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Freight-Truck-Pavement Interaction, Logistics, and Economics: Final Phase 1 Report (Tasks 7–8)

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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

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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 is to enable Caltrans to better manage the risks of decisions about 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 7 and 8
- Analyze data collected for Companies A and B
- Compare vehicle and freight data with riding quality

Conclusions

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

- The TruckSIM™ simulations provided reasonable estimates of the expected tire loads and vertical accelerations of the two trucks used in the simulations.
- The trends observed for the TruckSIM™ simulation data were similar to published and expected trends, and it appears as if the data can thus be used to model roads and vehicles where data cannot be collected on roads using real trucks.
- The measured data obtained from the two trucks on the various roads were consistent with expected trends in published literature.
- Measured data were used to analyze trends on the effects of riding quality on speeds, as well as the effect of unique features such as concrete slabs on the generated vertical accelerations in the vehicles.
- A high-level comparison between the simulated and measured data indicated similar trends and similar data obtained from the two processes.
- Matching locations exactly between the simulated and measured data proved to be complicated, but reasonable location comparisons could be obtained.
- If exact location comparisons and vehicle conditions (load, inflation pressure, suspension stiffness, etc.) could be obtained, the match between the two sets of data could be improved further.

Recommendations

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

- TruckSIM™ simulations should be incorporated into any further studies of this kind to enable a cost-effective option of generating realistic vehicle parameters (accelerations, tire loads, etc.) for a wide array of roads in California.
- Additional measurements of densification of tomatoes on trailers during transportation on a range of roads causing a range of vertical acceleration frequencies should be obtained to enable a detailed analysis of the potential damage to the transported tomatoes.
- The data measured and simulated for Tasks 7 and 8 should be incorporated into the methodologies for Tasks 9 to 11 to ensure that the map of road conditions and relationship for riding quality and tire loads/freight accelerations is realistic in terms of typical California data.

Keywords: vehicle-pavement interaction, pavement roughness

Proposals for Implementation:

This final Phase 2 report will be studied by the client and decisions regarding the remainder tasks of the project will be based on the outcome of this report.

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 and L. du Plessis. 2013. Freight-Truck-Pavement Interaction, Logistics, & Economics: Final Phase 1 Report (Tasks 9–11). Research Report prepared for Caltrans Division of Transportation Planning. (UCPRC-RR-2014-01)
- 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)

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TABLE OF CONTENTS

LIST OF FIGURES ..... **v**
LIST OF TABLES ..... **viii**
DISCLAIMER STATEMENT ..... **ix**
ACKNOWLEDGMENTS ..... **ix**
PROJECT OBJECTIVES ..... **x**
EXECUTIVE SUMMARY ..... **xi**
LIST OF ABBREVIATIONS ..... **xiv**
1 INTRODUCTION **1**
1.1 Introduction 1
1.2 Background 3
1.3 Scope 3
1.4 Objectives 6
1.5 Companies Used 6
1.6 Units 7
2 TASK 7—SIMULATION **9**
2.1 Introduction 9
2.2 Vehicle-Pavement Simulation 9
2.3 Vehicle Models 9
2.4 Pavement Models 10
2.5 Simulation Parameters 16
2.6 Simulation Data 16
2.6.1 Tire Load/Axle Load versus Distance 17
2.6.2 Tire Load/Axle Load Histogram 22
2.6.3 Vertical Acceleration versus. Distance 26
2.7 Summary 30
3 TASK 8—MEASUREMENTS **31**
3.1 Introduction 31
3.2 Field Measurement Methodology 31
3.3 Company A 32
3.3.1 Background 32
3.3.2 Trucks 32
3.3.3 Routes 34

3.3.4 Freight 35
3.3.5 Logistics 36
3.3.6 Company A Measurements 36
3.3.7 Summary—Company A 44
3.4 Company B 44
3.4.1 Background 44
3.4.2 Trucks 44
3.4.3 Routes 46
3.4.4 Freight 46
3.4.5 Logistics 46
3.4.6 Company B Measurements 46
3.4.7 Summary—Company B 51
3.5 Summary 51
4 DISCUSSION 53
4.1 Introduction 53
4.2 Data Comparison 53
4.2.1 Introduction 53
4.2.2 Acceleration Data 53
4.3 Data as Input to Tasks 9, 10, and 11 58
4.3.1 Introduction 58
4.3.2 Task 9 58
4.3.3 Task 10 59
4.3.4 Task 11 60
4.3.5 Other Analyses 60
4.4 Potential Economic Analysis Impacts 62
4.5 Summary 62
5 CONCLUSIONS AND RECOMMENDATIONS 63
5.1 Conclusions 63
5.2 Recommendations 63
REFERENCES 65

LIST OF FIGURES

Figure 1.1: Schematic layout and linkages between project tasks. 5
Figure 2.1: Road section location for Company B simulations. 11
Figure 2.2: ProVal analysis outputs for Company A road sections—riding quality. 13
Figure 2.3: ProVal analysis outputs for Company B road sections—riding quality. 13
Figure 2.4: ProVal analysis outputs for Company A road sections—spectral analysis. 14
Figure 2.5: ProVal analysis outputs for Company B road sections—spectral analysis. 14
Figure 2.6: Axle and axle group loads for Company A—steer axle. 19
Figure 2.7: Axle and axle group loads for Company A—drive axle. 19
Figure 2.8: Axle and axle group loads for Company A—trail axle. 20
Figure 2.9: Standard deviation of axle loads for Company A. 20
Figure 2.10: Axle and axle group loads for Company B—steer axle. 21
Figure 2.11: Axle and axle group loads for Company B—drive axle. 21
Figure 2.12: Axle and axle group loads for Company B—trail axle. 22
Figure 2.13: Standard deviation of axle loads for Company B. 22
Figure 2.14: Steer axle load distribution for Company A. 23
Figure 2.15: Drive axle load distribution for Company A. 23
Figure 2.16: Trail axle load distribution for Company A. 24
Figure 2.17: Steer axle load distribution for Company B. 24
Figure 2.18: Drive axle load distribution for Company B. 25
Figure 2.19: Trail axle load distribution for Company B. 25
Figure 2.20: Vertical acceleration over simulation section distance for Company A—location 1. 26
Figure 2.21: Vertical acceleration over simulation section distance for Company A—location 5. 26
Figure 2.22: Vertical acceleration distribution for Company A—location 1. 27
Figure 2.23: Vertical acceleration distribution for Company A—location 5. 27
Figure 2.24: Vertical acceleration over simulation section distance for Company B—location 1. 28
Figure 2.25: Vertical acceleration over simulation section distance for Company B—location 6. 28
Figure 2.26: Vertical acceleration distribution for Company B—location 1. 29
Figure 2.27: Vertical acceleration distribution for Company B—location 6. 29
Figure 3.1: Accelerometer used for collecting acceleration data from trucks and freight. 32
Figure 3.2: Typical Company A truck used for tomato transport. 33
Figure 3.3: Typical Company A Truck details *(3)*. 33

Figure 3.4: Company A trailer suspension. 34
Figure 3.5: Location of sensors on Company A truck for field work (body and freight in one combined figure).34
Figure 3.6: Typical tomato freight for Company A. 35
Figure 3.7: Typical Company A routes. 36
Figure 3.8: Typical accelerometer outputs. 37
Figure 3.9: Typical accelerometer outputs—top and bottom of trailer. 37
Figure 3.10: Typical PSD analysis output based on accelerometer data. 38
Figure 3.11: Typical accelerometer data and road conditions. 39
Figure 3.12: Typical accelerometer data and road conditions. 39
Figure 3.13: Typical accelerometer outputs—Company A, full truck. 40
Figure 3.14: Typical accelerometer outputs—Company A, empty truck. 40
Figure 3.15: Vertical acceleration distribution for empty conditions—Company A, drive axle. 41
Figure 3.16: Vertical acceleration distribution for full conditions—Company A, drive axle. 41
Figure 3.17: Vertical acceleration distribution for empty conditions—Company A, trailer 2, front axle. 42
Figure 3.18: Vertical acceleration distribution for full conditions—Company A, trailer 2, front axle. 42
Figure 3.19: Relationship between truck speed and riding quality—Companies A and B data. 43
Figure 3.20: Comparison between slab length frequency and frequency range on Company A truck and trailer. 44
Figure 3.21: Typical Company B truck. 45
Figure 3.22: Typical Company B truck details *(3)*. 45
Figure 3.23: Company B accelerometer detail. 46
Figure 3.24: Routes—Company B. 47
Figure 3.25: Half-laden freight for Company B. 47
Figure 3.26: Company B accelerometer output detail. 48
Figure 3.27: Company B PSD analysis output detail. 49
Figure 3.28: Company B severity output detail. 49
Figure 3.29: Company B accelerometer output detail. 50
Figure 3.30: Company B PSD and severity output detail for selected locations. 50
Figure 3.31: Relationship between truck speed and riding quality—Companies A and B data. 51
Figure 4.1: Vertical acceleration distribution for Company A, empty drive and trail axles. 54
Figure 4.2: Vertical acceleration distribution for Company A, full drive and trail axles. 54
Figure 4.3: Vertical acceleration for Road 1, Tasks 7 and 8 data, drive and trail axles. 55
Figure 4.4: Vertical acceleration for HM road, Tasks 7 and 8 data, drive and trail axles. 55

Figure 4.5: Vertical acceleration for L road, Tasks 7 and 8 data, drive and trail axles. 56
Figure 4.6: Vertical acceleration distribution for Company B, drive and trail axles. 56
Figure 4.7: Vertical acceleration for Road 17N02X00, Tasks 7 and 8 data, drive and trail axles. 57
Figure 4.8: Vertical acceleration for 1450J800, Tasks 7 and 8 data, drive and trail axles.................................... 57
Figure 4.9: Vertical acceleration for 1490B800, Tasks 7 and 8 data, drive and trail axles................................... 58
Figure 4.10: Example of a potential map showing roughness class levels. 59
Figure 4.11: Visual indication of densification of tomato cargo during transport.. 61

LIST OF TABLES

Table 1.1: Task Description for Project 4
Table 2.1: Vehicle Details Used in TruckSIM Model for Companies A and B 10
Table 2.2: Road Section Statistics for Company A Simulations 11
Table 2.3: Road Section Statistics for Company B Simulations 12
Table 2.4: ProVal Analysis Outputs for Company A Road Sections—Riding Quality 15
Table 2.5: ProVal Analysis Outputs for Company B Road Sections—Riding Quality 15
Table 2.6: ProVal Analysis Outputs for Company A Road Sections—Spectral Analysis 15
Table 2.7: ProVal Analysis Outputs for Company B Road Sections—Spectral Analysis 16
Table 2.8: Primary Simulation Parameters and Locations Used for Company A TruckSIM Analyses 16
Table 2.9: Primary Simulation Parameters and Locations Used for Company B TruckSIM Analyses 16
Table 2.10: Summary Statistics for Company A TruckSIM Simulations 18
Table 2.11: Summary Statistics for Company B TruckSIM Simulations 18
Table 3.1:Truck Type Used by Company A 33
Table 3.2:Company A—Empty Route Details 35
Table 3.3:Company A—Full Route Details 35
Table 3.4:Detail on Typical Company B Vehicle 45

DISCLAIMER STATEMENT

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- DOTP Economic Analysis Branch staff: Rose Agacer, Barry Padilla, and Austin Hicks
- Division of Research, Innovation, and System Information (DRISI), Office of Materials and Infrastructure: Joe Holland and Bill Nokes

PROJECT OBJECTIVES

The overall objectives of this project are to enable Caltrans to better manage the risks of decisions about 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 7 and 8
- Analyze data collected for Companies A and B
- Compare vehicle and freight data with riding quality

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 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 pilot study is not focusing 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 or district. It is anticipated that use of findings from this study as input by others into planning and economic models will enable calculation of 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 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.

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 will be conducted as a pilot study in a region/Caltrans district where the probability of collecting the maximum data on road quality, vehicle population, and operational conditions will be the highest, and where the outcomes of the study may be incorporated into economic and planning models. The final selection of the region/district will be made based on information collected during Tasks 3 to 5—the final selection of an appropriate region/district will be made by Caltrans. 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.

The overall objectives of this project are to enable Caltrans to better manage the risks of decisions about 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-PIV-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 for a specific region or Caltrans district.

The objectives of this report are to provide information on Tasks 7 and 8.

Report Issues

The purpose of this pilot study is to provide data and information that will provide input that supports Caltrans' freight program plans and the legislation 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 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.

This report focuses on the simulation of truck travel over selected road sections to evaluate the effect of riding quality on the tire loads and vertical accelerations inside the vehicle and freight. Two trucks were simulated (Companies A and B) transporting two types of cargo over a mostly interstate and state highway network. Data obtained from the simulations were compared to data collected during two road trips with the two companies. Comparisons showed reasonable data from both the simulations and field measurements, with generally published trends being followed by all data.

Conclusions

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

Task 7

- The TruckSIM™ simulations provided reasonable estimates of the expected tire loads and vertical accelerations of the two trucks used in the simulations.
- The trends observed for the TruckSIM™ simulation data were similar to published and expected trends, and it appears as if the data can thus be used to model roads and vehicles where data cannot be collected on roads using real trucks.

Task 8

- The measured data obtained from the two trucks on the various roads were consistent with expected trends in published literature.
- Measured data were used to analyze trends on the effects of riding quality on speeds, as well as the effect of unique features such as concrete slabs on the generated vertical accelerations in the vehicles.

Data Comparison

- A high-level comparison between the simulated and measured data indicated similar trends and similar data obtained from the two processes.
- Matching locations exactly between the simulated and measured data proved to be complicated, but reasonable location comparisons could be obtained.
- If exact location comparisons and vehicle conditions (load, inflation pressure, suspension stiffness, etc.) could be obtained, the match between the two sets of data could be improved further.

Recommendations

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

- *Task 7.* TruckSIM™ simulations should be incorporated into any further studies of this kind to enable a cost-effective option of generating realistic vehicle parameters (accelerations, tire loads, etc.) for a wide array of roads in California.
- *Task 8*. Additional measurements of densification of tomatoes on trailers during transportation on a range of roads causing a range of vertical acceleration frequencies should be obtained to enable a detailed analysis of the potential damage to the transported tomatoes.
- *Other*. The data measured and simulated for Tasks 7 and 8 should be incorporated into the methodologies for Tasks 9 to 11 to ensure that the map of road conditions and relationship for riding quality and tire loads/freight accelerations are realistic in terms of typical California data.

LIST OF ABBREVIATIONS

CIB/CTP	California Interregional Blueprint/Transportation Plan
CoG	Center of gravity
CoV	Coefficient of variation
DOTP	Division of Transportation Planning
DRISI	Division of Research, Innovation, and System Information
FHWA	Federal Highway Administration
GHG	Greenhouse gas
GMAP	Goods Movement Action Plan
GPS	Global Positioning System
IRI	International Roughness Index
LTL	Less than truckload
PMS	Pavement Management System
PPRC	Partnered Pavement Research Center
PSD	Power spectral density
SCAG	Southern California Association of Governments
SHS	State Highway System
TL	Truckload
UCPRC	UC Pavement Research Center
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 section is repeated from Report UCPRC-RR-2012-06 *(1)* to ensure that the context of the project remains clear in all subreports of the project.

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 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, 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 made 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 investigating 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 South African State of Logistics studies or 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 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. 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 require 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 the San Joaquin Valley and Reno-to-San Francisco I-80 corridor, where ample and reliable data could be obtained from active companies traveling the routes and willing to participate in the study. 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.

An augmented phase has been approved to run together with the initial study. The focus of the project augmentation is on specific logistics aspects identified during the Tasks 1-to-6 phase of the project. Reporting on the logistics study is done independently from these reports, and a final coordinated report will be provided where the outcomes of the two studies are detailed.

Table 1.1: Task Description for Project

Task description	Deliverable/Outcome	Timeframe
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

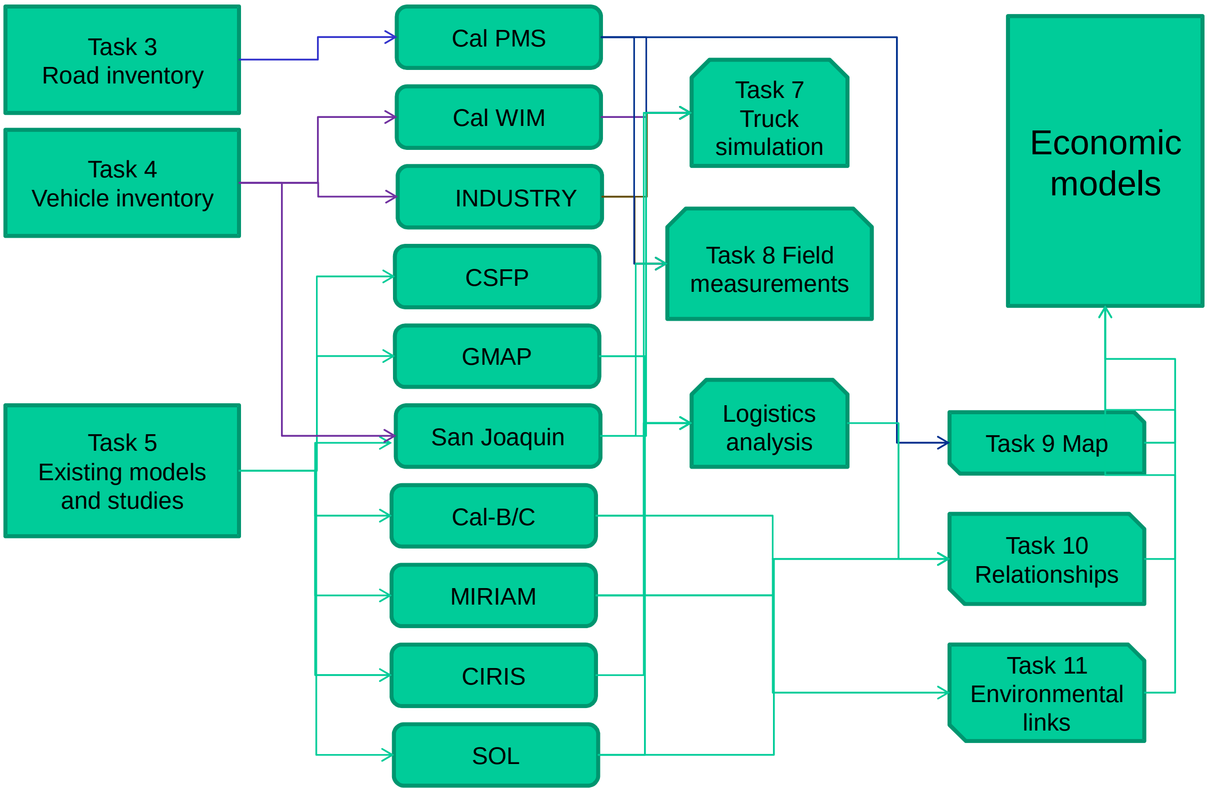

Figure 1.1: Schematic layout and linkages between project tasks.

The detailed scope of this report is:

- Summary of the project background
- Reporting on Tasks 7 and 8

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 (those focusing on shipping, cargo handling, logistics management, and associated private firms), which 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 includes transporting freight over public highways that the firm does not own, operate, or maintain—unlike its truck fleet—but on which its business survival depends. Not performing this pilot study would 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 sane district or even within the state, although the shipper earning revenue from the transport is based 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 about 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 for a specific region or Caltrans district.

The objectives of this report are to:

- Provide information on Tasks 7 and 8
- Analyze data collected for Companies A and B
- Compare vehicle and freight data with riding quality

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 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 LTL (less than truckload) shipments between the United States and Canada, domestic U.S. LTL shipments, and TL (truckload) shipments from Canada to the United States.

To protect the confidentiality of the information, pseudonymous 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 Units

In the report, use is made of dual units where possible. Typically, metric units are shown with customary U.S. units in brackets. Some of the road data were provided in metric units (i.e., 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.

2 TASK 7—SIMULATION

2.1 Introduction

This section provides information on the work conducted on Task 7. Task 7 focused on the simulation of a selection of California trucks on selected routes/segments to serve as generator of data for the study. 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, and to conduct the analysis on these routes to enable comparison with the data collected in Task 8.

Logistically, the project was conducted to do the Task 8 measurements first. before the simulations were conducted. This was due to the availability of agricultural trucks during the September harvest season for truck measurements. This allowed the Task 8 measurements to be conducted before the Task 7 simulations, enabling a selection of similar sections for the analyses.

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.

2.2 Vehicle-Pavement Simulation

A detailed background to vehicle-pavement interaction (V-PI) principles and V-PI simulations were provided in Steyn *(2)*; this is not repeated in detail in this report. In summary, a calibrated simulation package (TruckSIM^{TM}) is used to model the truck and allow it to operate at selected speeds and loads on the selected road profile (measured in the field). The simulation allows the calculation of various parameters, of which tire loads and accelerations at selected locations in the vehicle are primary for this report.

2.3 Vehicle Models

Two vehicle models were used in the analyses. These are similar to the vehicles used by Companies A and B on their respective routes. Details of the two vehicles are summarized in Table 2.1.

Table 2.1: Vehicle Details Used in TruckSIM Model for Companies A and B

	Company A	Company B
Vehicle type	CA Legal Double Type 11 (2S1-2)	STAA 48 feet (STAA Truck Tractor—Semitrailer), FHWA Class 9
Tare	Not available	16,300 kg (36,000 lb)
100% load	40,000 kg (88,000 lb)	20,000 kg (44,000 lb)
Typical load (estimate of % of 100% full)	100%	70%
(TT track width	2.5 m (8.2 ft)	2.5 m (8.2 ft)
TT suspension type	Air	Air
TT tire type	Single steer, dual drive 11R22.5	Single steer, dual-drive 275/80 R22.5
TT tire inflation pressure	760 kPa (110 PSI)	760 kPa (110 psi)
T track width	2.6 m (8.6 ft)	2.6 m (8.6 ft)
T suspension type	Steel	Steel
T tire type	Dual 11R22.5	Dual 275/80 R22.5
T tire inflation pressure	620 kPa (90 psi)	620 kPa (90 psi)
Axle Distances (Center of Tire to Center of Next Tire) for Whole Vehicle		
Axle 1–Axle 2	3.6 m (11 ft 10 in.)	3.6 m (11 ft 10 in.)
Axle 2–Axle 3	8.8 m (29 ft 10 in.)	1.3 m (4 ft 5 in.)
Axle 3–Axle 4	5.8 m (19 ft 8 in.)	10.2 m (33 ft 5 in.)
Axle 4–Axle 5	8.8 m (29 ft 10 in.)	1.2 m (4 ft 1 in.)

