary

The laboratory testing of the tomatoes indicated that:

- It is possible to objectively measure contact stresses between tomatoes in a laboratory model at a range of acceleration levels observed on trucks operated on real routes.
- The measured stiffness/firmness values of tomatoes were similar to those published in literature.
- It is possible to objectively calculate actual contact stresses as a percentage of damage/failure stresses.
- It is possible to relate the damage and failure levels to road conditions and to develop potential performance measurement indicators to be used in freight transport models.
- It is possible to calculate benefit/cost ratios for the lower damage and thus losses of agricultural produce transported on roads before and after being maintained to improve their riding quality.

Based on the results and experience of the laboratory testing of the tomatoes, the following actions are suggested:

- Discuss the final outcome and costs with various agricultural producers and associations to obtain their input regarding the applicability of the process and results.
- Develop a mechanism to access typical California market data to enable calculation of potential California-specific financial losses similar to the examples shown in this section.

- Continue with development of a performance measurement indicator incorporating the damage levels, financial aspects, and speeds due to inadequate road conditions, to objectively model the economic benefits of improving road conditions.
- Continue tests to address limitations in terms of California-specific tomatoes, trip duration, full-scale truck measurements using pressure sensors, and tests on other potentially sensitive agricultural produce.

5.5 Summary

In this section, some potential practical applications of the models and information presented and discussed in this report are introduced. The focus is on potential benefits to both Caltrans and private road users. It was shown that the models can be applied to improve the understanding of the effects of quality control on long-term costs of roads, the VOC of road users as affected by road conditions, and the potential of the models to aid in optimum route selection.

6 CONCLUSIONS AND RECOMMENDATIONS

This section contains only the major conclusions and recommendations for Tasks 9 to 11 of this project.

6.1 Conclusions

The following conclusions are drawn based on the information provided and discussed in this report:

- Data concerning road roughness can be used in conjunction with appropriate models and relationships to evaluate the economic effects of road use by logistics companies through evaluation of vehicle operating costs (VOCs) and potential damage to vehicles and freight.
- As road roughness generally deteriorates with road use, road owners can evaluate the economic changes in the VOCs of road users over time, and determine optimum times for maintenance and rehabilitation of existing transportation infrastructure.
- Road users can use relationships between road roughness and various parameters (VOCs, freight damage, etc.) to select optimal routes where VOCs and damage are minimized, and also objectively calculate the effect of these road conditions on their income.
- Road owners can evaluate the effect of different levels of construction and maintenance quality control on the outcome of these actions and the general transportation costs and deterioration rates of the infrastructure as affected by riding quality/road roughness.

6.2 Recommendations

The following recommendations are made based on the information provided and discussed in this report:

- The models and relationships in the report should be evaluated for incorporation into the appropriate Caltrans economic models, to enable modeling of the effects of riding quality and deterioration of riding quality over time on economic models.
- Analysis of the effect of construction and maintenance quality control using local maintenance options and their effects on the riding quality of roads should be evaluated to enable appropriate control levels to be determined.
- The effects of riding quality bonus-penalty schemes, and the effect of initial riding quality on the long-term performance of local roads should be incorporated into an overall transportation infrastructure model.
- Further studies on the damage determination of transported agricultural produce at a range of frequencies caused by various riding quality/truck combinations using laboratory-based bulk density measurements should be conducted (similar to the tomato tests discussed in this report).

- The pilot study should be expanded to cover more districts or corridors with complete coverage of the potential VOCs, freight damage, and environmental effects for at least a full additional district. This may include expansion of freight damage to other types of freight and more detailed freight damage relationships, and incorporation of pavement construction and maintenance quality control implications/effects of maintenance to specific levels of riding quality on larger economic outcome.
- The effect of recent technology advances such as the use of lower rolling resistance tires in the VOC and freight damage equations should be investigated.
- •A more detailed analysis of environmental/emissions effects should be investigated because these are only very briefly touched on in the pilot study. Sustainability aspects also warrant investigation.

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