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Freight-Truck-Pavement Interaction, Logistics, and Economics: Final Executive Summary Report

Compilation of Executive Summaries

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

PREPARED FOR:

California Department of Transportation
Division of Transportation Planning (DOTP)
Office of Materials and Infrastructure

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Caltrans Technical Leads: Nerie Rose Agacer-Solis and Bill Nokes

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Abstract:
This document is a compilation of the executive summaries of the four reports developed for this research project. Each of the four individual reports covers a specific aspect of the project, and this report provides an overview of the entire project. For details on each of the tasks in the overall project, readers should access the individual reports.

Keywords: vehicle-pavement interaction, freight, logistics

Proposals for Implementation:
This final report will be studied by the client and be available for decisions relating to the project objectives.

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

Signatures

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DISCLAIMER STATEMENT

ACKNOWLEDGMENTS

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

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

ABOUT THIS COMPILATION

This document is a compilation of the executive summaries of the four project reports developed 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. Each of the four reports covers a specific aspect of the project. This compilation provides an overview of the project. Readers should access the specific reports for details about each of the tasks in the overall project.

PROJECT OBJECTIVES

The overall objectives of this project (PPRC SPE 4.44) are to enable Caltrans to better manage the risks of decisions regarding freight and the management and preservation of the pavement network, as the potential effects of such decisions (i.e., to resurface and improve ride 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 the 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 objective of this compilation report is to collect the executive summaries of the Vehicle-Pavement Interaction and the Logistics Augmentation studies into one report. Details about each of the studies are available in each of the original project reports, which are referred to in the relevant sections of this compilation. The specific objectives of each of the four reports are as follows.

Tasks 1 to 6

The objectives of this report were to provide information on Tasks 1 to 6, and to provide guidance about the specific corridor or Caltrans district on which the remainder of the pilot study (Tasks 7 to 12) should be focused.

Tasks 7 to 8

This report had the following objectives:

- Provide information on Tasks 7 and 8
- Analyze data collected for two private firms, referred to as Companies A and B, that participated in field studies performed by the research team
- Compare vehicle and freight data with riding quality

Tasks 9 to 11

The objective of this report was to provide information on Tasks 9 to 11. These tasks have these specific objectives:

- Task 9, Maps: For selected freight corridors, develop maps showing the riding quality of roads and its effects on vehicles and freight
- Task 10, Relationships: Develop a simple relationship between riding quality and the additional loads on the pavement/expected freight damage/expected additional vehicle operating costs
- Task 11, Environmental: Explore potential links regarding environmental impacts and construction riding quality specifications
- Potential effects of riding quality that lead to damage of tomatoes being transported on roads was evaluated by a laboratory study described in the report.

Logistic Augmentation

This study had these objectives:

- Provide a basic understanding to Caltrans of private-sector decision making in road-freight transportation
- Identify and describe the comprehensive set of interactions between the efficiency and efficacy of road-freight transportation and the capacity, performance and regulation of road infrastructure in the state, and recommend which of these interactions warrant more in-depth assessment on a statewide scale to quantify the overall economic and efficiency impact road infrastructure decisions have on the economy of California
- Illustrate the value of direct interactions and consultations with private companies in exploring private-sector decision making and the interdependence of these decisions on public sector actions

Note on the text: 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 compilation report retains the future tense when referring to remaining tasks although all the tasks and the pilot study have been completed.

EXECUTIVE SUMMARY: FINAL PHASE 1 REPORT (TASKS 1–6)

From: W.J.vdM. Steyn, N. Viljoen, L. Popescu, and L. du Plessis 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)

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 toward planning and economic models to enable an improved evaluation of the freight flows and costs in the selected region/district. It is anticipated that use of findings from this study as input by others into planning and economic models will enable calculating the direct effects of ride 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 ride quality and subsequent increased vehicle operating costs, vehicle damage, and freight damage. The study will be conducted as a pilot study in a region or 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 3–5; the final selection of an appropriate region/district will be made by Caltrans. This focused pilot study enables the approach to be developed and refined 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 has been accepted and 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 regarding freight and the management and preservation of the pavement network, as the potential effects of such decisions (i.e., to resurface and improve ride 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 1–6, and to provide guidance about the specific corridor or district on which the remainder of the pilot study (Tasks 7–12) should be focused.