Note: TT = Truck tractor; T = Trailer.

2.4 Pavement Models

Road sections for the simulation were selected from the routes that the two companies' vehicles traveled during Task 8. A selection was made of representative sections with low, medium, and high road roughness. The locations of the three road sections used in the TruckSIM™ analysis for Company B are shown in Figure 2.1. The statistics of all available road sections, as well as those selected for the simulations are shown in Table 2.2 (Company A) and Table 2.3 (Company B).

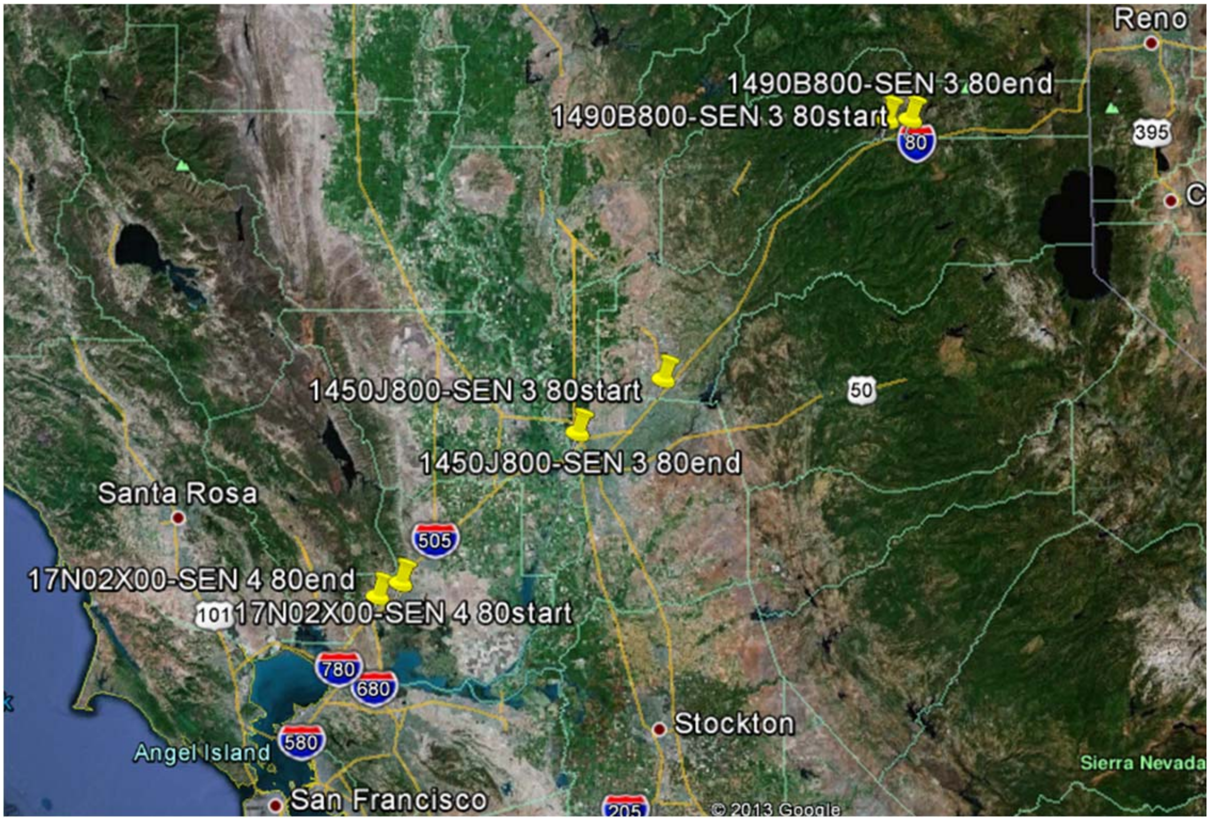

Figure 2.1: Road section location for Company B simulations.
(Note: Image from Google Earth™.)

Table 2.2: Road Section Statistics for Company A Simulations

Road Name	**Location (km post)**	**Average IRI (m/km) [inch/mile]**
1E Outbound	7,000 – 8,000	0.90 [57]
1W Inbound	1,000 – 2,000	0.87 [55]
HM Road Inbound	8,000 – 9,000	2.13 [134]
HM Road Outbound	9,000 – 10,000	1.99 [125]
L Road Inbound	0 – 1,000	5.07 [319]
L Road Outbound	1,000 – 2,000	4.50 [284]

Table 2.3: Road Section Statistics for Company B Simulations

File Name	Road Number	Location (km post)	Average IRI (m/km) [in./mile]
17N02X00	I80, D4, SOL	2,000 – 3,000	0.61 [38]
1450J800	I80, D3, SAC	3,000 – 4,000	2.17 [137]
1490B800	I80, D3, NEV	5,000 – 6,000	5.05 [318]

The selected road sections were analyzed using ProVal to evaluate the riding quality in terms of the International Roughness Index (IRI) as well as dominant wavelengths (from spectral analysis) in the profiles. The outcome of these analyses are shown below for Company A (in Figure 2.2 and Figure 2.4, and in Table 2.4 and Table 2.6) and for Company B (in Figure 2.3 and Figure 2.5, and in Table 2.5 and Table 2.7).

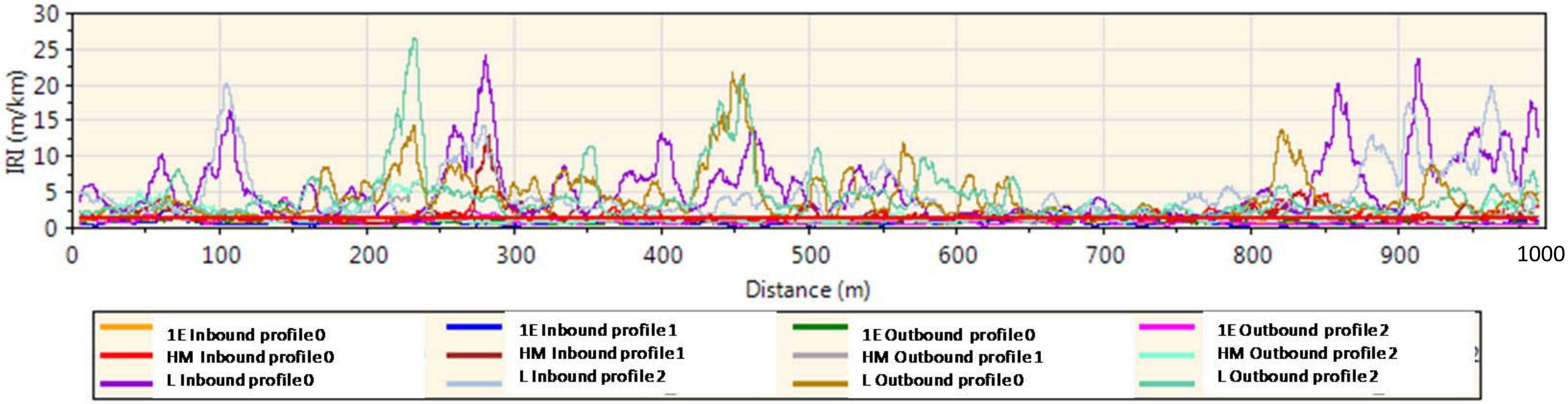

Figure 2.2: ProVal analysis outputs for Company A road sections−riding quality.

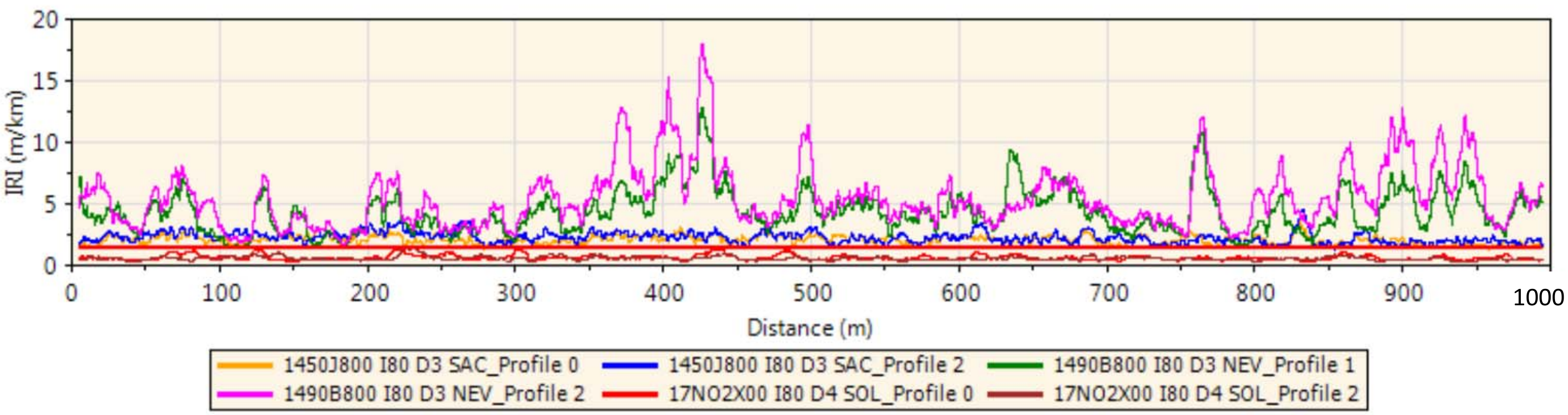

Figure 2.3: ProVal analysis outputs for Company B road sections−riding quality.

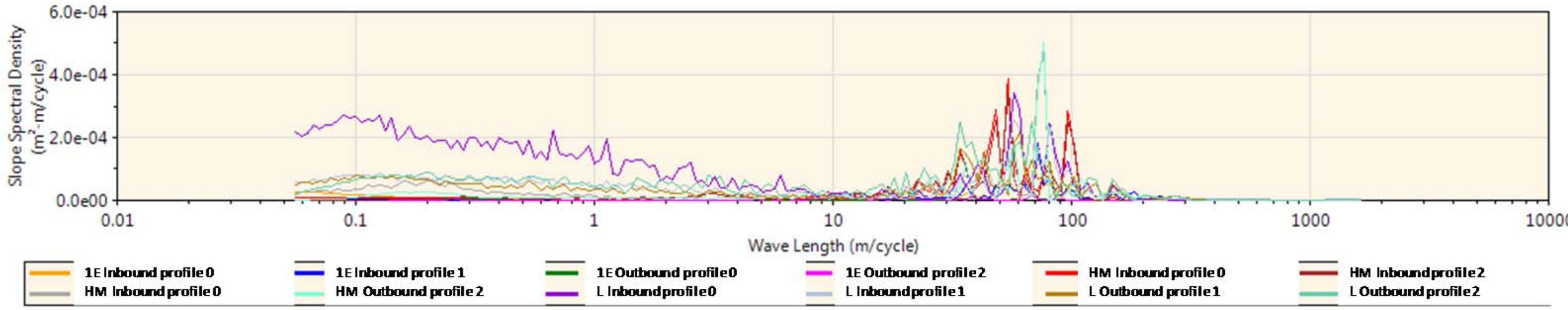

Figure 2.4: ProVal analysis outputs for Company A road sections—spectral analysis.

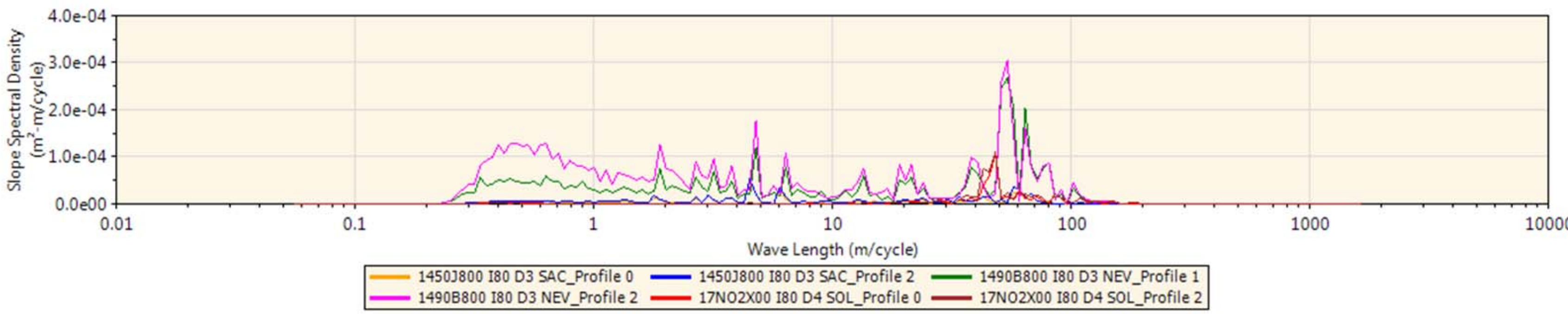

Figure 2.5: ProVal analysis outputs for Company B road sections—spectral analysis.

Table 2.4: ProVal Analysis Outputs for Company A Road Sections−Riding Quality

	1E Inbound	1E Outbound	HM Inbound	HM Outbound	L Inbound	L Outbound
Minimum (m/km)[in./mi]	0.3 [19]	0.3 [19]	0.5 [32]	0.4 [25]	1.0 [63]	0.8 [50]
Average (m/km) [in./mi]	0.8	0.9 [57]	1.9 [120]	1.7 [107]	5.1 [321]	4.4 [277]
90th percentile (m/km) [in./mi]	1.3 [82]	1.3 [82]	2.9 [183]	3.1 [195]	10.6 [668]	8.2 [517]
Maximum (m/km) [in./mi]	3.2 [202]	4.3 [271]	12.9 [813]	7.2 [454]	24.1 [1,518	26.5 [1,670]
Standard deviation (m/km) [in./mi]	0.4 [25]	0.4 [25]	1.2 [76]	1.1 [69]	3.9 [246]	3.4 [214]
Coefficient of variation (%)	52%	47%	65%	65%	78%	77%

Table 2.5: ProVal Analysis Outputs for Company B Road Sections−Riding Quality

	1450J800 I80 D3 SAC	1490B800 I80 D3 NEV	17NO2X00 I80 D4 SOL
Minimum (m/km) [in./mi]	1.3 [82]	1.3 [82]	0.3 [19]
Average (m/km) [in./mi]	2.2 [139]	4.9 [309]	0.6 [36]
90th percentile (m/km) [in./mi]	2.7 [170]	7.5 [473]	0.9 [57]
Maximum (m/km) [in./mi]	4.5 [284]	18.0 [1,134	1.5 [95]
Standard deviation (m/km) [in./mi]	0.4 [25]	2.2 [139]	0.2 [13]
Coefficient of variation (%)	18%	45%	31%

Table 2.6: ProVal Analysis Outputs for Company A Road Sections−Spectral Analysis

Dominant wavelengths (m) [ft]	152E Inbound	152E Outbound	Henry M Inbound	Henry M Outbound	Linden Inbound	Linden Outbound
Primary	72 [236]	68 [223]	54 [177]	76 [249]	57 [187]	34 [112]
Secondary	64 [210]	38 [125]	48 [157]	72 [236]	61 [200]	68 [223]
Tertiary	54 [177]	18 [59]	96 [315]	57 [187]	81 [266]	61 [200]

Table 2.7: ProVal Analysis Outputs for Company B Road Sections—Spectral Analysis

Dominant wavelengths (m) [ft]	1450J800 I80 D3 SAC	1490B800 I80 D3 NEV	17NO2X00 I80 D4 SOL
Primary	5 [16]	54 [177]	48 [157]
Secondary	6 [20]	51 [167]	43 [141]
Tertiary	57 [187]	64 [210]	45 [148]

2.5 Simulation Parameters

The simulation parameters selected as primary outputs for the TruckSIM™ simulations are summarized in Table 2.8 (Company A) and Table 2.9 (Company B). These parameters and locations were selected to highlight the primary parameters potentially affected by road roughness changes, as well as the locations at which measurements were done during Task 8.

Table 2.8: Primary Simulation Parameters and Locations Used for Company A TruckSIM Analyses

Simulation parameter	Location
Tire load Axle load	At each of the tires (18 tires) Steer axle, Drive axle, Trailer axle group 1, Trailer axle group 2
Acceleration (vertical)	Steer axle, Drive axle, Trailer axle group 1, Trailer axle group 2

Table 2.9: Primary Simulation Parameters and Locations Used for Company B TruckSIM Analyses

Simulation parameter	Location
Tire load Axle load	At each of the tires (18 tires) Steer axle, Drive axle 1, Trailer axle 1, Trailer axle 2, Trailer axle 3
Acceleration (vertical)	Steer axle, Drive axle 1, Trailer axle 1, Trailer axle 2, Trailer axle 3

2.6 Simulation Data

In this section the following standard analysis outputs are provided for each of the vehicles/simulations:

- Tire load/axle load vs. time/distance
- Tire load/axle load histogram
- Vertical acceleration vs. time/distance
- Vertical acceleration histogram

To keep the data understandable and clear, use is made of summary statistics as far as possible to illustrate the specific relationships. All data are available, and could be accessed for further analysis. However, restatement of all data for each simulation (where simulations were conducted at 0.025 m intervals over 1,000 road lengths) would just clutter the outcome of the analyses.

2.6.1 Tire Load/Axle Load versus Distance

The simulation data statistics are shown in Table 2.10 (Company A) and Table 2.11 (Company B), while the tire/axle load vs. distance data are shown in Figure 2.6 to Figure 2.9 (Company A) and Figure 2.10 to Figure 2.13 (Company B). Analysis of the data focuses on the following:

- Load values and ranges
- Standard deviation and coefficient of variation (CoV)

Load Values and Ranges

The axle loads (Figure 2.6 to Figure 2.8 and Figure 2.10 to Figure 2.12) show standard patterns with variation due to the moving dynamic nature of the loads, as affected by the pavement roughness. Load values are affected by the speed and the load levels of each of the vehicles in the simulations.

Standard Deviation and Coefficient of Variation

The standard deviation and CoV data (Figure 2.9 and Figure 2.13) show the standard outputs with rougher road sections causing higher standard deviation and CoV values for similar speeds and load conditions. The steer axle typically shows lower variability, with the trail axle mainly affected by changes in load level.

Table 2.10: Summary Statistics for Company A TruckSIM Simulations

	Steer Axle					Drive Axle					Trail Axles				
	1E Outbound	1W Inbound	HM Road Outbound	L Road Inbound	L Road Outbound	1E Outbound	1W Inbound	HM Road Outbound	L Road Inbound	L Road Outbound	1E Outbound	1W Inbound	HM Road Outbound	L Road Inbound	L Road Outbound
Minimum (kN) [kip]	27 [6.0]	0 [0]	25 [5.6]	12 [2.6]	0 [0]	0 [0]	26 [5.80]	0 [0]	34 [7.6]	0 [0]	17 [3.7]	50 [11.2]	16 [3.5]	59 [13.3]	7 [1.5]
Average (kN) [kip]	50 [11.2]	23 [5.2]	46 [10.4]	32 [7.1]	25 [5.7]	11 [2.4]	63 [14.2]	11 [2.4]	62 [14.0]	11 [2.3]	54 [9.9]	134 [30.1]	44 [9.8]	117 [26.3]	39 [8.7]
90th percentile (kN) [kip]	54 [12.1]	29 [6.4]	56 [12.5]	40 [9.0]	29 [6.5]	15 [3.3]	69 [15.5]	17 [3.8]	70 [15.6]	18 [4.0]	59 [13.2]	170 [38.2]	59 [13.2]	136 [30.5]	45 [10.2]
Maximum (kN) [kip]	62 [13.9]	42 [9.4]	78 [17.6]	52 [11.7]	51 [11.6]	24 [5.4]	85 [19.0]	46 [10.3]	90 [20.2]	52 [11.6]	122 [27.4]	252 [56.7]	122 [27.5]	195 [43.9]	119 [26.7]
Standard deviation (kN) [kip]	3 [0.7]	5 [1.1]	7 [1.6]	7 [1.5]	4 [0.8]	4 [0.8]	6 [1.4]	5 [1.1]	6 [1.4]	6 [1.4]	10 [2.2]	32 [7.1]	10 [2.3]	17 [3.8]	6 [1.4]
CoV(%)	6%	22%	73%	49%	31%	76%	72%	81%	9%	67%	74%	77%	74%	18%	31%
MRI (m/km) [in./mi]	0.9 [57]	0.87 [55]	1.99 [125]	5.07 [319]	4.50 [284]	0.9 [57]	0.87 [55]	1.99 [125]	5.07 [319]	4.50 [284]	0.9 [57]	0.87 [55]	1.99 [125]	5.07 [319]	4.50 [284]

Note: CoV = coefficient of variation; MRI = mean roughness index.

Table 2.11: Summary Statistics for Company B TruckSIM Simulations

	Steer Axle			Drive Axles			Trail Axles		
	17N02X00	1450J800	1490B800	17N02X00	1450J800	1490B800	17N02X00	1450J800	1490B800
Minimum (kN) [kip]	42 [9.5]	41 [9.3]	0 [0]	87 [19.5]	87 [19.6]	48 [10.8]	65 [14.7]	65 [14.7]	30 [6.7]
Average (kN) [kip]	52 [11.6]	52 [11.6]	51 [11.6]	130 [29.2]	130 [29.2]	130 [29.1]	98 [22.1]	99 [22.2]	98 [22.1]
90th percentile (kN) [kip]	53 [12.0]	55 [12.5]	58 [13.0]	136 [30.6]	147 [33.0]	157 [35.3]	104 [23.3]	113 [25.4]	122 [27.5]
Maximum (kN) [kip]	57 [12.9]	62 [13.8]	77 [17.2]	158 [35.5]	167 [37.6]	200 [45.0]	119 [26.7]	130 [29.2]	159 [35.8]
Standard deviation (kN) [kip]	1 [0.3]	3 [0.7]	6 [1.4]	5 [1.2]	13 [2.9]	22 [4.9]	4 [1.0]	11 [2.4]	19 [4.3]
CoV(%)	3%	6%	12%	4%	10%	17%	4%	11%	20%
MRI (m/km) [in./mi]	0.61 [38]	2.17 [137]	5.05 [318]	0.61 [38]	2.17 [137]	5.05 [318]	0.61 [38]	2.17 [137]	5.05 [318]

Note: CoV = coefficient of variation; MRI = mean roughness index.

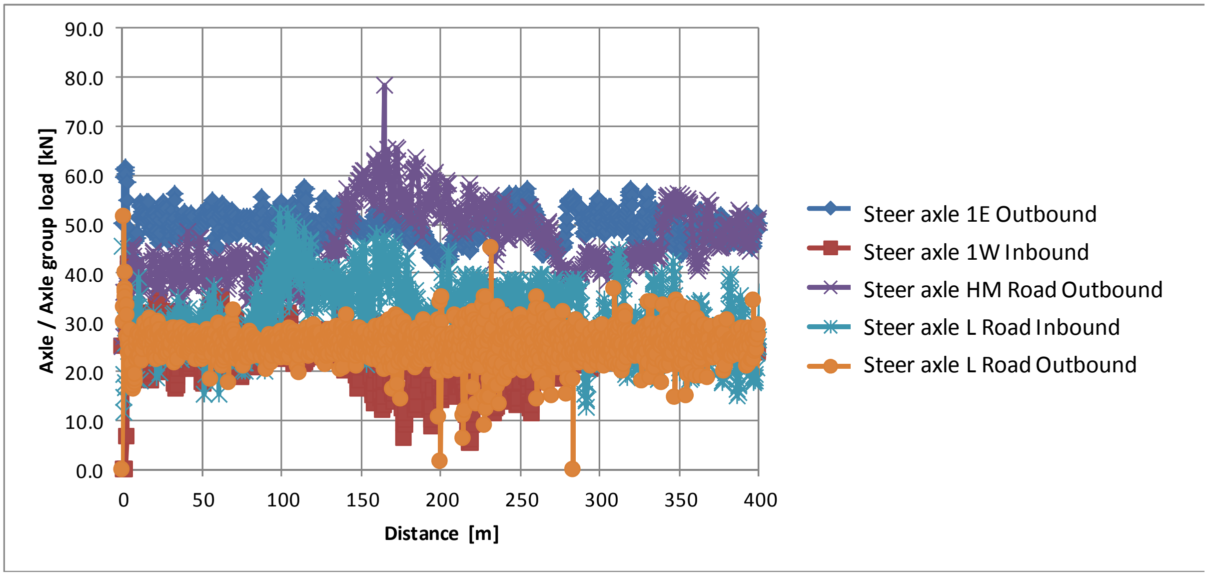

Figure 2.6: Axle and axle group loads for Company A—steer axle.

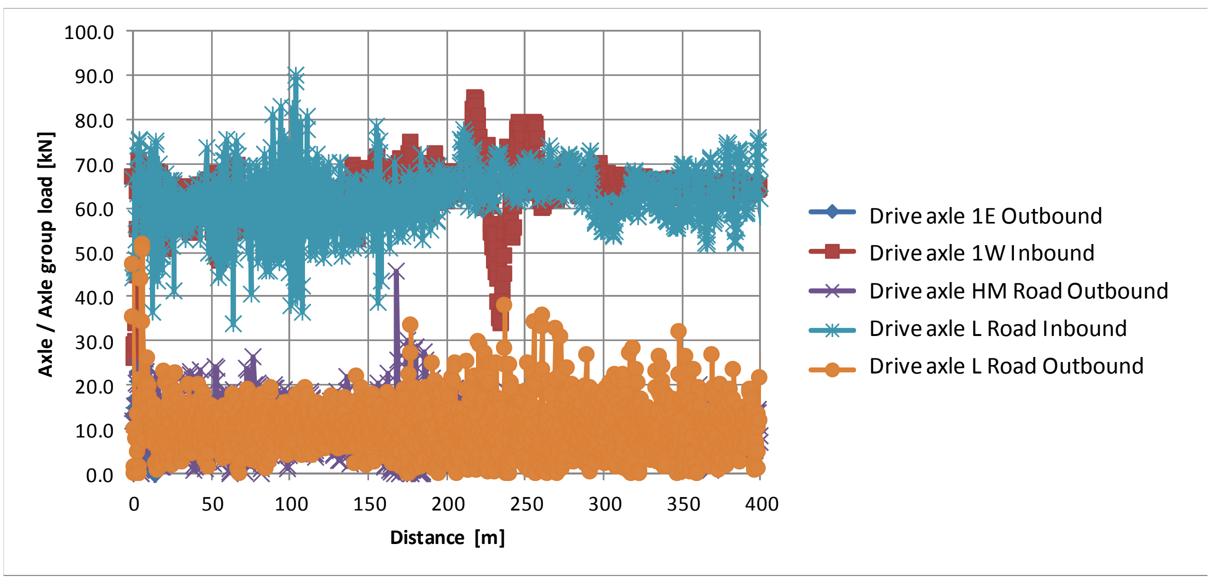

Figure 2.7: Axle and axle group loads for Company A—drive axle.

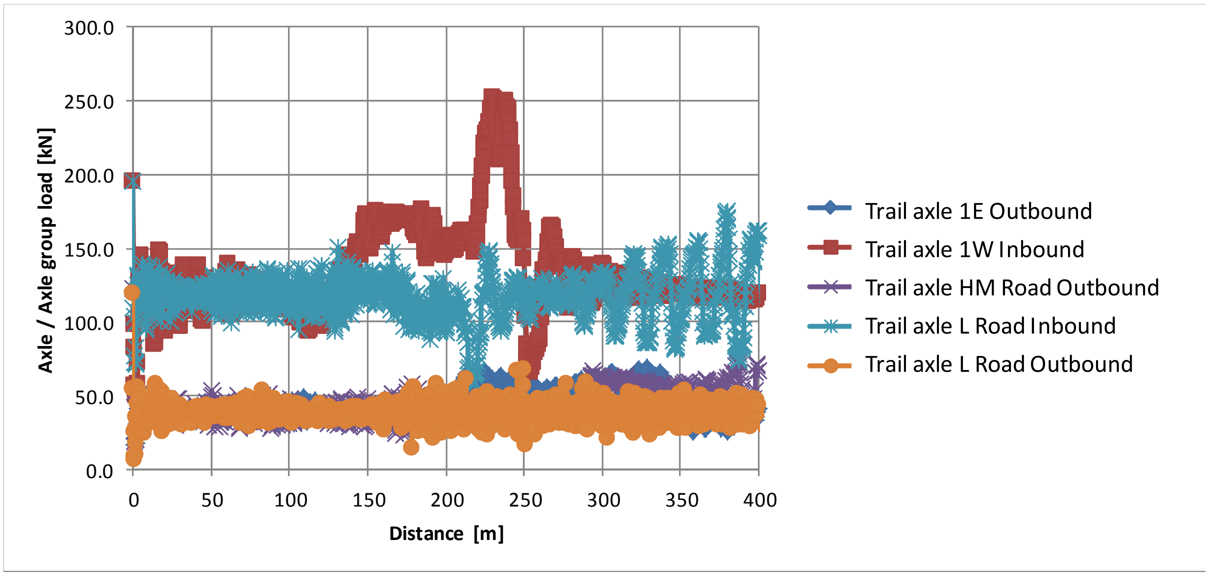

Figure 2.8: Axle and axle group loads for Company A—trail axle.

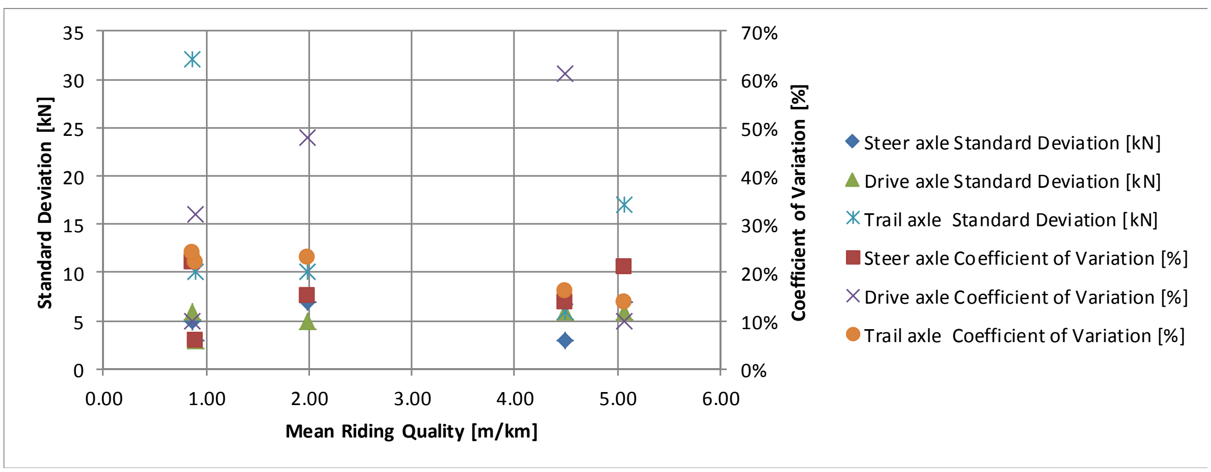

Figure 2.9: Standard deviation of axle loads for Company A.

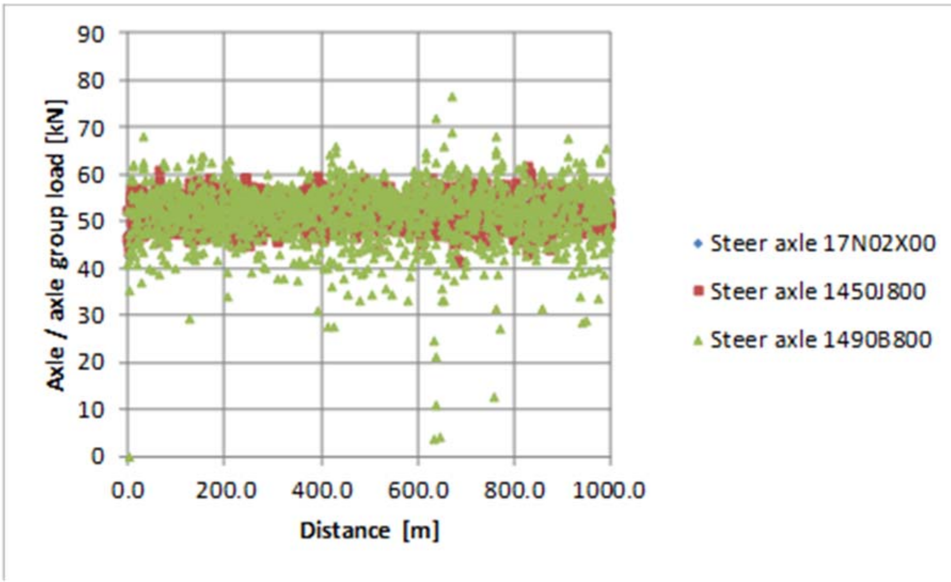

Figure 2.10: Axle and axle group loads for Company B—steer axle.

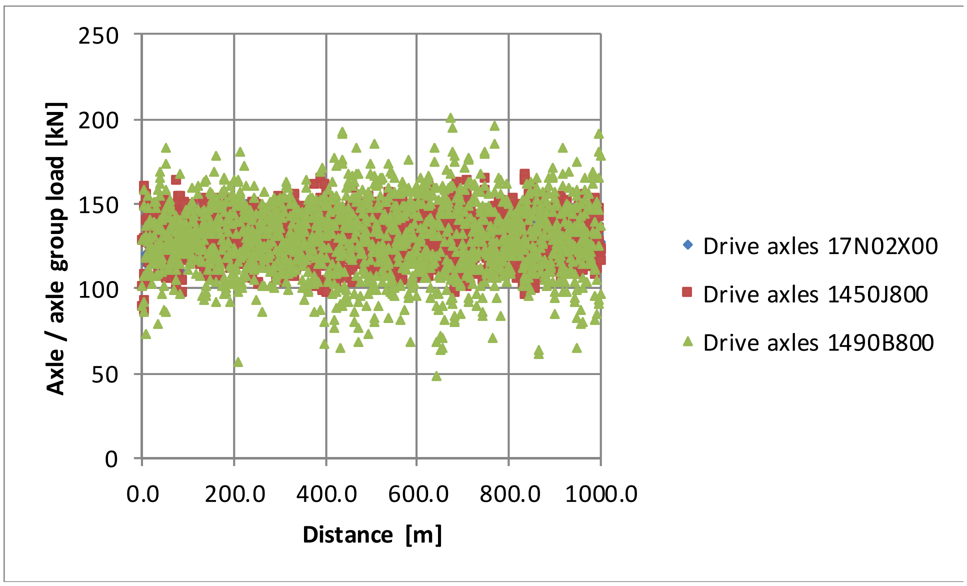

Figure 2.11: Axle and axle group loads for Company B—drive axle.

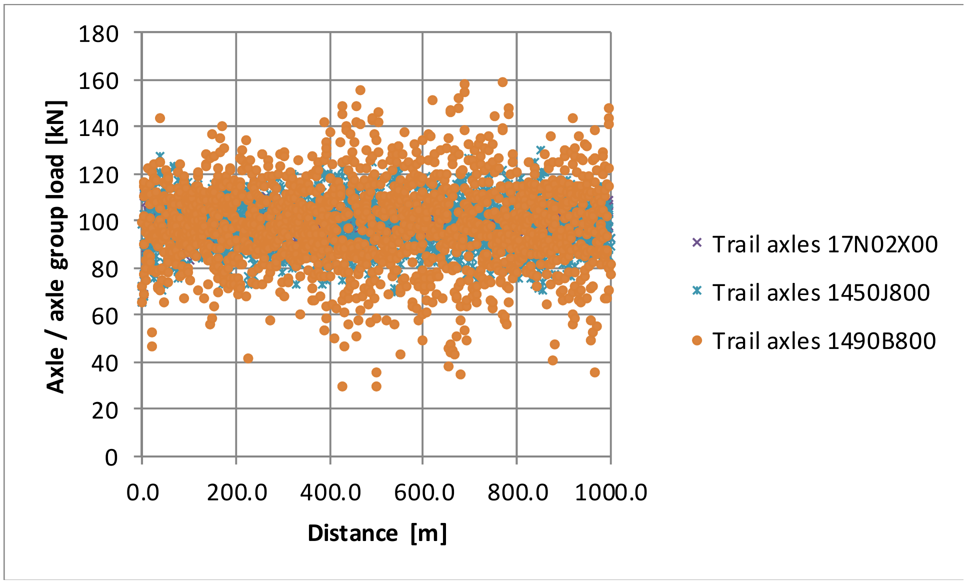

Figure 2.12: Axle and axle group loads for Company B—trail axle.

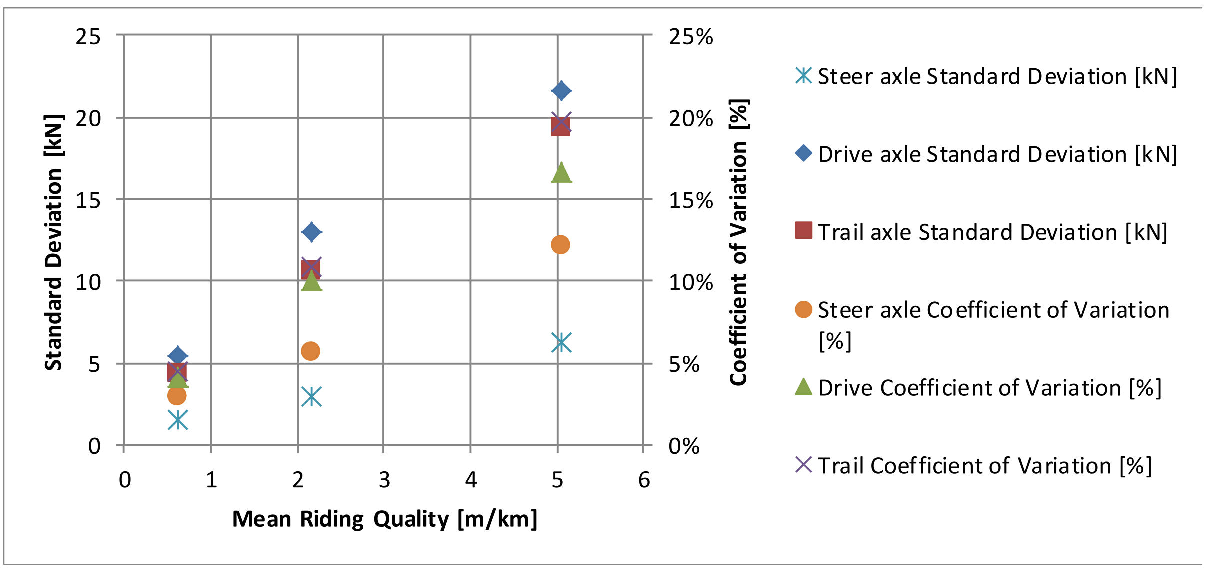

Figure 2.13: Standard deviation of axle loads for Company B.

2.6.2 Tire Load/Axle Load Histogram

The histograms of data originating from the simulation data are shown in Figure 2.14 to Figure 2.16 (Company A) and Figure 2.17 to Figure 2.19 (Company B). The data indicate the typical distribution of axle load values due to the moving dynamic nature of the load, with empty (Outbound) axles showing lower values than full (Inbound) axles. The road with higher roughness (Linden road) typically shows a wider distribution of data.

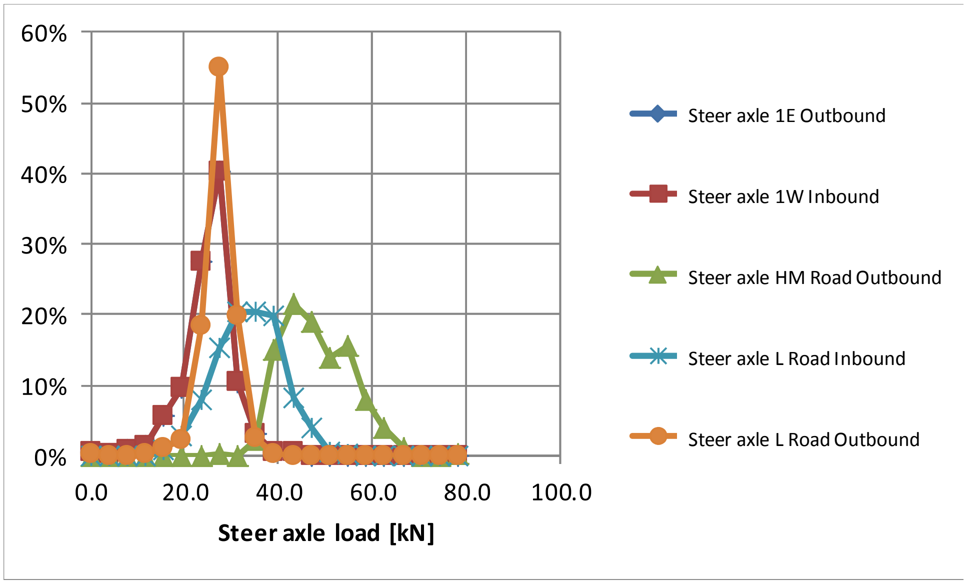

Figure 2.14: Steer axle load distribution for Company A.

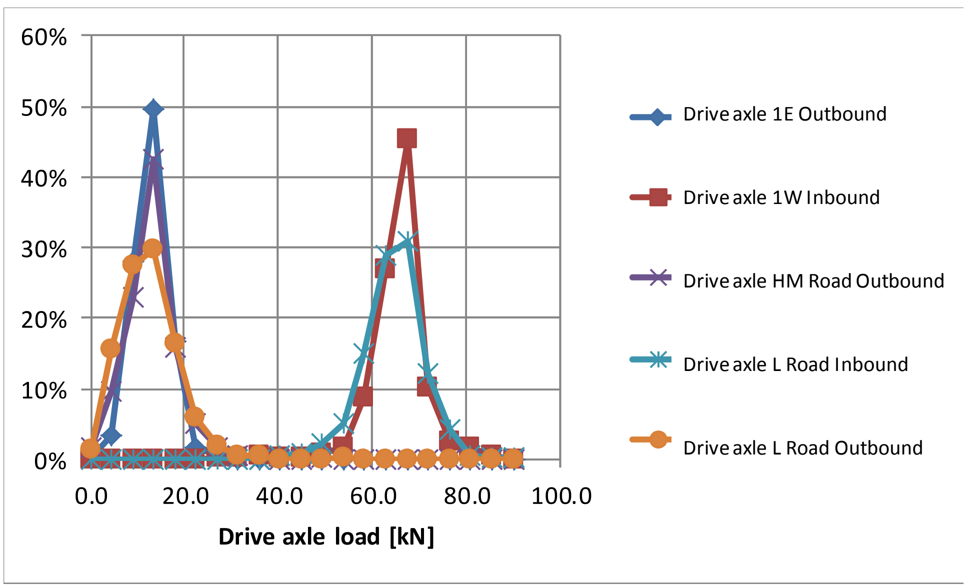

Figure 2.15: Drive axle load distribution for Company A.