The data presented and discussed in Sections 3 to 5 of this document presents information sourced from a range of independent sources. Each of the sets of information is discussed in detail as individual information. Relevant information originating from Sections 3 to 5 is combined to present a case for a specific region/corridor to be focused on. The details of the specific data sets are not necessarily repeated, but reference is made to the relevant sources and locations in the report.

Report Issues

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

Road Inventory

The main outcome of Task 3 is to identify routes in each district and county for which ride quality data exists, as well as the actual ride quality for these routes (due to the volume of data, the actual data are kept only in electronic form). Routes in California have been identified and a database containing actual road profiles and ride quality data is available for use in the remainder of the pilot project.

Vehicle Inventory

The deliverable for Task 4 is a table of current vehicle population per standard FHWA vehicle classifications for Caltrans. Based on the various sources used in this task (FHWA truck classifications, commodity flow analysis, and weigh-in-motion [WIM] data), the following was identified:

- The most common truck types in the pilot study area are FHWA Class 9 and 12 (up to 48 percent of the trucks on selected routes), followed by Class 5.
- High truck flows are experienced in District 6, part of the San Joaquin Valley.
- Axle load spectra are heavier at night than in the daytime.
- Axle load spectra and truck type distribution show very little seasonal variation.
- Axle load spectra are much higher in the Central Valley than in the Bay Area and Southern California, particularly for tandem axles.
- More than 90 percent of the truck traffic traveled in the outside or two outside lanes (two- or three-lane [in one direction] highways) or two outside (three-lane [in one direction] highways) lanes.
- Truck speeds typically fall within the range of 50 to 75 mph (80 to 120 km/h).
- Leaf springs are predominantly used in steering axles, with drive axles using air suspension and trail axles using leaf suspension.

Information Review

Task 5 focuses on evaluating the data obtained from the various resources for Tasks 3–4, as well as additional relevant information that may add to the project. The deliverable of Task 5 is a detailed understanding and input to the 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.

California Statewide Freight Planning

The purpose of the California Statewide Freight Forecast (CSFF) model is to provide a policy-sensitive model to forecast commodity flows and commercial vehicle flows within California, addressing socioeconomic conditions, land-use policies related to freight, environmental policies, and multimodal infrastructure investments. Appropriate information and data about freight movements and costs are needed to enable accurate modeling.

Commodity Flow Survey

It is evident that truck-based transportation dominates the freight transportation scene in California. Eighty-two percent of the freight tons shipped from California utilizes only trucks. The data indicate that the highest percentage of commodities (in terms of value, tons, and ton-miles) transported by truck consists of manufacturing goods, wholesale trade, and nondurable goods for the whole of California. No specific information for commodity flows into California (destination California) could be identified in this pilot study.

San Joaquin Information

The San Joaquin Valley is composed of eight counties and 62 cities. It has a diverse internal economy and also plays a major role in the distribution of agricultural materials throughout California, the United States, and the world. Trucks are the dominant mode, with more than 450 million tons of goods moved by truck into, out of, or within the San Joaquin Valley in 2007—more than 85 percent of all tonnage associated with these types of moves in the San Joaquin Valley. Truck movement in the San Joaquin Valley relies on a combination of all levels of highways and roads in the area. Key regional highways include the primary north-south corridors (I-5 and SR 99) and east-west corridors (I-580, SR 152, SR 41, SR 46, and SR 58), which in total constitute more than 31,000 lane-miles. There are over 2,700 lane-miles of truck routes in the San Joaquin Valley region, with over 80 percent designated as national STAA Truck Routes.

Farm products are the dominant commodity carried outbound from the San Joaquin Valley, comprising 33 percent of the total outbound movements. These consist of fresh field crops (vegetables, fruit and nuts, cereal grains, and animal feed). Stone and aggregates account for 18 percent of the total, food and tobacco products around 10 percent, and waste and mixed freight 6 percent and 4 percent of the total tonnage, respectively.

The region accounts for over 8 percent of the total gross domestic product (GDP) for California. However, the region accounts for a much higher proportion of output within sectors such as agriculture (nearly 50 percent) and mining and mineral extraction (25 percent). The San Joaquin Valley includes 6 of the top 10 counties in California in total value of agricultural production.

Goods Movement Action Plan

California's Goods Movement Action Plan (GMAP) includes a compiled inventory of existing and proposed goods movement infrastructure projects, including previously identified projects in various regional transportation plans and transportation improvement programs prepared by metropolitan planning organizations, regional transportation planning agencies, and county transportation commissions. One of the four priority regions and corridors identified in the GMAP is the Central Valley region, which coincides with the San Joaquin Valley.

California Life-Cycle Benefit/Cost Analysis Model

Caltrans uses the California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C) to conduct investment analyses of projects proposed for the interregional portion of the State Transportation Improvement Program (STIP), the State

Highway Operations and Protection Program (SHOPP), and other ad hoc analyses requiring benefit-cost analysis. The following required inputs are deemed to be potentially affected by the work conducted in this pilot study: roadway type, number of general traffic lanes, number of HOV lanes, HOV restriction, highway free-flow speed, current and forecast average annual daily traffic (AADT), hourly HOV/HOT volumes, percent trucks, truck speed, and pavement condition.

Industry

Potential involvement of industry in Task 8 activities includes:

- GPS tracking and acceleration measurements on selected trucks traveling on designated State Highway segments—need for trucks, trailers and freight
- Truck trailer information as input into computer simulations of vehicles traveling over a range of pavements

Models for Rolling Resistance in Road Infrastructure Asset Management Systems Project

The objective of the Models for rolling resistance In Road Infrastructure Asset Management systems (MIRIAM) project is to conduct research to provide sustainable and environmentally friendly road infrastructure, mainly through reducing vehicle rolling resistance, and subsequently lowering CO_2 emissions and increasing energy efficiency. Potential links between the MIRIAM project and the pilot study mainly lie in the possible use of selected rolling resistance models originating from MIRIAM in the evaluation of the effects of pavement roughness on vehicle energy use, emissions, and rolling resistance. Caltrans and UCPRC have participated in MIRIAM Phase I and plan to continue participating in Phase II. Initial MIRIAM studies indicated that:

- Rolling resistance is a property of tires and the pavement surface.
- A proposed source model for the pavement influence on rolling resistance contains mean profile depth (MPD), pavement roughness (IRI), and pavement stiffness as significant pavement parameters.
- For light vehicles the effect of pavement roughness on rolling resistance is probably around a third of the effect of MPD, and it appears to be higher for heavy vehicles.

California Inter-Regional Intermodal System

The California Inter-Regional Intermodal System (CIRIS) was envisioned as an umbrella concept for rail intermodal service to and from the Port of Oakland and other Northern California locations. The increased use of rail options for these transportation options will affect truck volumes and deterioration of the pavement infrastructure.

I-5/SR 99 Origin and Destination Truck Study

This study indicated that:

- Traffic volumes within the study area were found to be consistent for fall and spring seasons, with the some exceptions, whereas overall truck percentages were higher in spring compared to fall, with a few exceptions.
- Little variance was observed in truck travel patterns between fall and spring.
- The majority of trucks (83.8 percent) were 5-axle double-unit type.
- Seventy percent of the trucks were based within California: 47 percent of these were based in the San Joaquin Valley region, and 34 percent in the Southern California region.
- The top five commodity types by percentage are food and similar products (21 percent), empty trucks (18 percent), farm products (14 percent), miscellaneous freight (12 percent), and transportation equipment (4 percent).

State of Logistics South Africa

The ride quality of a road has, for many years, been used as the primary indication of the quality of a road—mainly due to findings that deterioration in the road structure ultimately translates into a decrease in the ride quality of the road. Various studies about the effect of the ride quality of roads on the vibrations and responses in vehicles have been conducted, with the main conclusions indicating that a decrease in the ride quality of a road is a major cause of increased vibrations and subsequent structural damage to vehicles. These increased vibrations and structural damage to vehicles potentially have many negative effects on the transportation cost of companies (including both truckers/carriers and manufacturers/producers of goods) and the broader economy of a country.