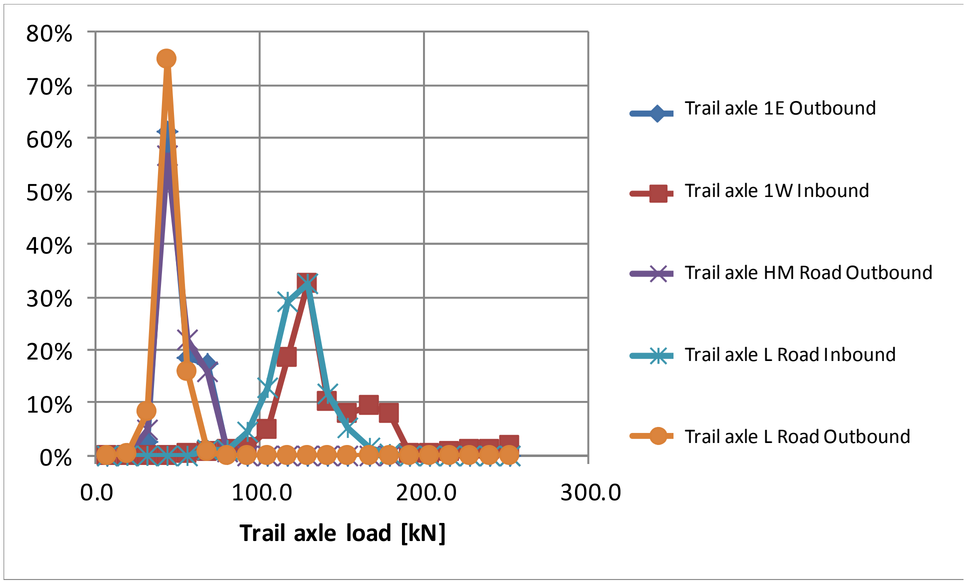

Figure 2.16: Trail axle load distribution for Company A.

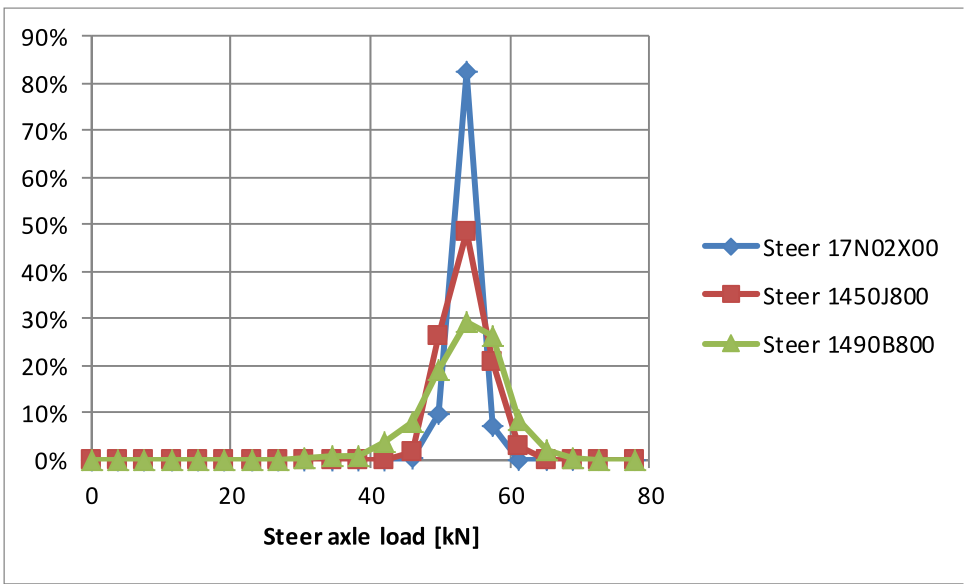

Figure 2.17: Steer axle load distribution for Company B.

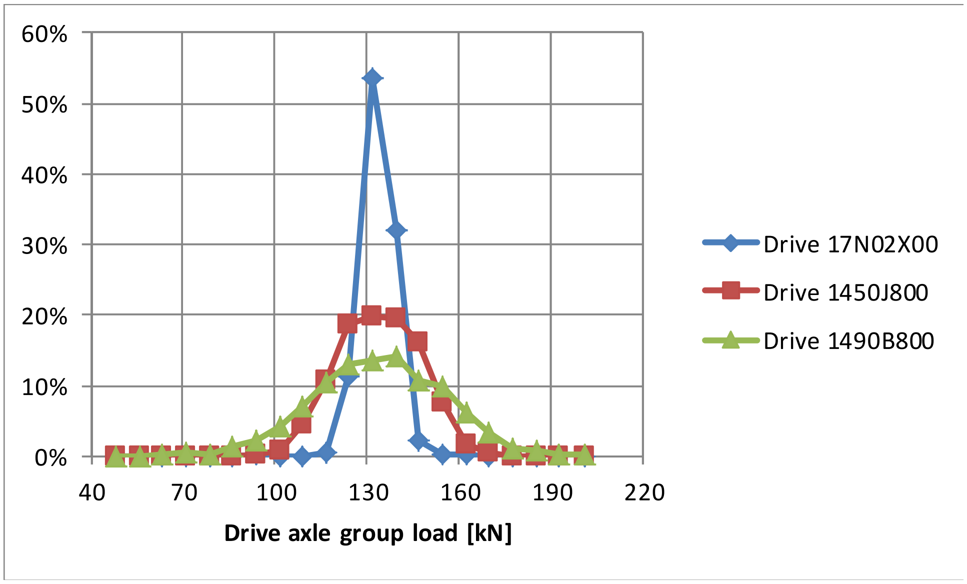

Figure 2.18: Drive axle load distribution for Company B.

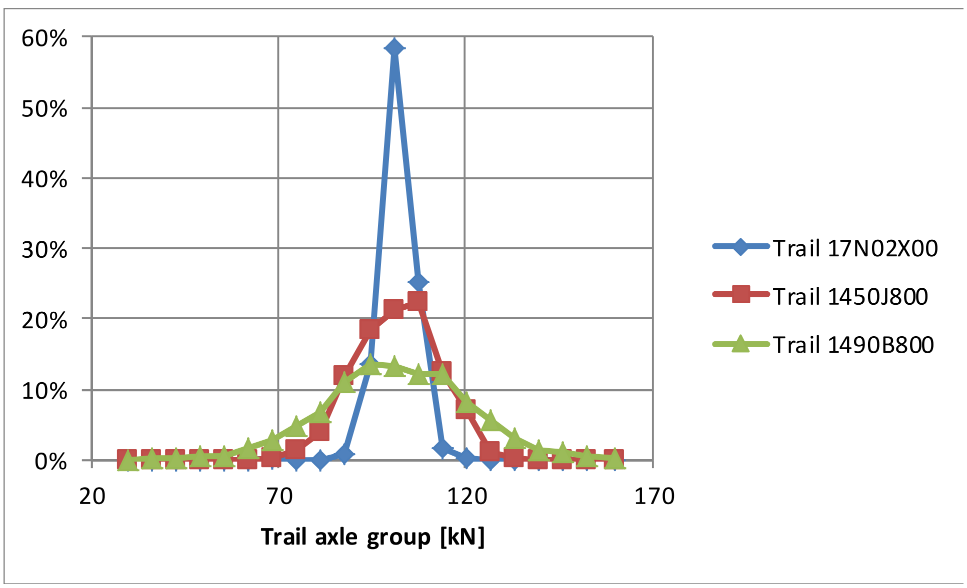

Figure 2.19: Trail axle load distribution for Company B.

2.6.3 *Vertical Acceleration versus Distance*

The vertical acceleration data were simulated for six locations on each of the vehicles (Section 2.3). In this section, two examples of vertical acceleration data are shown for each of Companies A (Figure 2.20 to Figure 2.23) and B (Figure 2.24 to Figure 2.27), and the full dataset discussed.

Analysis of the data in these figures shows the standard effect of roughness on the vertical acceleration data, with the smoother roads showing narrower distributions of accelerations and the rougher road sections showing a higher CoV and distribution of vertical acceleration data.

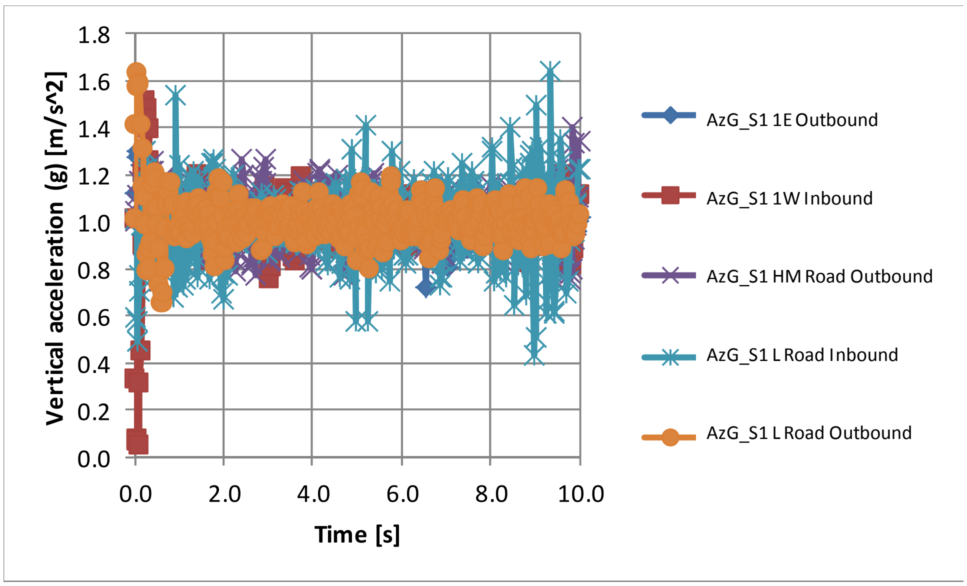

Figure 2.20: Vertical acceleration over simulation section distance for Company A—location 1.

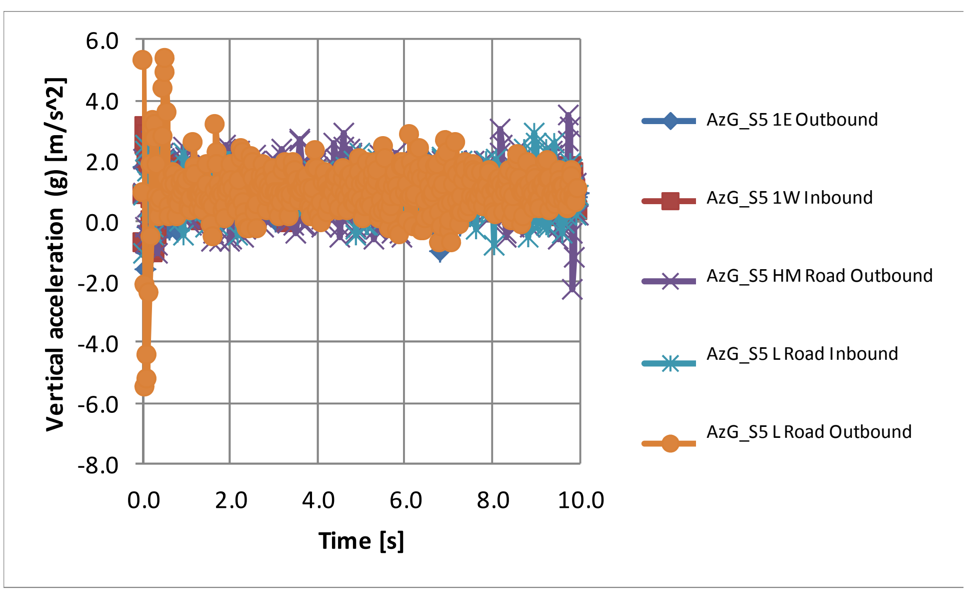

Figure 2.21: Vertical acceleration over simulation section distance for Company A—location 5.

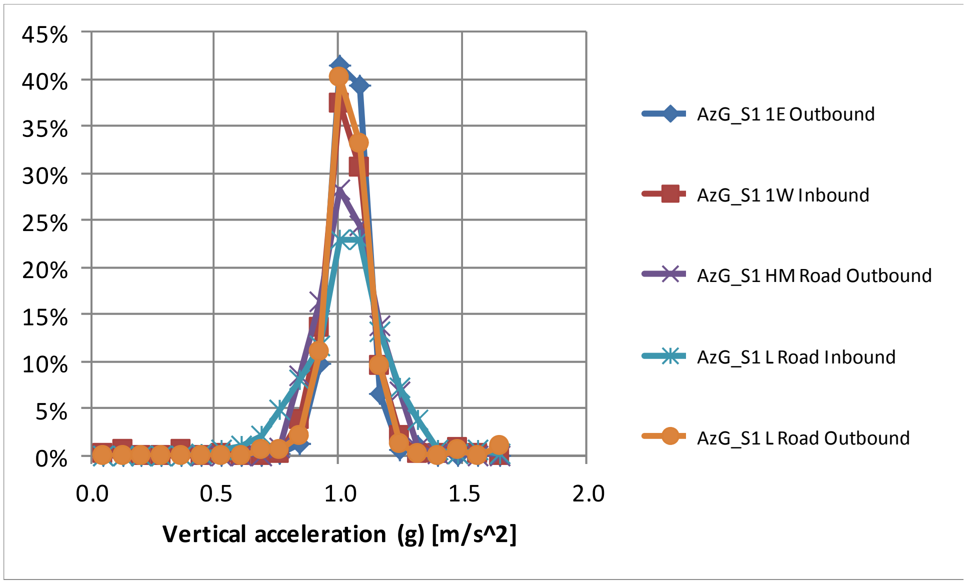

Figure 2.22: Vertical acceleration distribution for Company A—location 1.

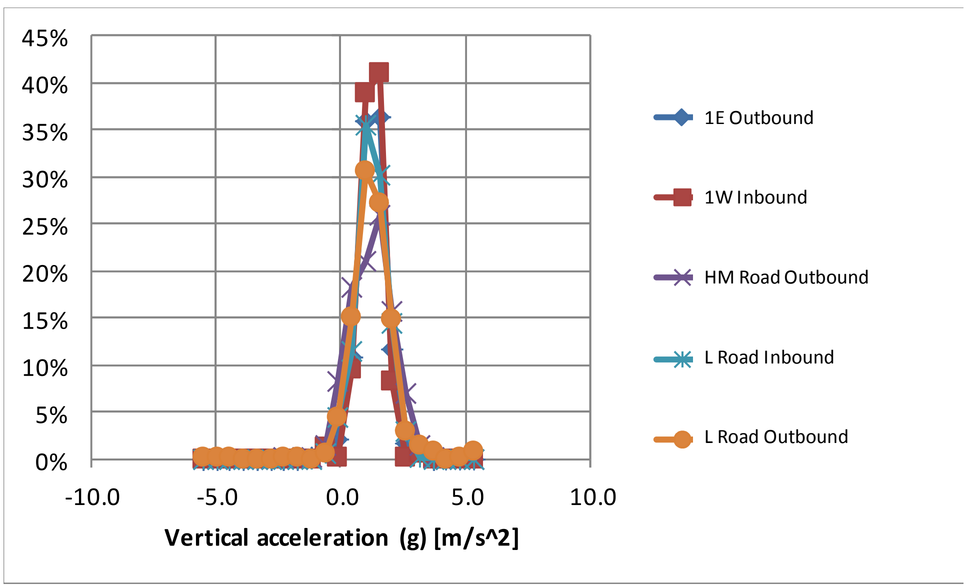

Figure 2.23: Vertical acceleration distribution for Company A—location 5.

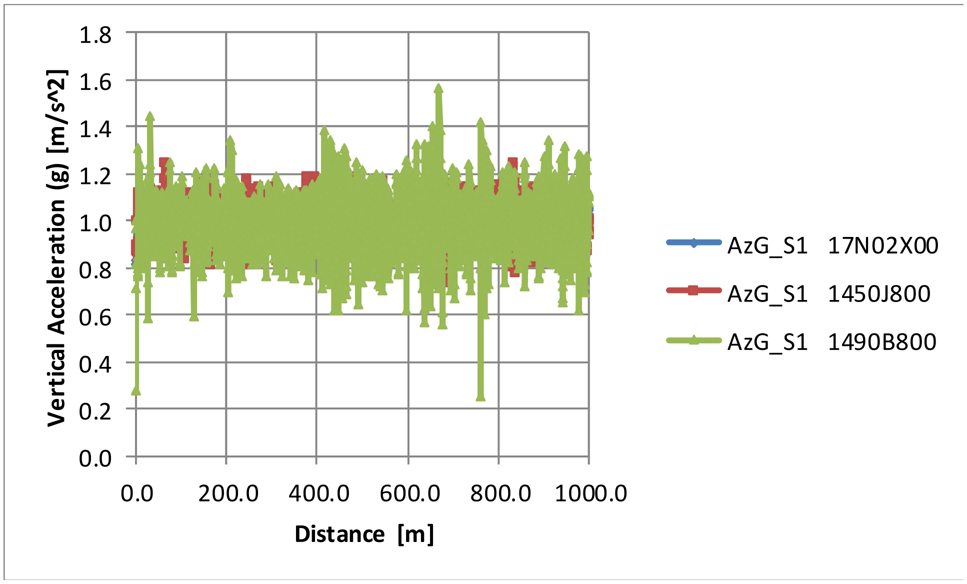

Figure 2.24: Vertical acceleration over simulation section distance for Company B—location 1.

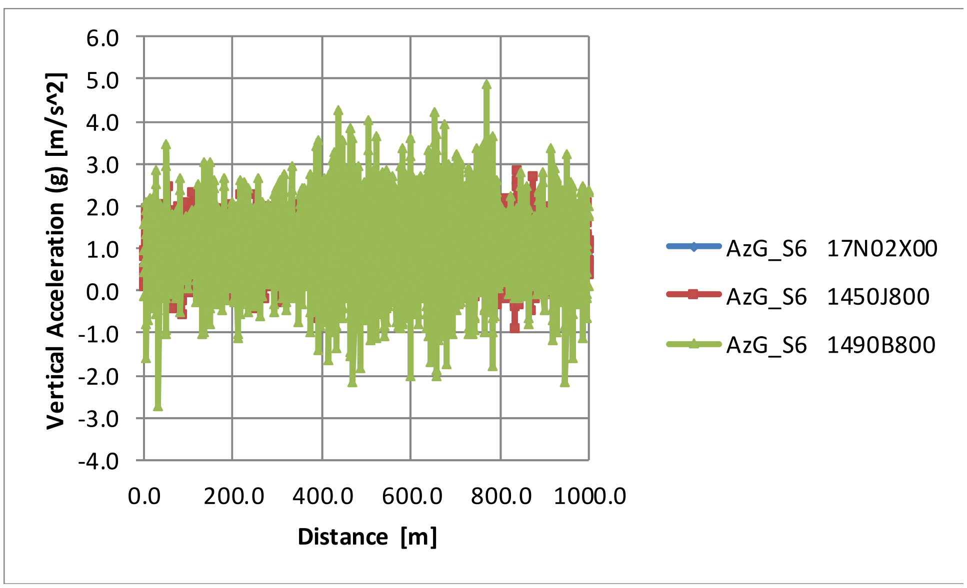

Figure 2.25: Vertical acceleration over simulation section distance for Company B—location 6.

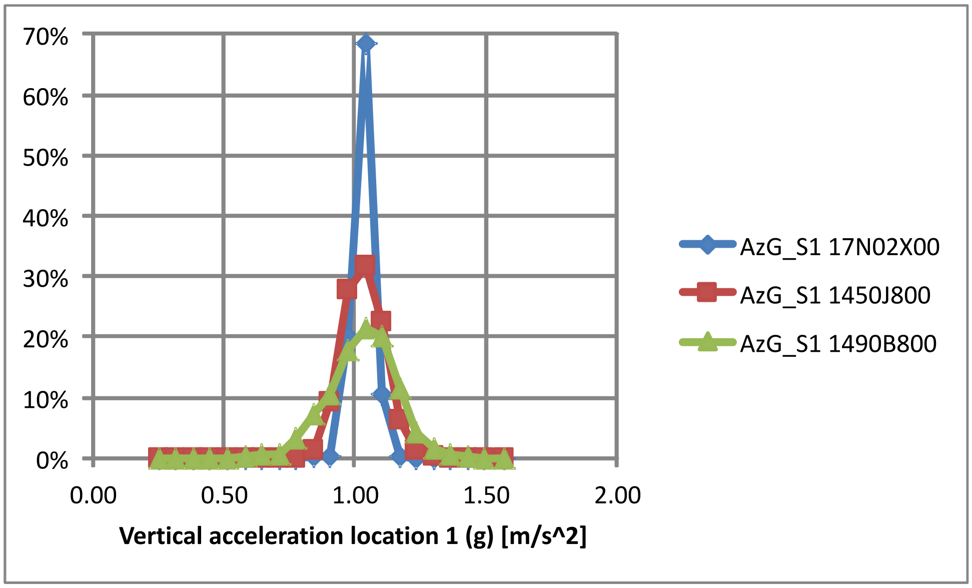

Figure 2.26: Vertical acceleration distribution for Company B—location 1.

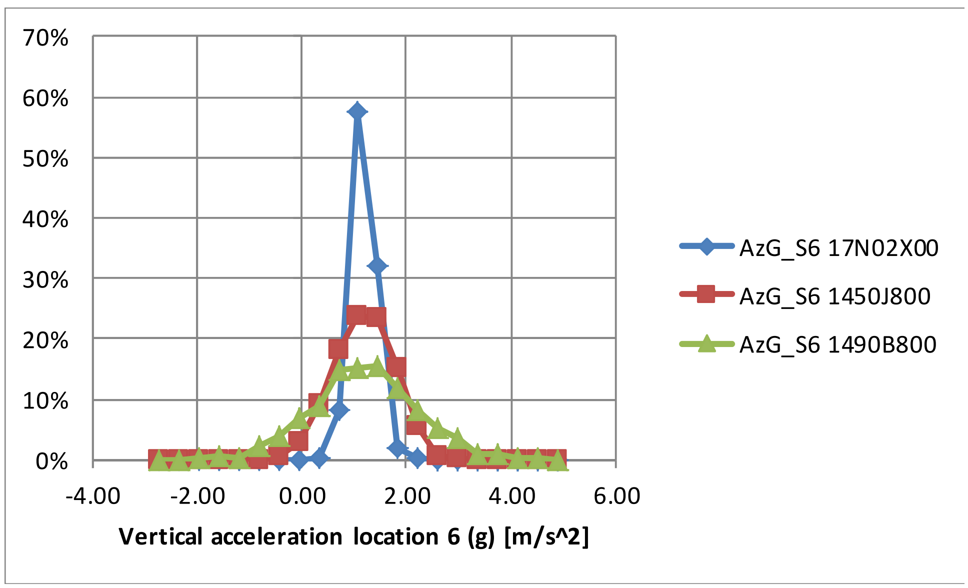

Figure 2.27: Vertical acceleration distribution for Company B—location 6.

2.7 Summary

In this section, data obtained from the V-PI simulation were presented and compared to identify trends. The focus is on those aspects of vehicle behavior apparently influenced by road riding quality conditions. In summary, the V-PI simulation data show the following information and trends:

- *Comparison of vehicles over different road sections (effect of riding quality).* Both axle loads and vertical accelerations show wider distribution of data with higher roughness roads, and narrower distributions (lower CoV) for smoother roads, as well as for higher load levels. This is in agreement with literature and previous studies.
- *General comparison of applied tire loads and accelerations experienced.* The output from the simulations provided reasonable load level and acceleration data when compared to measured data and published literature. The values are reasonable and show expected trends with increases in tire loads for full vehicles compared to empty vehicles, and increases in variation of tire loads and vertical accelerations when traveling over sections with worse riding quality.

3 TASK 8—MEASUREMENTS

3.1 Introduction

This section contains information on Task 8, which focused on measurements of accelerations on selected locations of selected California vehicles on specific routes. The objective of Task 8 is 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. Data were collected using trucks of two companies in California (Company A and Company B) as they traveled on their normal routes.

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 are 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 (SR 152) 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

3.2 Field Measurement Methodology

The methodology followed for the field measurements consisted of the following steps:

1. Identification of companies, vehicles and routes to use for the study
2. Identification of appropriate locations on the vehicles for measuring vertical accelerations
3. Attaching the sensors to the appropriate locations and measuring the vertical accelerations, as well as the location and speed of the vehicle traveling over the selected route
4. Validation of the collected data
5. Analysis of collected data mainly in terms of the effect of road riding quality on the vertical accelerations of the vehicles and freight

The primary data collected from the trucks and freight are vertical, horizontal, and longitudinal accelerations, measured using off-the-shelf accelerometers (Figure 3.1). In this study, the focus of the analysis is on the vertical acceleration data, as this proved to be by far the largest value of the three. Vehicle location and road condition were monitored using a GPS and a video camera, both installed in the truck cabin.

Figure 3.1: Accelerometer used for collecting acceleration data from trucks and freight.

3.3 Company A

3.3.1 Background

Company A transports agricultural freight, and specifically tomatoes for the work conducted in this study. It operates a large fleet of trucks and runs a well-designed and -managed operation where the logistics of movements between the farms and processing plant is vital to ensure that the plant can function optimally. It collects logistics information for its operations and actively analyzes and uses this information in its management operations. Trucks from Company A travels on routes around the main facility. The typical truck used for the collection and transport of tomatoes is shown in Figure 3.2.

3.3.2 Trucks

Company A operates CA Legal Double—Type 11 (2S1-2) trucks (Figure 3.2 and Figure 3.3). Typical axle distances for the CA Legal Double trucks operated in California are provided in Table 3.1. Dual tires are used on all axles except the steering axle. The tires are 11R22.5-sized tires. Steel suspension is used for the trailers (Figure 3.4), while the truck tractor uses air suspension.

Figure 3.2: Typical Company A truck used for tomato transport.

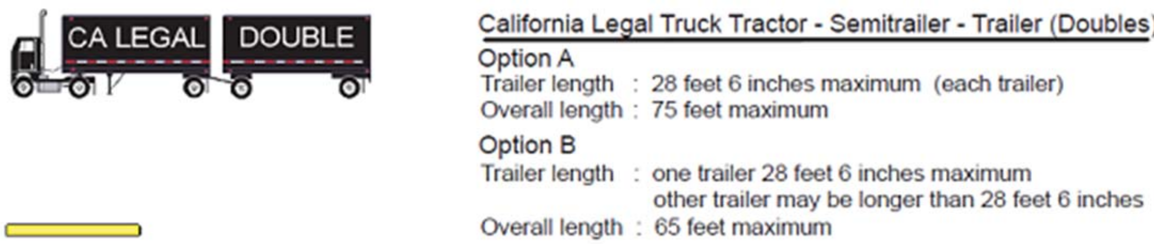

Figure 3.3: Typical Company A Truck details *(3)*.

Table 3.1:Truck Type Used by Company A

CA Truck Type Nomenclature	Distance Between Axles (m) [ft]			
	Axle 1 to 2	Axle 2 to 3	Axle 3 to 4	Axle 4 to 5
CA Legal Double (California Legal Truck Tractor-Semitrailer-Trailer [Doubles]), FHWA Class 9	1.8 to 7.9 [6 to 26]	3.4 to 7.9 [11 to 26]	1.8 to 6.1 [6 to 20]	3.4 to 7.9 [11 to 26]

Figure 3.4: Company A trailer suspension.

The locations of the sensors on the truck are shown in Figure 3.5.

Figure 3.5: Location of sensors on Company A truck for field work (body and freight in one combined figure).

3.3.3 Routes

Most of the routes center around the processing plant for Company A. It consists of a mixture of interstate, state highway, and county roads, with limited farm roads involved. The same route was used for both an empty truck and a full load; the distances and speeds traveled for each of the routes are summarized in Table 3.2 and Table 3.3, respectively.

Table 3.2:Company A–Empty Route Details

Road	Distance (km) [mi]	Time (s)	Average Speed (km/h) [mph]
V	0.8 [0.5]	216	13.3 [8.3]
HM	14.4 [9.0]	695	74.6 [46.6]
D	4.8 [3.0]	219	78.9 [49.3]
1	8.0 [5.0]	374	77.0 [48.1]
A	2.4 [1.5]	150	57.6 [36.0]
L	2.4 [1.5]	204	42.4 [26.5]
R	0.5 [0.3]	58	29.8 [18.6]

Table 3.3:Company A–Full Route Details

Road	Distance (km) [mi]	Time (s)	Average Speed (km/h) [mph]
R	0.5 [0.3]	58	29.8 [18.6]
L	2.4 [1.5]	204	42.4 [26.5]
A	2.4 [1.5]	150	57.6 [36.0]
1	8.0 [5]	374	77.0 [48.1]
D	4.8 [3]	219	78.9 [49.3]
HM	14.4 [9]	695	74.6 [46.6]
V	0.8 [0.5]	216	13.3 [8.3]

3.3.4 Freight

The freight for the study consisted of loose tomatoes destined for the processing plant (Figure 3.6). The trucks transported 20 tons of tomatoes per trailer, equivalent to 40 tons per truck (two trailers), and the plant required a delivery every three minutes.

Figure 3.6: Typical tomato freight for Company A.

3.3.5 Logistics

The trip with Company A was made on Saturday, September 22, 2012. Tomatoes were harvested on Field 1402 and transported over the routes indicated (Figure 3.7).

Figure 3.7: Typical Company A routes.

3.3.6 Company A Measurements

Validation of the data obtained for Company A indicated that the dataset was reasonable to work with and that reasonable trends were visible in the data. Two sensors (out of 15) were lost during the process: one was damaged by water during the unloading process, and one was lost during the unloading process.

In terms of the general trends observed, it was seen that rougher roads showed higher accelerations than smoother roads and the accelerations were higher on top of the loads than at the bottom of the loads. In the analysis process, typical examples of the acceleration data were extracted.

In Figure 3.8 typical accelerometer data (vertical, longitudinal, and transverse) for the first trailer's second axle are shown for the full trip, starting as an empty trailer and finishing the trip fully loaded. The data indicate the higher accelerations expected when the trailer is empty than when it is fully loaded.

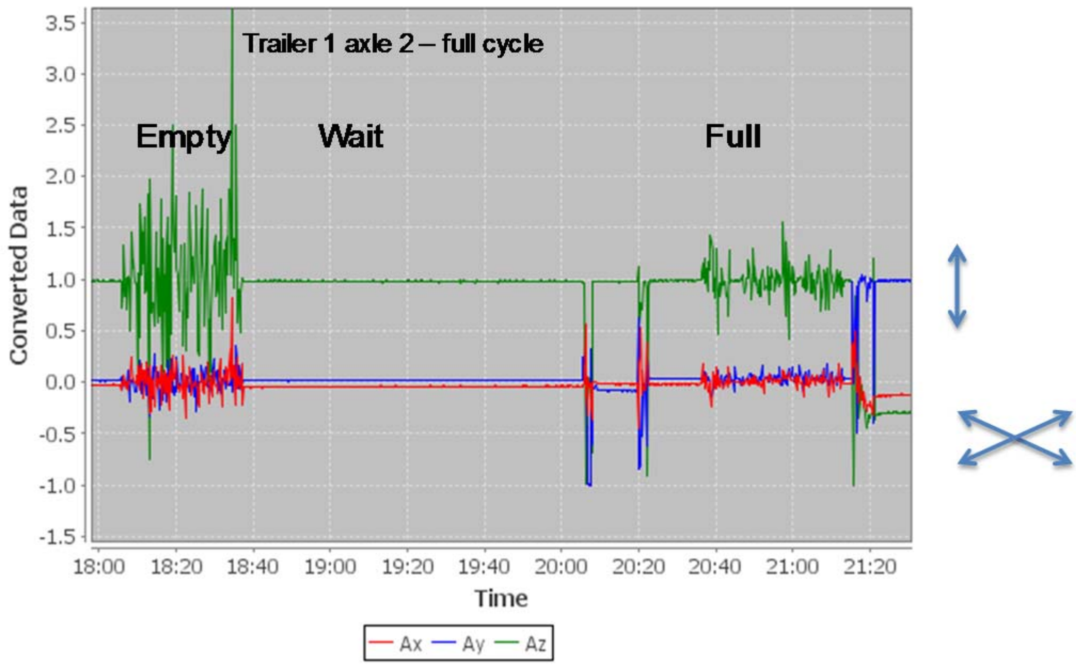

Figure 3.8: Typical accelerometer outputs.
(Ax = transverse, Ay = longitudinal, Az = vertical).

The data in Figure 3.9 indicate the difference between the accelerations measured at the top of the trailer and the bottom of the trailer. The y-scale of the two graphs covers the same range, with the vertical sensor measuring negative g due to being placed upside down on the bottom of the trailer.

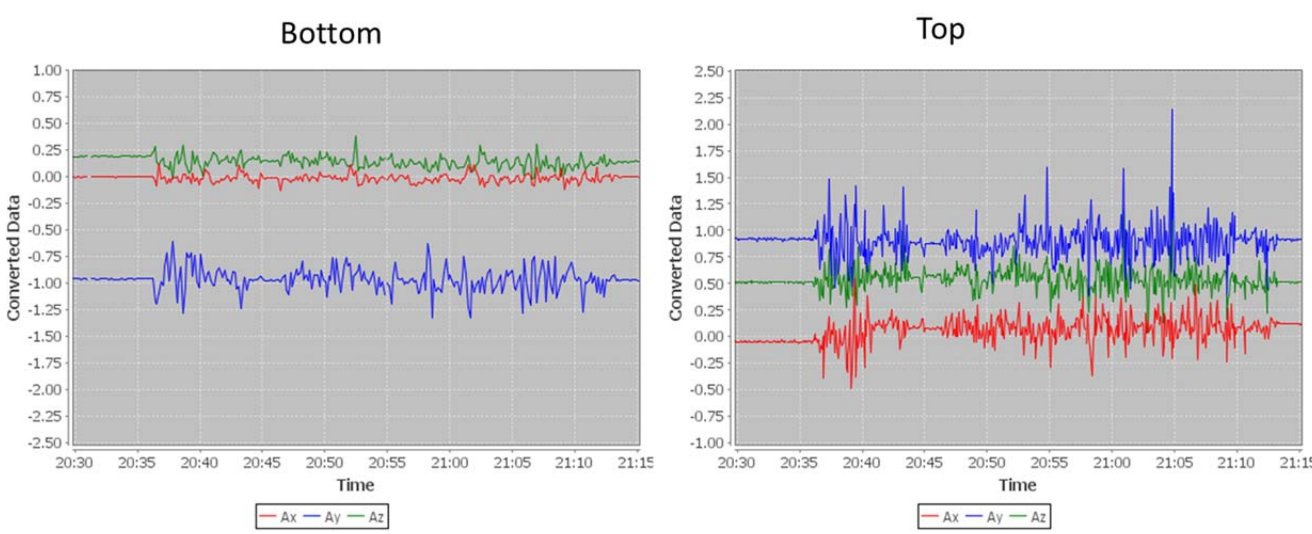

Figure 3.9: Typical accelerometer outputs—top and bottom of trailer.
(Ax = transverse, Ay = longitudinal, Az = vertical).

The standard data analysis procedure requires calculation of the dominant frequencies for each of the location using a power spectral density (PSD) analysis. Figure 3.10 shows typical PSD analysis graphs (upper graphs) for the truck drive axle and second trailer front axles. The bottom of the figure shows the total area underneath the PSD curve, which is used to provide an indication of the severity of the total movement at the specific location. The data indicate that the trailer axle on Road D experienced the greatest severity of accelerations, with the same axle on Road HM having the least severity.

In Figure 3.11 and Figure 3.12 an indication is provided of the relationship between the visual condition of the various routes and the PSD output and severity.

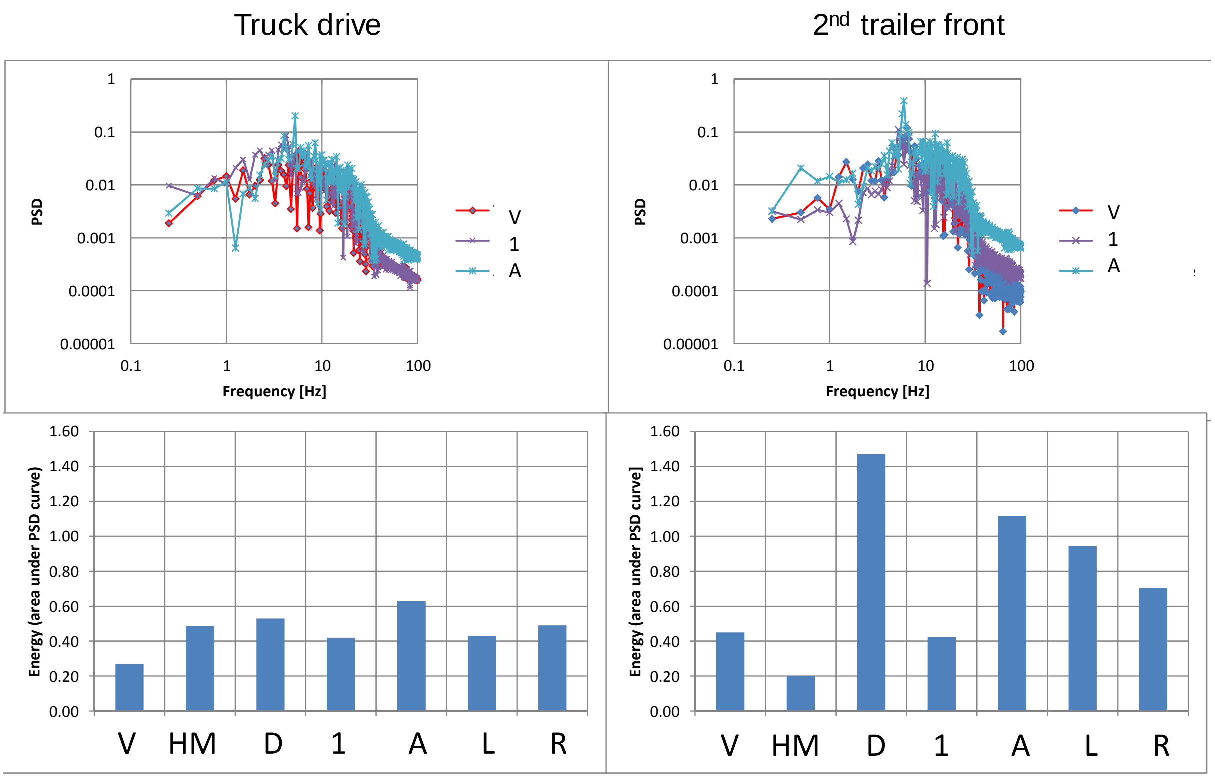

Figure 3.10: Typical PSD analysis output based on accelerometer data.

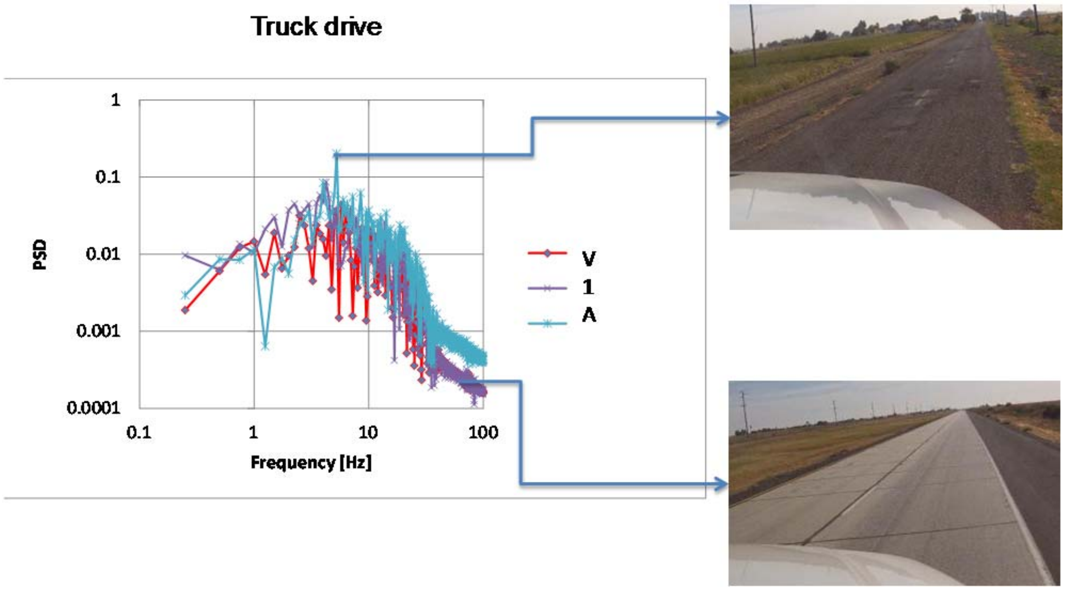

Figure 3.11: Typical accelerometer data and road conditions.

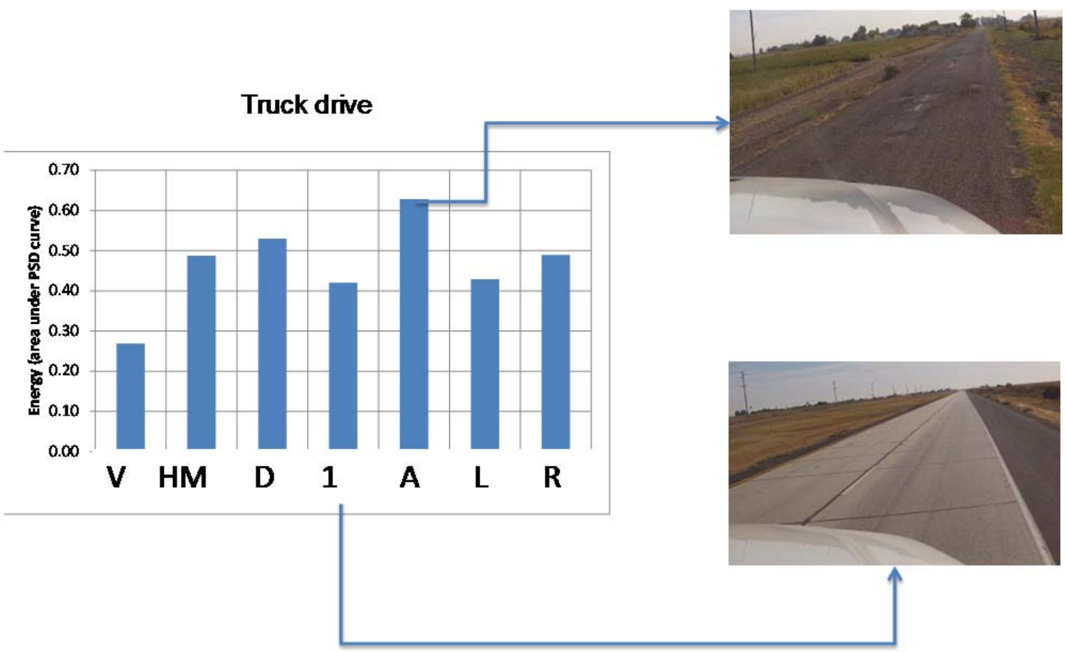

Figure 3.12: Typical accelerometer data and road conditions.

In Figure 3.13 and Figure 3.14 the summaries of the severity at each of the various locations on the truck for the full and empty conditions are shown. It indicates that the greatest severity is experienced at the back of the front trailer when loaded, and also when empty, although the first axle of the second trailer had a higher severity for one road when empty. The summaries of the severity for each of the various roads for full conditions indicate that the greatest severity is experienced on Roads D, A, and L with the least severity on Roads HM and 1.

Figure 3.13: Typical accelerometer outputs—Company A, full truck.

Figure 3.14: Typical accelerometer outputs—Company A, empty truck.

In Figure 3.15 the distribution of vertical accelerations are shown for the drive axle location under empty conditions, while the same location's data for full conditions are shown in Figure 3.16. The data indicate that the worse riding quality sections had a slightly wider distribution of data, while the empty conditions also show a slightly wider distribution, although the distributions are very similar for the drive axle. In Figure 3.17 and Figure 3.18 the same data are shown for the second trailer's front axle, and, while under empty conditions the distribution of vertical accelerations is similar for the three sections, the full conditions indicate the better riding quality section (Road 1) with a narrower distribution than the worse riding quality section (Road L).