The increase in internal logistics costs due to inadequate road conditions is experienced by most, if not all, transportation companies. This figure eventually adds up to a massive increase in the logistics costs of a country as a whole. As the logistics costs of a country increase, the cost of its products in the global marketplace increases, which can have devastating effects on the global competitiveness of that country. It is therefore of critical importance to manage logistics costs effectively and to minimize unnecessary costs that can translate into higher product costs.

Comparing the estimated annual road maintenance costs per kilometer with the potential savings in vehicle operating costs shows significant benefits that can be realized by keeping the road in a good condition.

The vertical acceleration experienced when traveling over rough road surfaces is what causes damage to vehicles, increased wear and tear and, potentially, damage to and loss of transported cargo. The economic impact of damaged agricultural cargo is absorbed differently by large- and small-scale farming companies.

Freight Logistics

When freight is damaged it results in both direct and indirect losses in potential revenue through effects on logistical operations. These operational repercussions depend on the type of freight and the standard operating procedures of shipper and receiver. They include:

- Product is sent back to the shipper for replacement, repair, or repackaging—placing a burden on the reverse supply chain.
- Product is "written off" and must be disposed of by the receiver.
- Product must be reclassified as damaged before selling.

The most prominent implications for the freight logistics aspect is the link to the Cal-B/C model. To perform a benefit-cost analysis of upgrading/repairing a certain stretch of road, potential freight damage savings accrued by the upgrade must be given as input into the Cal-B/C model. Therefore, the pilot study should develop a methodology whereby field measurements, stakeholder engagements, and existing data sources can be used to estimate freight damage savings along a certain stretch of road.

To achieve the objectives discussed above requires cost calculations at a disaggregate level (consisting of many aspects, including type of goods, type and attributes of truck/trailer, and attributes of roadway). Firstly, the expected freight damage cost incurred by a particular type of shipment must be quantified. Secondly, the individual shipment costs must be aggregated to provide higher-level cost estimates.

Based on the available information, the following commodities should be most relevant for this pilot study:

- Various kinds of manufactured goods, particularly nondurable or electronic goods
- Agricultural and various other food products
- Mining products, such as coal, minerals, gravel

Summary

Based on the information in Section 6.2.2, there exists a good understanding of the SHS pavement conditions in terms of ride quality in California, as well as the major truck types and operational conditions on these pavements. The major commodities being transported have been identified, and the potential links with models such as the

Cal-B/C models are apparent. Most of the information on commodity flows and truck operations are available for the San Joaquin Valley, which forms a major corridor for transport of agricultural and related freight.

Motivational Reasons for Recommended Region/Corridor

The information presented in this report provides a good basis of information to describe the freight movement and transport infrastructure conditions in the San Joaquin Valley region in California.

Transportation and logistics in this corridor are being studied in detail in various studies, supporting the notion that the corridor is important for the economy of California. This idea is also supported by data indicating that a large proportion of freight originates, passes through, or is destined for companies and markets in this region.

Based on the information provided in this report, it is thus recommended that the San Joaquin Valley region be used in the remaining tasks of this pilot study. Routes I-5, SR 58, and SR 99 are recommended as suitable routes for the pilot field study. Specific commodities and trucks in the valley need to be identified for the details of Tasks 7–8.

EXECUTIVE SUMMARY: FINAL PHASE 1 REPORT (TASKS 7–8)

From: W.J.vdM. Steyn. 2013. Freight-Truck-Pavement Interaction, Logistics, and Economics: Final Phase 1 Report (Tasks 7–8). Research Report prepared for Caltrans Division of Transportation Planning. (UCPRC-RR-2013-08)

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 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.