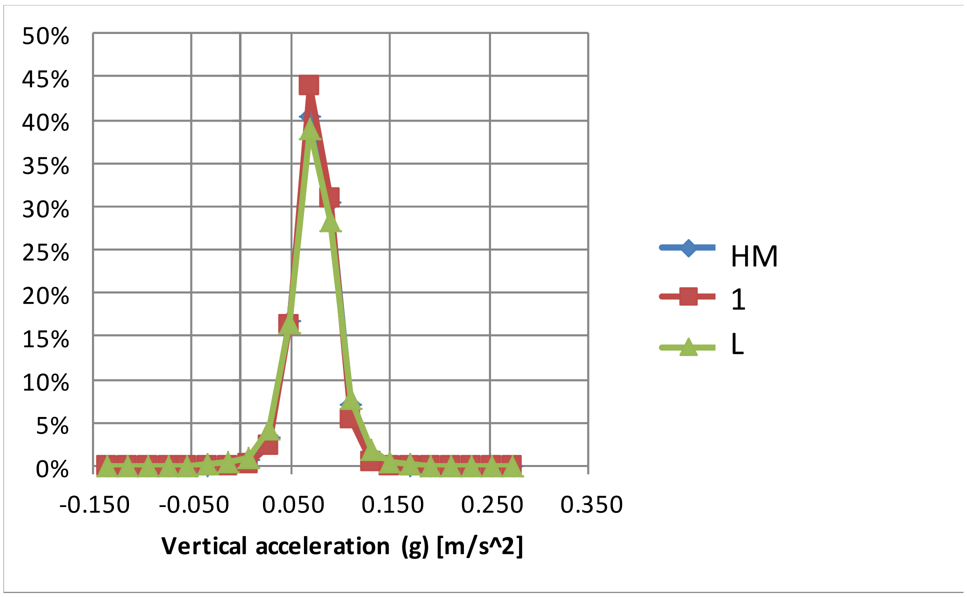

Figure 3.15: Vertical acceleration distribution for empty conditions—Company A, drive axle.

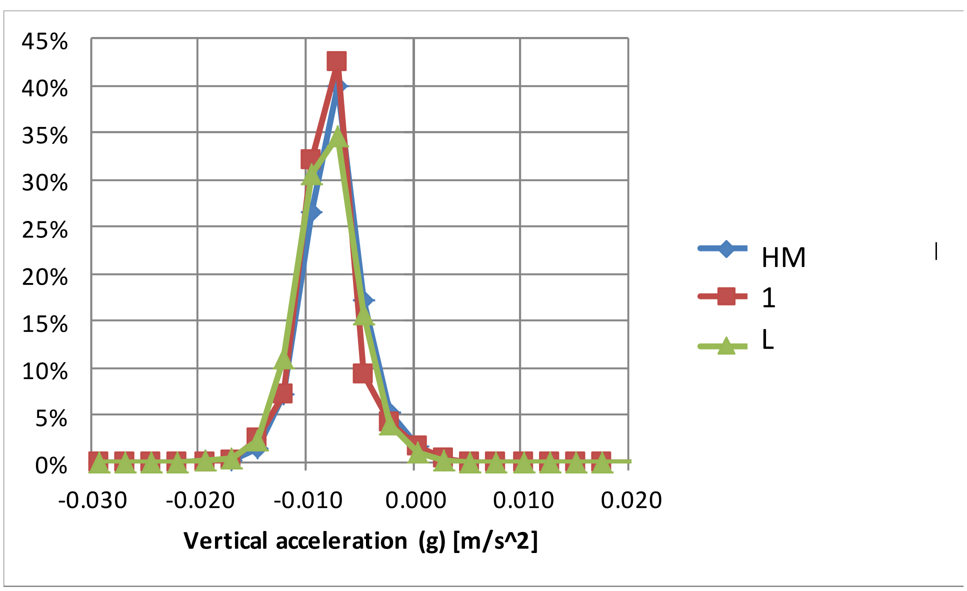

Figure 3.16: Vertical acceleration distribution for full conditions—Company A, drive axle.

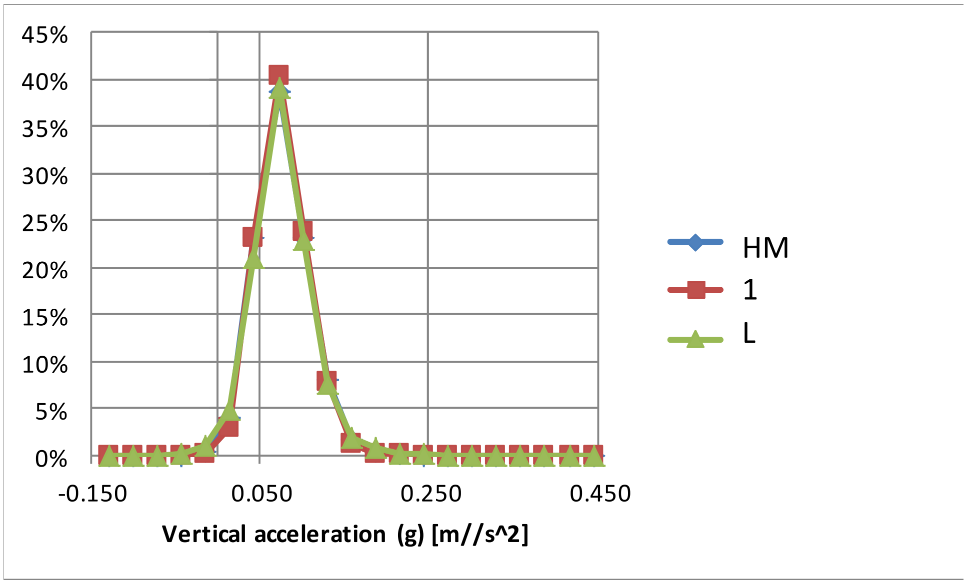

Figure 3.17: Vertical acceleration distribution for empty conditions–Company A, trailer 2, front axle.

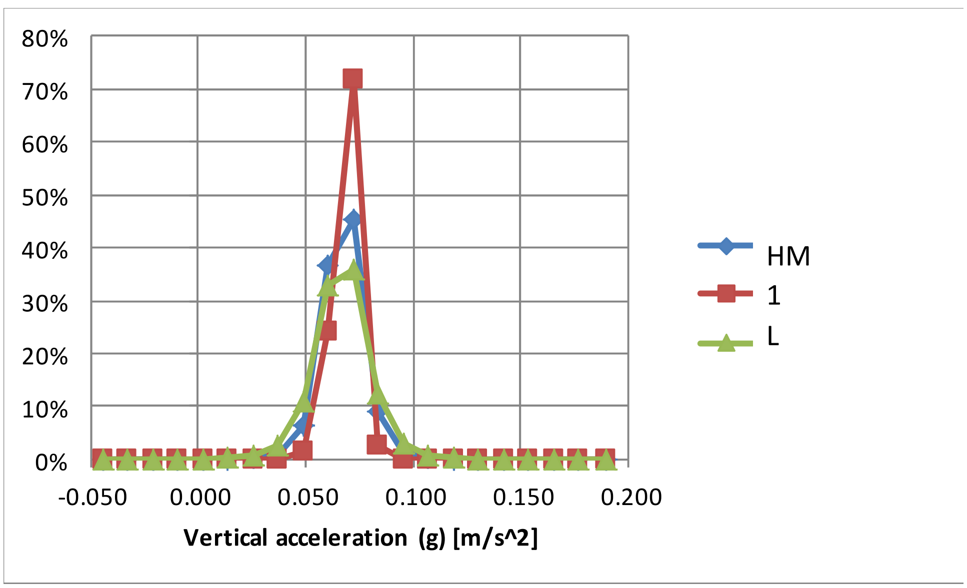

Figure 3.18: Vertical acceleration distribution for full conditions–Company A, trailer 2, front axle.

Figure 3.19 shows the average speeds attained on each of the sections of road with the full vehicle. Analysis of this data, together with the riding quality of each of the road sections, provides a relationship (shown below for metric and customary units) indicating that the speed of the trucks drops as the riding quality deteriorates. Although the relationship is based on only one trip (in the context of the preliminary evaluation) and the standard route that was followed by the truck, it appears as if this may be a significant outcome. All the road sections included in the analysis were long enough that the truck could keep to the speed that was safe for the driver to travel at, and there was no significant traffic on any of the roads that artificially affected the speed of the truck. (This part of the analysis focuses on Company A; the discussion on speed effects for Company B is shown in Section 3.4.6.)

Speed (km/h) = –12.643 (IRI [m/km]) + 88.888 (R^2 = 0.88)

Speed (mph) = –0.1254 (IRI [in./mi]) + 55.55

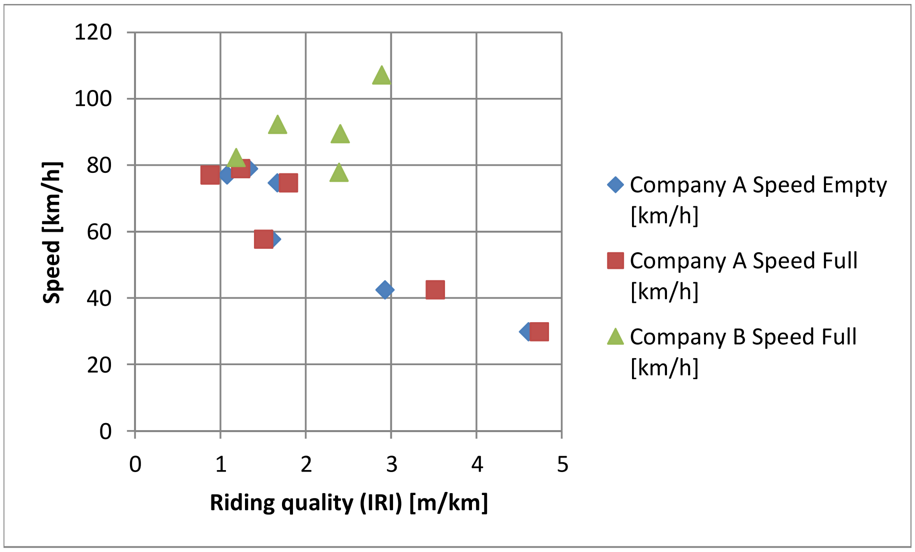

Figure 3.19: Relationship between truck speed and riding quality—Companies A and B data.

The surfacing on Road 1 consists of jointed concrete slabs with slab lengths of 3.6–5.5 m (11.8–18.0 ft). The acceleration data were analyzed to determine whether the effect of these slabs could be observed in the dominant frequencies observed on the truck and trailer. In Figure 3.20 expected frequencies for the two slab lengths when traveling at speeds of 77 km/h (48 mph) (as was observed on Road 1) are compared with the range of dominant frequencies measured on the truck and trailer. It does appear as if the slab length frequencies form part of the dominant frequencies observed; however, it would be necessary to conduct a more extended evaluation of the data where the same vehicle travels at different speeds on the specific road to determine without doubt to what extent the slab joints affect the measured and experienced accelerations on the truck, trailer, and freight.

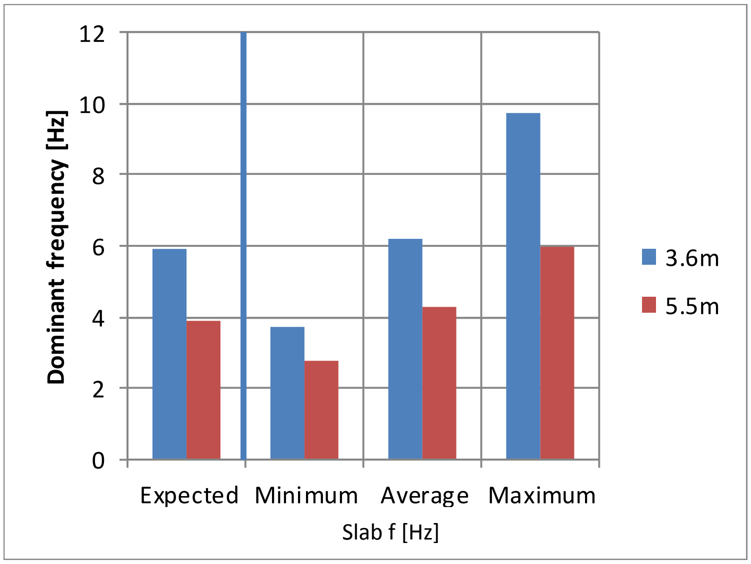

Figure 3.20: Comparison between slab length frequency and frequency range on Company A truck and trailer.

3.3.7 Summary—Company A

Measured data for Company A agree with the expected outcomes, showing increased variation and severity on rougher road sections than on smoother road sections. Selected locations on the trailer—positions farthest from the center of gravity (CoG)—showed greater severity than locations closer to the CoG. The speed at which the truck traveled appears to be directly influenced by the riding quality of the road. The effect of the concrete slab sections on the vertical accelerations measured while traveling on Road 1 is visible, but more detailed measurements are required to state this conclusively.

3.4 Company B

3.4.1 Background

Company B transports packaged goods (part loads) between the Bay Area and locations on I-5 and I-80. It ships freight as booked by clients. and the freight therefore consists of many different types of goods. Most are packaged on pallets and then placed inside semitrailers for transportation between warehouses. The main objective of the field measurements was to obtain data on the accelerations experienced by the transported freight due to uneven road conditions.

3.4.2 Trucks

Company B operates STAA Truck Tractor—Semitrailer (FHWA class 9) vehicles on the route evaluated (Figure 3.22 and Table 3.4). The locations of the sensors on the truck are shown in Figure 3.23.

Figure 3.21: Typical Company B truck.

Figure 3.22: Typical Company B truck details *(3)*.

Table 3.4:Detail on Typical Company B Vehicle

California Truck Type Nomenclature	Distance Between Axles (m) [ft]			
	Axle 1 to 2	Axle 2 to 3	Axle 3 to 4	Axle 4 to 5
STAA 48 feet (STAA Truck Tractor—Semitrailer), FHWA Class 9	1.8 to 7.9 [6 to 26]	0.9 to 1.8 [3 to 5.99]	1.8 to 14.0 [6 to 46]	0.9 to 3.4 [3 to 10.99]

Figure 3.23: Company B accelerometer detail.

3.4.3 Routes

Company B traveled round trip mainly on I-80 between Reno, Nevada, and Newark, California, with the last part of the trip on I-880 (Figure 3.24). The truck tractor's origin and final destination was Newark. One set of cargo was transported to Reno, where a second set was picked up and transported to Newark on a return trip.

3.4.4 Freight

Company B transports packaged goods, mainly on pallets. During the trips monitored the truck was almost half-laden (Figure 3.25).

3.4.5 Logistics

The trip with Company B was made on Wednesday Thursday, September 26 and 27, 2012.

3.4.6 Company B Measurements

Validation of the data obtained for Company B indicated that the dataset was reasonable to work with and that reasonable trends were visible in the data.

It was observed that rougher roads showed higher accelerations than smoother roads and the accelerations on the back axle of the truck were higher than those inside the trailer. In the analysis process typical examples of the acceleration data were extracted.

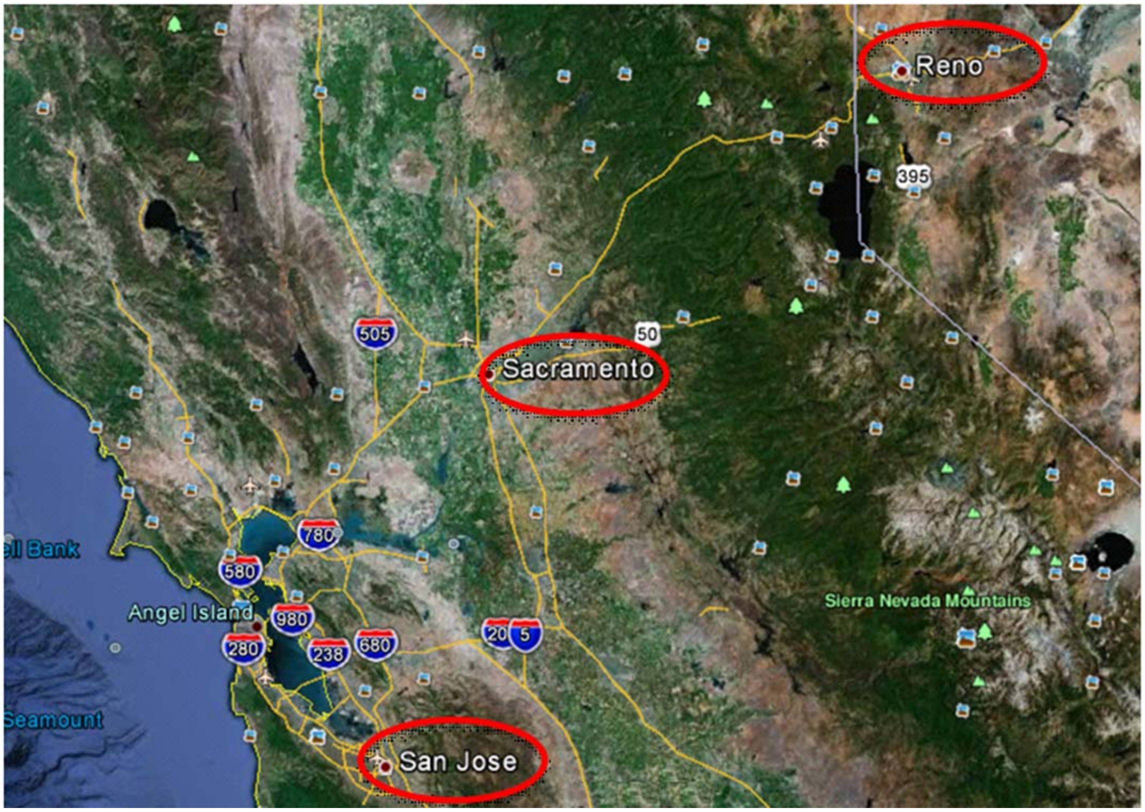

Figure 3.24: Routes—Company B.
(Note: Image from Google Earth™.)

Figure 3.25: Half-laden freight for Company B.

In Figure 3.26 typical accelerometer data (vertical, longitudinal, and transverse) for the trailer body location on top of the trailer axle, as well as on the trailer axle itself, are shown for the full trip. The data indicate the higher accelerations on the unsuspended axle compared to the suspended trailer body.

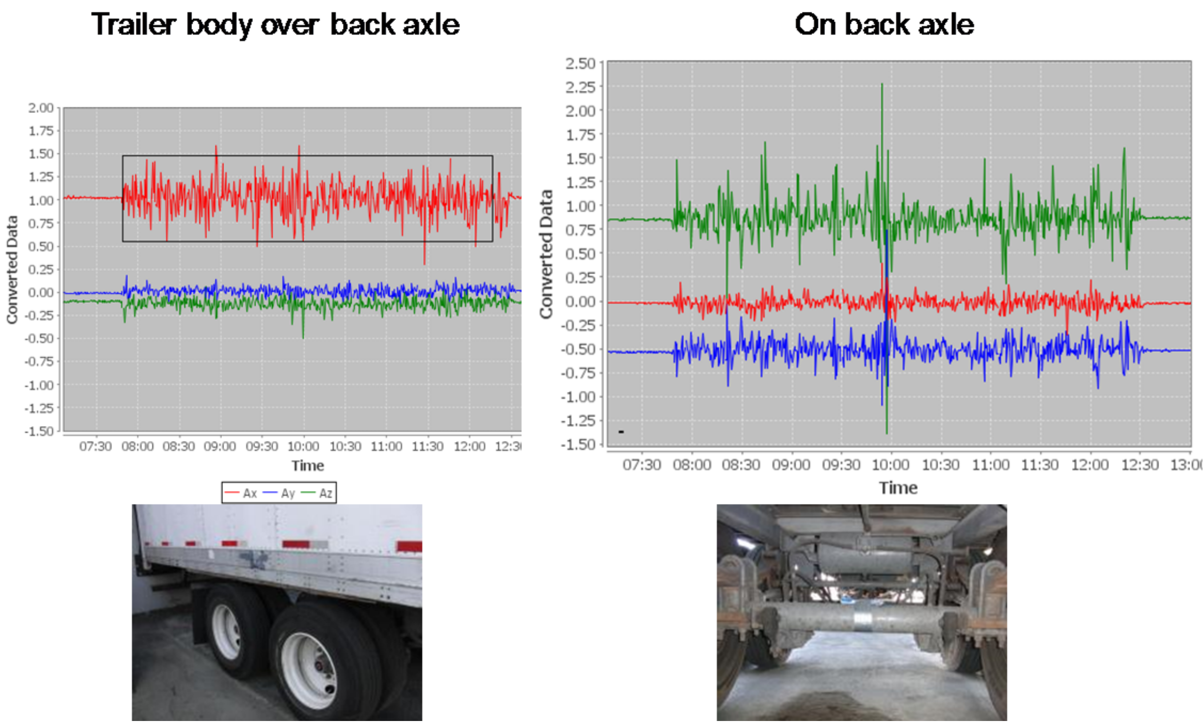

Figure 3.26: Company B accelerometer output detail.

In Figure 3.27 the basic PSD analysis detail for Company B is shown. It indicates the dominant frequencies at which the vehicle moved at the different locations in the vehicle for all the sensors (upper left), the drive and trail locations versus the on-axle location (upper right), the freight sensors on top of the back axle and the on-axle location (lower left), and the freight location on top of the drive axle versus the trailer body at the same location (lower right).

Analysis of these data shows that greater severity is being experienced at locations farther from the CoG of the vehicle, with rougher roads causing greater severity of vertical accelerations.

In Figure 3.28 the severity (area under PSD curve) for the various locations on the truck and freight is shown. It indicates that the greatest severity of accelerations was found on the trail axle and the top of the freight location. The least severity was measured on the trailer above the drive axle and on the middle bottom location for the freight. This freight location has the least opportunity of movement, as freight is stacked on top of it.

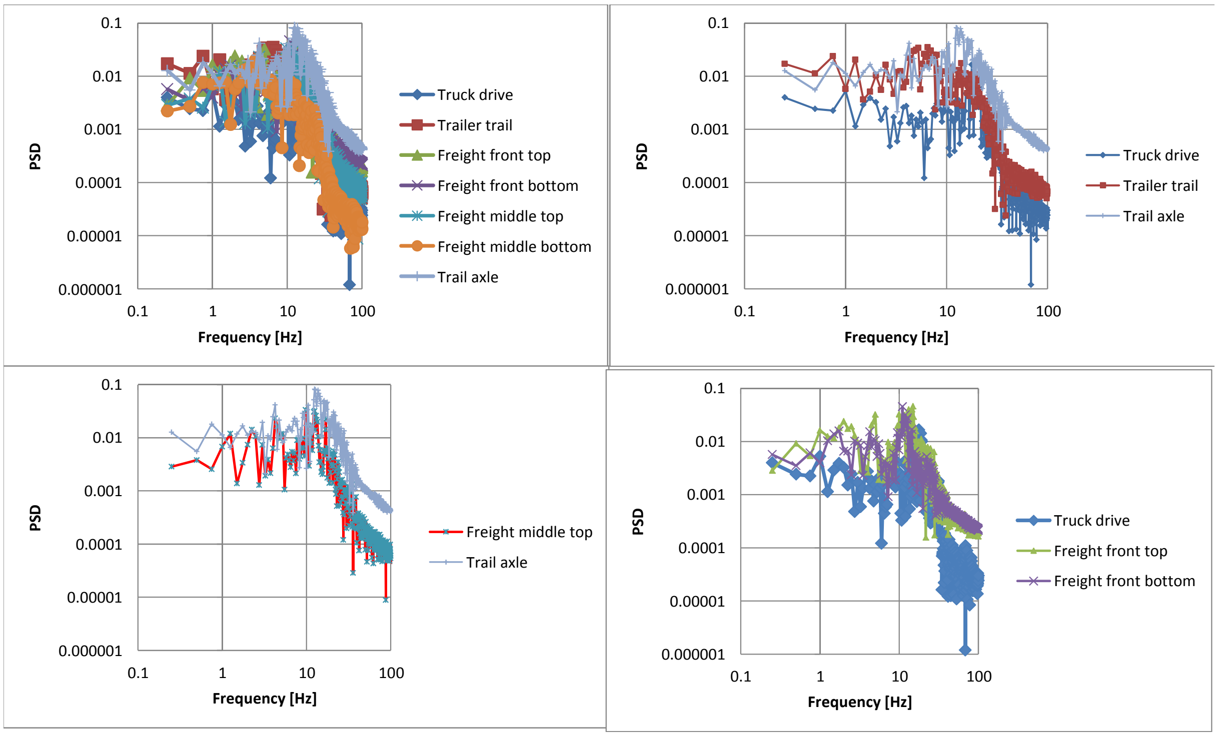

Figure 3.27: Company B PSD analysis output detail.

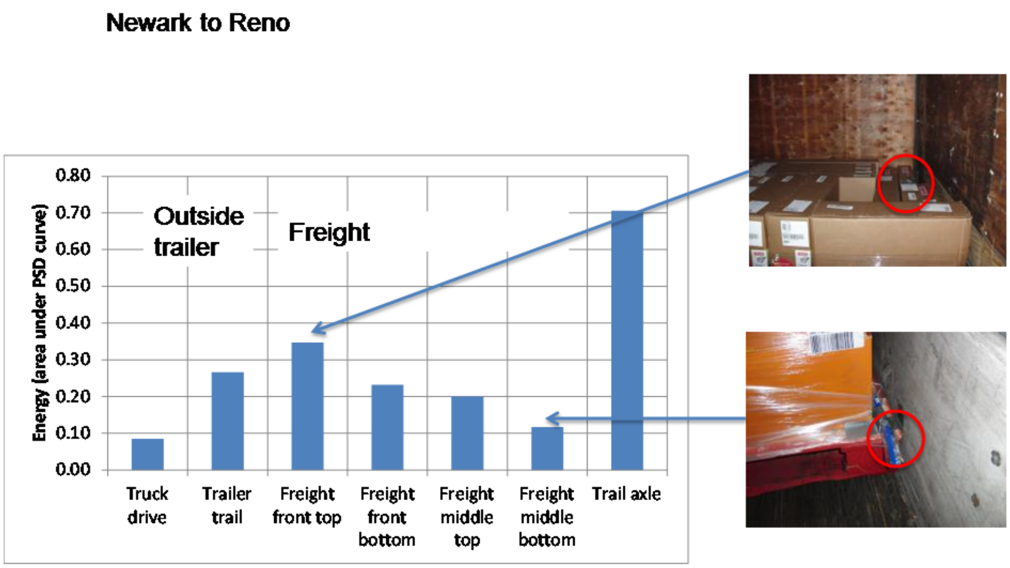

Figure 3.28: Company B severity output detail.

In Figure 3.29 the peak accelerations measured along the route are highlighted. These accelerations occurred on I-80 close to Sacramento, which is one of the last locations on the specific route that are being rehabilitated. Figure 3.30 indicates dominant frequency and severity levels for four different locations on the route, indicating that the unrehabilitated section next to Sacramento has a significantly higher severity than the street in Reno (slow speed) and both the good asphalt and damaged asphalt sections of I-80.

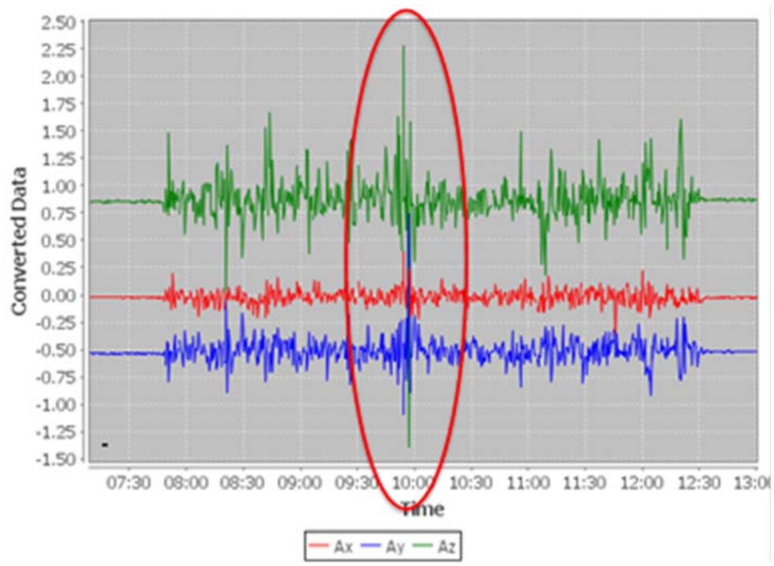

Figure 3.29: Company B accelerometer output detail.
(Ax = transverse, Ay = longitudinal, Az = vertical)

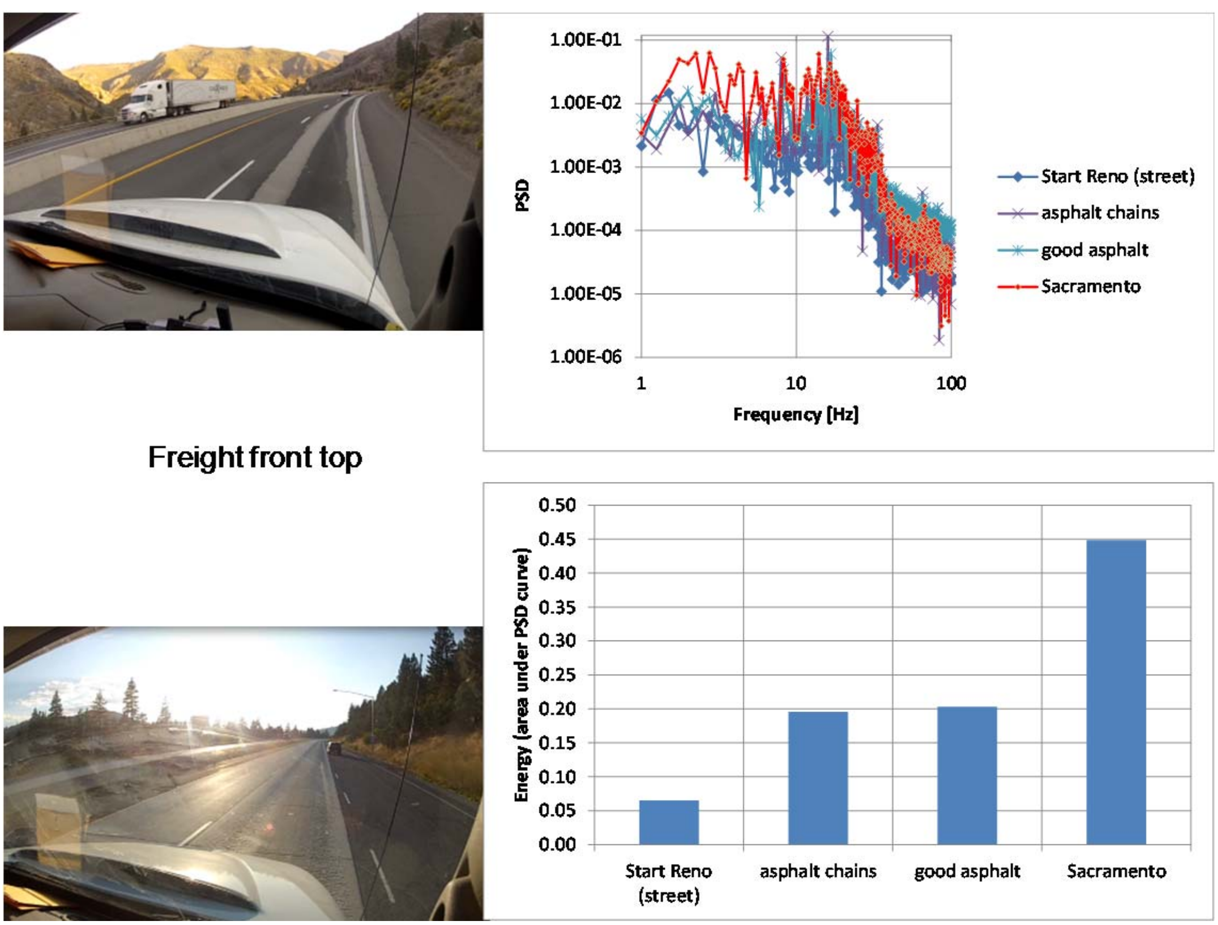

Figure 3.30: Company B PSD and severity output detail for selected locations.

Figure 3.31 again shows the average speeds attained on each of the sections of road with the full vehicle. For I-80, where the road was generally in a better condition than the routes traveled by Company A, a strong relationship was not evident between the riding quality and the speeds attained on the route. The relationship (shown below for metric and customary units) is much weaker than that obtained for the Company A analysis, and more data are required to really draw appropriate conclusions around the speed-roughness relationships for the Company B routes. Microanalysis of short sections such as the unrehabilitated section close to Sacramento was not analyzed separately in this analysis.

Speed (km/h) = 8.771 (IRI [m/km] + 71.246 ($R^2 = 0.27$)

Speed (mph) = 0.0870 (IRI [in./mi] + 44.53 ($R^2 = 0.27$)

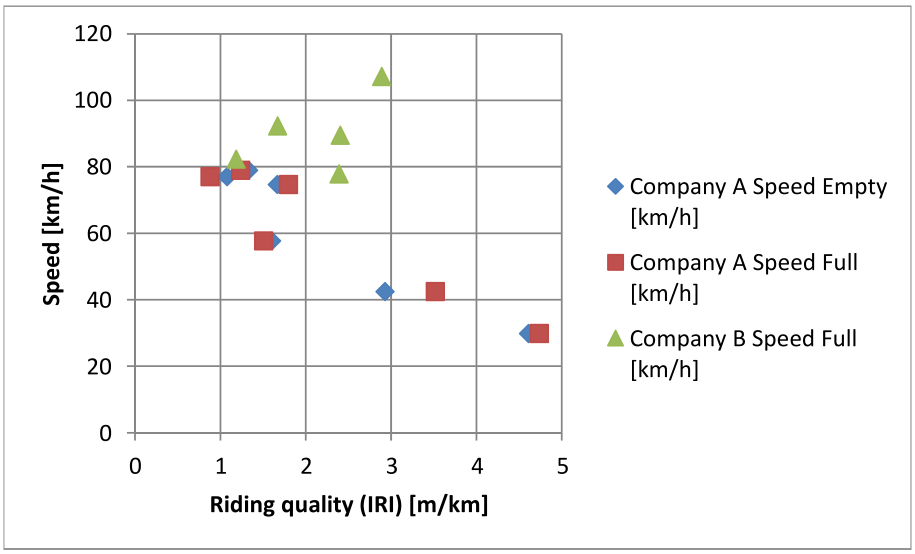

Figure 3.31: Relationship between truck speed and riding quality—Companies A and B data.

3.4.7 Summary—Company B

Measured data for Company B agree with the expected outcomes, showing increased variation and severity on rougher road sections than on smoother road sections. Selected locations on the trailer—positions farthest from the center of gravity (CoG)—showed greater severity than locations closer to the CoG. The speed at which the truck traveled was not affected in the same manner as in the Company A measurements, and it appears as if the combination of wider and smoother roads (Company B) causes the speeds attained on the roads to be less affected by riding quality than those on the narrower and rougher roads (Company A routes).

3.5 Summary

Task 8 focused on collection of acceleration data on the trucks of Companies A and B, and on the analysis of these data to determine trends with the riding quality of the road as the main influencing parameter.

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 farthest from the center of gravity of the trailer typically showing the worse conditions.

For Company A, a good 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. The same relationships could not be observed on the Company B routes, probably due to generally better riding quality on these routes.

4 DISCUSSION

4.1 Introduction

This section focuses on a discussion and comparison between the simulation and field measurement data discussed in Sections 2 and 3.

4.2 Data Comparison

4.2.1 Introduction

A general comparison is made in this section between the data obtained from the simulation (Task 7) and the data measured on the trucks (Task 8). The following notes and precautions should be appreciated in the interpretation and analysis of the data comparisons:

- The analysis method selected is to compare the histograms/distributions of data for a selected location and road.
- The objective of the analysis is not to calibrate the simulation outputs, but rather to compare and determine whether a reasonable comparison is possible. As indicated in Steyn *(2)*, TruckSIM^{TM} has been calibrated before using various truck combinations.
- As this is a pilot study, all the available options in terms of the on-truck measurements and simulations have not been used. There are various truck and trailer options that can still be changed in the simulation option, as there could be different locations to measure the vertical accelerations on the vehicles. Such options will be investigated when a full project is conducted and time and resources allow.
- Data comparisons are only made for vertical accelerations, as tire loads were not measured during Task 8.

4.2.2 Acceleration Data

Company A

In Figure 4.1 the vertical acceleration distribution for the empty drive and trail axles are shown, while the full drive and trail axle distributions are shown in Figure 4.2. Comparison of the graphs indicates the wider and flatter distribution of the empty axles' data, compared to the narrower distribution of the full axles' distribution. This indicates that there is greater variability in the empty axle data for both Task 7 and Task 8 data. The focus is on the trends in the data, and as the lines are mostly crossing each other, no specific legend is shown.

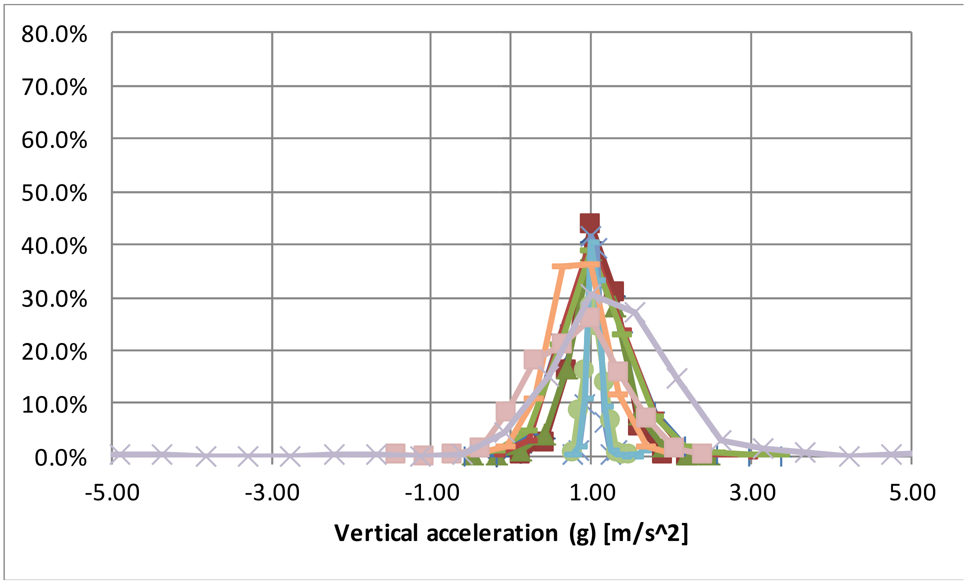

Figure 4.1: Vertical acceleration distribution for Company A, empty drive and trail axles.

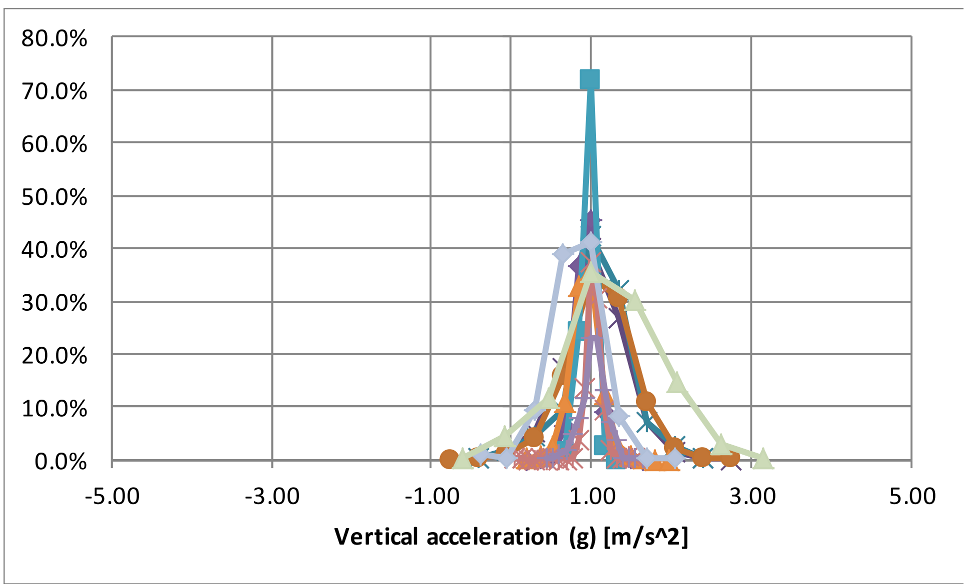

Figure 4.2: Vertical acceleration distribution for Company A, full drive and trail axles.

In Figure 4.3, Figure 4.4, and Figure 4.5 the distributions for Roads 1, HM, and L are shown for both Task 7 and Task 8 data. The same axis scaling is used to enable comparison between the graphs. Comparison of the data shows the wider distribution in data for the rougher section (L—MRI 4.8 m/km [301 in./mi]) compared to the average section (HM—MRI 2.0 m/km [125 in./mi]) and the good section (Road 1—MRI 0.9 m/km [56 in./mi]). Analysis of the data indicates that generally similar outputs are obtained for the Task 7 and Task 8 data, with the major differences between the datasets caused by the road riding quality and axle type.

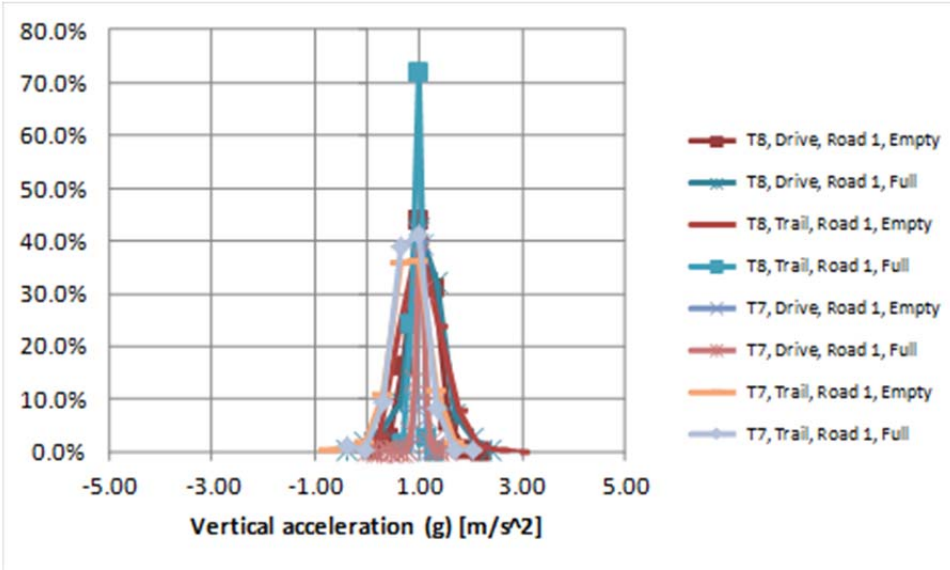

Figure 4.3: Vertical acceleration for Road 1, Tasks 7 and 8 data, drive and trail axles.

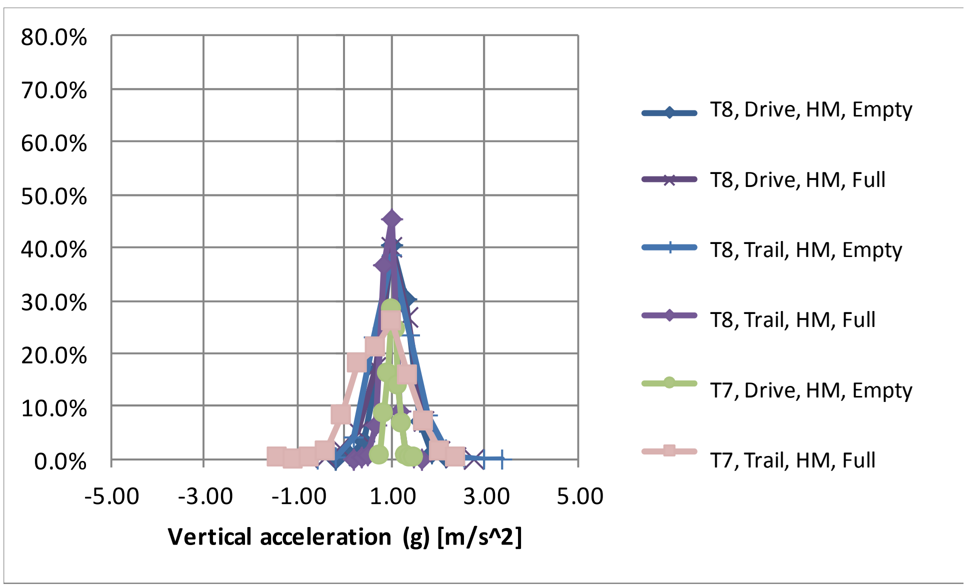

Figure 4.4: Vertical acceleration for HM road, Tasks 7 and 8 data, drive and trail axles.