EXECUTIVE SUMMARY: FINAL PHASE 1 REPORT (TASKS 9–11)

From: 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)

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

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

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

Report Issues

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

Task 9 – Maps

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

Task 10 – Relationships

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

Task 11 – Environmental

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

Applications and Implications

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

From the Caltrans (public agency) viewpoint, the potential benefits of the information and models provided and discussed in this report are the following:

- Tire loads on specific routes: Tire loads generated on roads with different levels of roughness can be determined, and this information can be used as input for road pavement design, specifically catering for changes in the road roughness over the life of the pavement.
- Construction/maintenance quality control evaluation: The information can be used to determine the effects of different levels of quality control during construction and/or maintenance of the roads, as the effect of quality control on road roughness is known, and these changes can be related to expected life and user costs for the road.
- User costs on specific routes: Models are presented that can be used to calculate the user costs on roads with different roughness levels, serving as input to various economic models and calculation of benefit/cost ratios of maintenance and upgrading actions on these routes.

For private companies using the roads in California for transportation of goods, the potential benefits of these models and data are:

- Evaluation of potential VOCs on specific routes: The data can be used to calculate the costs of traveling specific routes, as well as in the selection of routes that may be longer in distance, but more cost effective due to lower roughness levels.
- Route planning: Based on the potential damage to sensitive freight, and the potential damage due to road roughness, alternative routes may be evaluated and smoother routes selected where available.
- Evaluation of the potential losses and additional costs due to transportation of agricultural produce (specifically tomatoes) over roads with less-than-desirable road roughness levels.

EXECUTIVE SUMMARY: LOGISTICS AUGMENTATION REPORT

From: 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)

The efficient movement of goods within an economy is a crucial lever to competitiveness. Road freight is the predominant freight transportation mechanism in California, with 78 percent of communities connected exclusively by road and 88 percent of manufactured goods being transported by truck. The efficiency of road-freight transportation depends on the capacity and performance of publicly owned and managed road networks as well on as the capacity and performance of privately owned truck fleets. Growing freight volumes and increasing demands on freight transportation systems to be reliable, cost efficient, time efficient, flexible and adaptable have highlighted the importance of the interdependence between the public and private sector in providing the population with the essential freight systems it requires. Despite the importance of this interdependence between the public and private sector in road-freight transportation, the divergent decision-making styles of the two parties hamper collaboration. In essence, the differences between these two parties arise from the fundamentally different roles they play. The purpose of this logistics augmentation pilot study is to identify and examine those interdependencies that have particular bearing on road-freight transportation in California.

SECTION 1: BACKGROUND INVESTIGATION AND LITERATURE STUDY

Overview of California Freight Transportation

Freight transport is the cornerstone of California's economy, and with 40 percent of freight entering and exiting the U.S. through California's sea, land and air gateways, the state's freight systems are critical to the overall U.S. economy. A significant component of California's freight flows arise from through traffic of international shipments. California is regarded as the breadbasket of the U.S. economy, supplying more than 50 percent of its agricultural goods, and combined with manufacturing, and especially the high-value manufacturing industries, California has a freight-heavy economy. The freight growth drivers impacting California are:

- The growth in international trade;
- Growth in the local consumer population, and
- A move towards inventory-pull systems and an increase in manufacturing output.

The four priority freight regions identified in California (Los Angeles/Inland Empire Region, Bay Area Region, San Diego/Border Region, Central Valley Region) all experience very high levels of road-freight volumes that result in rapid infrastructure deterioration and congestion. Capacity constraints hamper all transport modes in

California but are especially acute for road infrastructure. Deterioration and aging road infrastructure also pose a critical problem for freight movement in California. However, there is great opportunity for road-rail intermodal solutions, specifically long-haul rail services and short-haul rail shuttle services, to reduce congestion and overall transport costs in California.

Public Sector Perspective

The role of the public sector is in the planning, ownership and maintenance of road-freight infrastructure as well as in creating the economic environment within which private entities operate through regulations. There are key role players on every level of government that directly impact road-freight transportation in California. Key drivers of public sector decision making include investment and financing, economic regulation, providing and maintaining infrastructure, land use, environmental issues, safety, operations and jobs and employment.