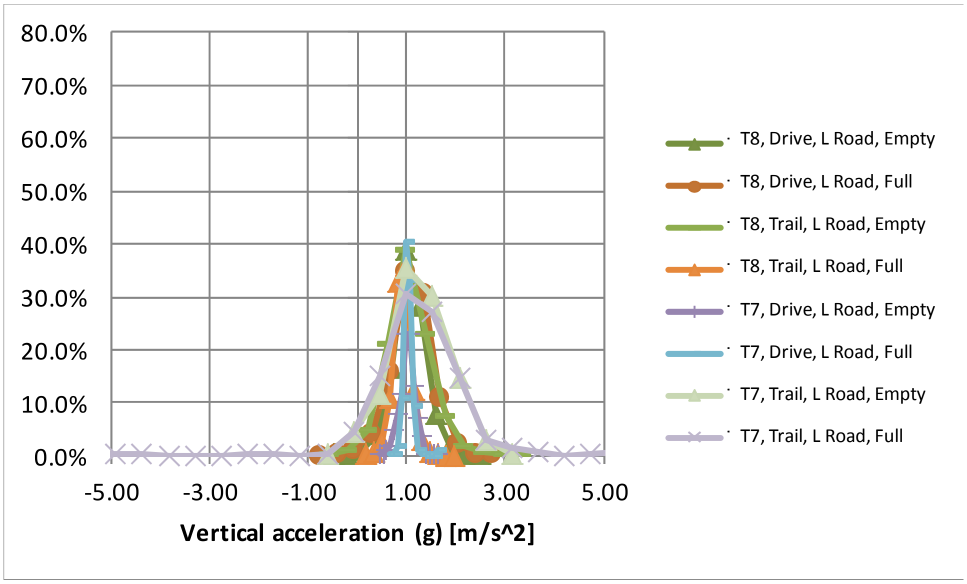

Figure 4.5: Vertical acceleration for L road, Tasks 7 and 8 data, drive and trail axles.

Company B

In Figure 4.6 the vertical acceleration distribution for the drive and trail axles is shown. Comparison of the graphs indicates the wider and flatter distribution of the trail axles on the road with worse riding quality (1490B800) compared to the narrower distribution of the drive axles on the smoother road (17N02X00), indicating greater variability in the rougher road accelerations.

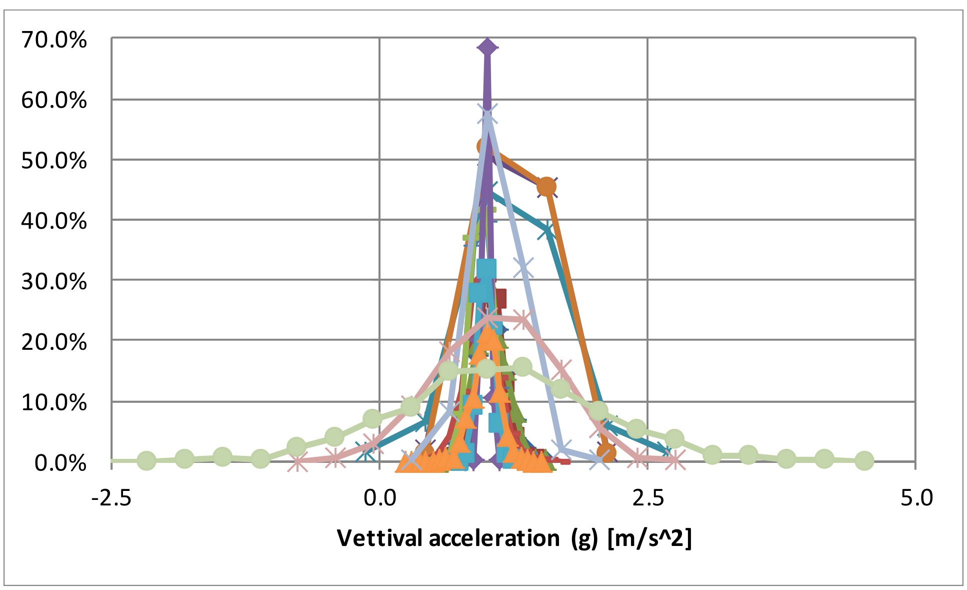

Figure 4.6: Vertical acceleration distribution for Company B, drive and trail axles.

In Figure 4.7, Figure 4.8, and Figure 4.9 the distributions for roads 17N02X00 (I-80, D4, SOL), 1450J800 (I-80, D3, SAC), and 1490B800 (I-80, D3, NEV) are shown for both Task 7 and Task 8 data. The same axis scaling is used to enable comparison among the graphs. Comparison of the data shows the wider distribution in data for the rougher section (1490B800—MRI 5.1 m/km [321 in./mi]) compared to the average section (1450J800—MRI 2.2 m/km [137 in./mi]) and the good section (17N02X00—MRI 0.6 m/km [38 in./mi]). Analysis of the data indicates that generally similar outputs are obtained for the Task 7 and Task 8 data, with the major differences between the datasets caused by the road riding quality and axle type.

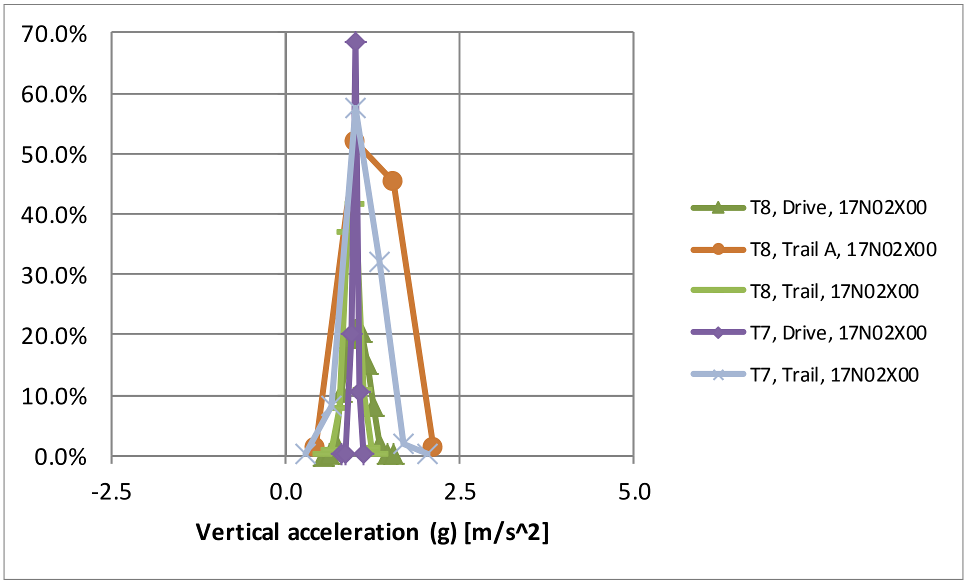

Figure 4.7: Vertical acceleration for Road 17N02X00, Tasks 7 and 8 data, drive and trail axles.

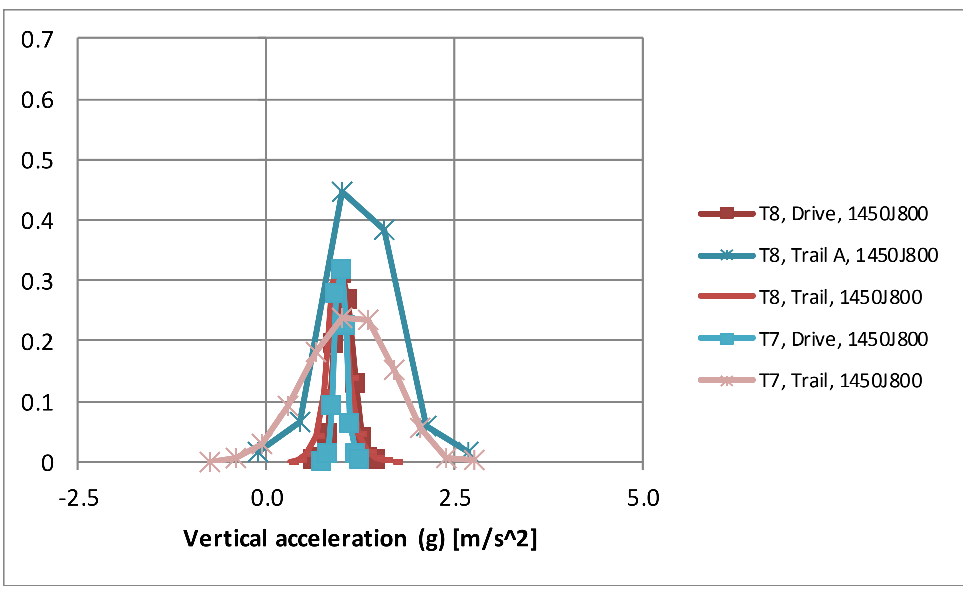

Figure 4.8: Vertical acceleration for 1450J800, Tasks 7 and 8 data, drive and trail axles.

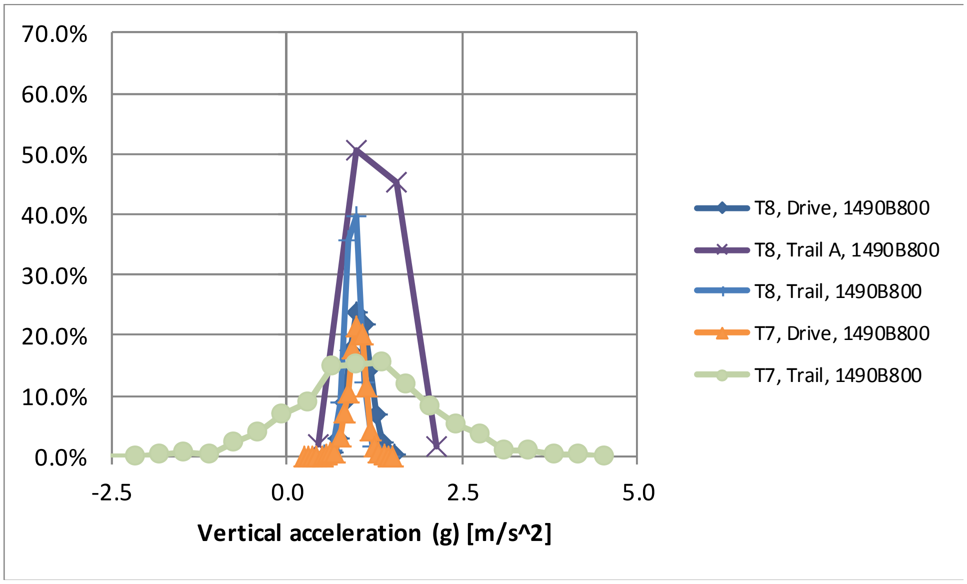

Figure 4.9: Vertical acceleration for 1490B800, Tasks 7 and 8 data, drive and trail axles.

4.3 Data as Input to Tasks 9, 10, and 11

4.3.1 Introduction

The information collected in Tasks 7 and 8 are used as input into the analyses of Tasks 9 to 11. In this section a short summary is provided of the methodology planned to incorporate this data into the remaining tasks. For most of the analyses, the riding quality of the road section is being used as the major parameter influencing outcomes of the analyses.

4.3.2 Task 9

The objective of Task 9 is to develop a map of road conditions and freight corridors as well as indications of what types of cargo can and should be transported in various locations, e.g., for selected region/district routes and outside lanes on multilane routes. The deliverable of Task 9 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. The map will be linked to speed profiles and be lane dependent (outside lane only, initially).

For Task 9 the riding quality of the routes in the regions investigated for this study have been obtained, and a basic process developed for the evaluation of the data in terms of the minimum, average, 90th percentile, and maximum values, as well as frequency distribution curves of the data by road section. The roughness data (obtained from Task 3) and acceleration data (obtained from Tasks 7 and 8) will be used in Task 9. Figure 4.10 is an example of a potential map that shows road roughness in different colors.

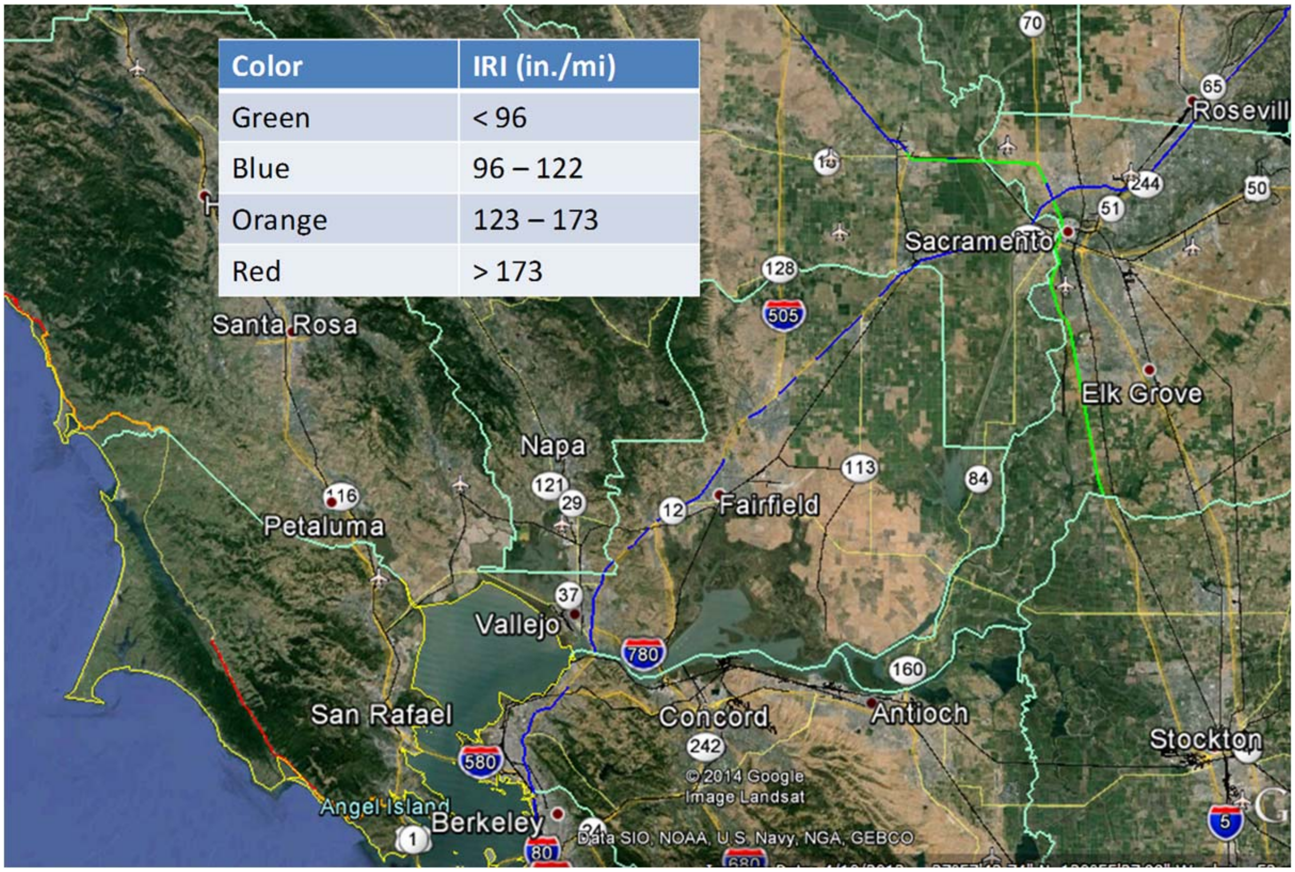

Figure 4.10: Example of a potential map showing roughness class levels.
(Note: Image from Google Earth™.)

4.3.3 Task 10

The objective of Task 10 is the development of a simple relationship between the riding quality and the additional loads on the pavement, expected freight damage, expected additional vehicle operating costs, etc. Such a relationship can then be used to expand the initial data to other routes and corridors without a full detailed analysis of each such route or corridor. These relationships will not be developed for load compliance or enforcement, but will be focused on generating data for subsequent use in planning and economic models (activities not included in this pilot study).

The recently published NCHRP 720 models *(4)* will be used together with the riding quality data (Task 3) and the measured and simulated acceleration data (Tasks 7 and 8) to develop the relationships.

4.3.4 Task 11

The objective of Task 11 is exploration of 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 will be used to generate a first version of such an outcome, and the information will again be shown on a map of the selected corridor (similar to Task 9). Recently published information and relationships from the Center for the Commercialization of Innovative Transport Technologies (CCITT) *(5)* will be used in these analyses. Again, data originating from Tasks 3, 7, and 8 will be used in developing the relationships and maps.

4.3.5 Other Analyses

Application—Empty Tin Analysis

An analysis is being conducted on three routes used by Company A to transport empty tins from the factory to the processing plant. Riding quality was measured on the three routes typically used to transport empty tins from the manufacturing plant to the processing plant. The relationships and models to be developed in Tasks 9 and 10 of this study will be used to evaluate the potential effect of the surface roughness of the three routes on damage to freight. This analysis will be discussed in the report covering Task 9 to 11. Riding quality data collected for Tasks 7 and 8 are used as input to these relationships.

Application—Comparison Between Tomato Damage and Acceleration Frequency

The ultimate additional damage caused to transported tomatoes when traveling over roads with worsening riding quality is one of the aspects that this pilot study attempts to address. Initial evaluation of the difference in tomato quality after being transported over roads of differing riding qualities did not prove sufficient to enable a quantitative evaluation of this damage.

A recent unpublished project where the impact of compaction frequency on the ultimate densities attained for different types of soils were evaluated led to the development of a methodology to determine density changes in the material being compacted at a range of compaction frequencies. The initial project indicated clearly that compaction at an optimum frequency leads to a quick increase in density and a higher density of the material being compacted. As this experiment has only been conducted recently, the application towards the tomato damage evaluation could not be completed in time for the Tasks 7 and 8 report.

A similar experiment is planned that will use tomatoes in a large container vibrated at frequencies similar to those found to be the dominant frequencies measured on the various roads traveled by Company A. The results will be compared to visual evidence of the change in density of a truckload of tomatoes during the field work for Company A.

The concept is illustrated in Figure 4.11. The top row shows tomatoes on the truck just after loading, while the bottom images show tomatoes after arrival at the plant. The height above the truck body before transportation is around 31 percent of the total height of the cargo, while the height after transportation is around 21 percent of the total height. No detailed analyses were conducted on the current data, as details on the actual volume and mass of the cargo from Company A are still to come. The results of this analysis will be reported in the final project report.

Figure 4.11: Visual indication of densification of tomato cargo during transport.

4.4 Potential Economic Analysis Impacts

One of the overall objectives of the pilot project is to evaluate the outputs from the project as input or insights towards planning and economic models to enable an improved evaluation of the freight flows and costs in the selected region/district. The following potential economic analysis impacts are identified based on the Tasks 7 and 8 analyses:

- Impact of riding quality on the generation of overloaded conditions on a pavement, and subsequent decrease in available life of the pavement
- Impact of riding quality on the general speeds attained on roads, and the resulting effect on productivity of the vehicle fleet, specifically for rougher rural roads
- Impact of riding quality on vehicle operating costs and environmental emissions (Tasks 9 to 11)

4.5 Summary

The comparison between Tasks 7 and 8 data and the subsequent data analyses provided support for the notion that worsening riding quality affects the distribution of vertical accelerations as well as tire loads on pavements, potentially leading to premature deterioration of the road pavement and subsequent damage to vehicles and freight.

5 CONCLUSIONS AND RECOMMENDATIONS

This section only contains the major conclusions and recommendations for Tasks 7 and 8 of this project.

5.1 Conclusions

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

Task 7

- The TruckSIM™ simulations provided reasonable estimates of the expected tire loads and vertical accelerations of the two trucks used in the simulations.
- The trends observed for the TruckSIM™ simulation data were similar to published and expected trends, and it appears as if the data can thus be used to model roads and vehicles where data cannot be collected on roads using real trucks.

Task 8

- The measured data obtained from the two trucks on the various roads were consistent with expected trends in published literature.
- Measured data were used to analyze trends on the effects of riding quality on speeds, as well as the effect of unique features such as concrete slabs on the generated vertical accelerations in the vehicles.

Data Comparison

- A high-level comparison between the simulated and measured data indicated similar trends and similar data obtained from the two processes.
- Matching locations exactly between the simulated and measured data proved to be complicated, but reasonable location comparisons could be obtained.
- If exact location comparisons and vehicle conditions (load, inflation pressure, suspension stiffness, etc.) could be obtained, the match between the two sets of data could be improved further.

5.2 Recommendations

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

- *Task 7.* TruckSIM™ simulations should be incorporated into any further studies of this kind to enable a cost-effective option for generating realistic vehicle parameters (accelerations, tire loads, etc.) for a wide array of roads in California.

- *Task 8.* Additional measurements of densification of tomatoes on trailers during transportation on a range of roads causing a range of vertical acceleration frequencies should be obtained to enable a detailed analysis of the potential damage to the transported tomatoes.
- *Other.* The data measured and simulated for Tasks 7 and 8 should be incorporated into the methodologies for Tasks 9 to 11 to ensure that the map of road conditions and relationship for riding quality and tire loads/freight accelerations are realistic in terms of typical California data.

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2. Steyn, W.J.vdM. *Analysis of Vehicle-Pavement Interaction Effects on Vehicular Loads and Transported Freight.* Report prepared for the Caltrans Division of Research and Innovation. Davis and Berkeley, CA: UCPRC, 2011. (In process.)
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