State-level strategic plans that hold particular relevance for this study are the California Transportation Plan 2025, the California State Rail Plan 2007-08 to 2017-18 and the Goods Movement Action Plan. The recent San Joaquin Valley Interregional Goods Movement Plan and the Central Coast California Commercial Flows Study are also of particular interest as they followed a directed and successful private and public sector engagement approach in identifying and prioritizing regional freight challenges and projects. In addition, the 2010 Regional Transportation Plan Guidelines are explicit about freight modeling requirements and cooperation and collaboration requirements for Regional Transport Plans. The move towards activity-based freight models will provide better decision support and it will also require a far better understanding of private sector operations and decision making, as well as extensive access to private sector data; this will not be achieved without close cooperation and collaboration with a large number of private companies. The guidelines now also require explicit private sector involvement in the formulation of regional plans, similar to the extensive public participation processes currently employed during the development of plans. Insights and findings relevant to road-freight transportation were extracted from a selected number of Regional Transport Plans relevant to the operational investigation that will be conducted in Task L3 of this pilot study.

Private Sector Perspective

The role of the private sector is to generate earnings for shareholders through the selling of goods and services. In fulfilling this role, the private sector is a user of the available road-freight systems to transport goods in the most competitive manner possible. Private sector decisions can be strategic (long-term), operational (short- to medium-term) or tactical (short-term) in nature. The key decision drivers that cut across all levels of private sector decisions are market and shipper demand, financial performance metrics, efficient operational management, and regulatory issues.

Outsourcing is a growing logistics trend even despite tough market conditions and the growing volatility of logistics chains. Outsourcing practices obscure the locus of control for many logistics decisions in the private sector. These days, shippers are demanding disruptive innovation from third-party logistics (3PL) providers, which requires real-time information technology solutions and the ability to extract business value from big data—and herein lies an opportunity for the public sector to collaborate with the private sector and obtain the data required for accurate freight modeling.

The move toward inventory-pull systems is greatly increasing the demand for transportation, generally negating the benefits of economies of scale. Higher-value inventory is being reduced at the cost of increasing lower-value transport activities. However, this trend greatly contributes to congestion and emissions, especially in urban areas where the e-commerce industry has skyrocketed.

The need for road-rail intermodal services is increasingly apparent among rising fuel costs, increased congestion and escalating environmental pressures. But for intermodal solutions to be viable alternatives to door-to-door trucking requires efficient and reliable rail service (akin to trucking performance) and efficient and aptly located intermodal terminals.

Some trends in the trucking industry also have bearing on the efficiency of road-freight transport in California. In particular, the disaggregated nature of the industry, with 90 percent of motor carriers having six or less power units, has a distinct impact on private sector decision making and behavior. Fleet capacity constraints caused by driver shortages and increased regulation of driver working conditions and vehicles is anticipated to become a major choke point for the logistics industry in the future. Road congestion is also especially rife in California with dire consequences to trucking competitiveness. Fifteen of the 250 truck bottlenecks identified by the Federal Highway Administration (FHWA) and American Transportation Research Institute (ATRI) in the U.S. are in California *[1]*.

Interdependence of Public and Private Decisions

Differences in decision-making paradigms between the public and private sector arise from their fundamentally different roles and objectives when engaging with road-freight systems. Particular differences relate to the following decision characteristics: scale of investment, geography, the process whereby decisions are reached, planning horizons and timing, the objectives of decisions and the decision-making attitude. Recommendations for successful private-public interactions based on case studies conducted by the National Cooperative Freight Research Program (NCFRP) highlight the importance of communication, education and appreciation between the two parties.

SECTION 2: CASE STUDY RESEARCH REGARDING THE INTERSECTION OF SUPPLY CHAINS AND ROAD INFRASTRUCTURE AND REGULATION

Section 2 of this study is specifically targeted to apprise Caltrans (public sector) of the practical ways in which California road infrastructure and regulations affect daily supply chain management practices within specific economic sectors.

Task L3: Operational Investigation

Within the scope of this pilot study, the operational investigation served to show how the case study method could yield useful practical insights for specific industries when founded on a comprehensive literature review. Narrowing the focus to road-freight systems under the jurisdiction of Caltrans, this operational investigation explores and describes the practical elements of the interdependence between the public and private sector by observing operations at companies and conducting structured interviews with private sector managers. A case study approach is used for this exploratory and descriptive investigation. In order to validate the empirical evidence from the case studies, the findings will be tested against the literature review and various triangulation methods have been designed into the case study methodology. Explicit privacy and confidentiality protocols were also developed to safeguard the anonymity and confidentiality of the companies that participated in this study. Operational investigations were conducted at two companies, Company A and Company B.

Company A

Company A is in the agricultural and food processing sector. Its primary business is the production of a range of bulk food products from fresh produce. The company harvests its own fresh produce from farms in northern and southern California and it leases and operates a truck fleet that transports the produce from the farms to the processing facilities. The company also owns and operates a number of processing and storage facilities in California, and its transport division handles the staging of empty tins and packaging materials between these facilities. Company A's transport division also handles some deliveries of finished products to customers. The operational investigation of Company A was conducted over three days, May15, 16, and 17, 2013.

The scope of business operations and resource planning in Company A hinges on the seasonality of the fresh produce. This is typical of agricultural supply chains where the harvesting cycle sets the tempo for downstream logistics activities. Due to peak-season surges in supply and the fact that there is no inventory buffer between the inbound logistics and the processing facilities, the timing and efficiency of inbound logistics are critical. Road works and traffic congestion pose the greatest threat to the efficiency of inbound logistics.

Outbound logistics efficiency is decoupled from processing plant operations by a significant inventory buffer. Although outbound logistics efficiency does not affect plant operations, it is still important from a cost-saving and customer service point-of-view. The biggest threat to outbound logistics efficiency is erratic customer orders.

Drivers are highly motivated as a result of the following organizational practices:

- None of the drivers at Company A are unionized;
- Drivers are all paid per load and distance (not per hour), and
- The majority of drivers are employed seasonally with stringent recruitment/readmission criteria.

Compliance, Safety, Accountability (CSA) regulations are strictly enforced using an On Board Computer (OBC) system and there is no leniency for safety or regulatory violations. Three factors that dampen driver morale are situations where drivers believe they are not being fully utilized (and therefore not accruing maximum earnings), physical comfort while driving, and road safety. Rough road conditions increase driver discomfort and physical fatigue. The short merging lanes on some highways and the mixing of passenger and truck traffic both pose significant road safety hazards and frustrate the drivers. Drivers generally know the predetermined routes by heart, and when traffic is diverted from these routes (due to road works or accidents) it can be tricky to recalculate the shortest route while taking into consideration prevailing route restrictions. As key motivators, drivers cited their love of driving, the freedom and independence of driving their own truck, and their self-determination.

A successful example of public-private interaction is where one of the processing plants joined forces with other companies in the area to contribute financially to the upkeep and maintenance of the rural road leading to their facilities. This ensured that local agencies promptly attend to road repairs. Other than this initiative, Company A had minimal interaction with public agencies. The Senior Manager agreed that there would definitely be mutual benefit to more structured interaction between public and private agencies, and he indicated willingness to dedicate a couple of days to such initiatives. A quick-win in this regard would be better communication regarding the scheduling of road works during peak-season, as these could greatly disrupt inbound logistics.

Road infrastructure considerations contribute marginally to Company A’s decisions regarding whether to take on certain customers or suppliers; this is a strategic-level decision. On the operational and tactical levels, the daily scheduling and routing of pickups and deliveries are affected by road works and congestion while CSA regulations affect driver management and trip planning.

Company B

Company B is an asset-based motor carrier with two primary business streams:

- Consolidating less-than-truckload (LTL) shipments from the continental U.S. for shipment to Canadian terminals, and
- Domestic LTL shipments across the continental U.S.

Company B has a number of terminals within its network in the U.S. as well as partner terminals in Canada and the U.S. The California terminal where the researchers conducted their operational investigation has an additional business stream that was inherited from the company that previously operated from that terminal and it is unique within Company B's network. This business stream is the pickup and delivery of intrastate LTL freight. The operational investigation of Company B was conducted over two days, May 21 and 22, 2013.

LTL shippers need to be very flexible and adaptable to serve their customer's transport needs amid volatile business cycles. The efficacy and efficiency of the consolidation and synchronization of shipments is critical in keeping costs and lead times down. Achieving this requires constant coordination and communication among the terminals in the network and thus the physical structure of the network, i.e., the location of terminal facilities and their interconnectivity, greatly influences the business's performance.

Drivers are permanently employed by Company B, are paid by the hour (and compensated for distance) and are not unionized. Drivers that can adhere to Company B's stringent safety requirements and have the right credentials for CSA accreditation are in short supply. CSA accreditation is essential for drivers crossing the Canadian border. Drivers cite the thrill of driving and the freedom and autonomy of truck driving as primary motivators. Meanwhile, road safety, congestion and waiting at client terminals cause great frustration. Drivers at Company B also state that the short merging lanes and mixing of passenger and truck traffic are road safety hazards and they suggest truck-only lanes. Narrow streets and driveways and a lack of truck parking also cause great frustration when executing pickups and deliveries in urban areas. Drivers noted a clear difference in road conditions between California and neighboring states, and reported that rougher road conditions affect their driving comfort and fatigue.

Road regulation hampers Company B's operations, especially when compared with other states. Firstly, the process to register new trucks is reportedly cumbersome. Secondly, the implementation schedule of the new environmental efficiency regulations for trucks is forcing Company B to retire trucks long before their 750,000 mile cut-off point, causing severe financial repercussions. The excessive inspections performed on trucks also waste a lot of time. While the content of environmental and road safety regulations are supported in principle, their implementation causes operational inefficiencies. Route restrictions in Northern California are considered excessive and are causing severe traffic chokepoints in the Bay Area. Company B makes two pertinent suggestions regarding road regulations: allowing triple trailers and opening of the road to trucks through truck-only lanes and the lifting of route restrictions.

Road infrastructure and regulation can play a key role in deciding where to build a network terminal, which is a strategic level decision. Conversely, although congestion, road works and road conditions frustrate drivers and managers, these factors do not seem to affect actual operational and tactical level decisions.

The issues uncovered and suggestions made during the case studies were congruent with those challenges identified and projects prioritized in the San Joaquin Valley Interregional Goods Movement Plan.

Supply Chain Design and Vulnerability

Transport infrastructure and regulation affects the supply chain in two ways:

- The design, location, performance and regulation of transport infrastructure are critical inputs to the design of the supply chain network, and
- The propensity of transport disruptions and delays caused by infrastructure failure contributes to overall supply chain vulnerability.

There are three classes of supply chain risk sources, namely demand-side risk sources, supply-side risk sources, and supply chain structure risk sources. Road infrastructure and regulation can render supply chains more vulnerable to these risk sources on three levels—on the product or process level, on the asset and infrastructure dependency level, or on the operating environment level. The analysis of how road infrastructure and regulation affects supply chain vulnerability was conducted considering industry/economic sector aggregation. In this pilot study, two of the ten goods movement-dependent economic sectors of California were considered in case studies, namely the Agriculture, Forestry and Fishing sector and the Transportation and Warehousing sector.

The major hazards facing the agricultural industry in general are broad-based, contributing to each one of the three supply chain risk source categories. In the case of Company A, weather-related hazards, natural disasters and biological or environmental hazards can have a great impact because all of their suppliers are geographically concentrated. Logistics and infrastructure hazards are also especially detrimental due to the perishable nature of its products and the seasonal pressures of inbound logistics. Agricultural products are generally low margin products and thus changes in input costs (such as energy or transport costs) can be debilitating. Transport efficiency plays a tremendous role in ensuring that product is not lost and that costs are kept low. In addition, studies have shown that food supply chains are very vulnerable to terrorist attacks and that targeting the transport function (either through jeopardizing infrastructure or vehicles) would be the most effective way to undermine these supply chains.

The Transport and Warehousing sector is comprised mostly of third-party logistics (3PL) companies to whom one or more logistics activity has been outsourced. The U.S. 3PL sector has grown significantly, with revenue quadrupling between 1996 and 2008. 3PL companies are mostly exposed to two groups of risks: volatility in business demand as a result of any one of the previously mentioned risk sources in their clients' supply chains; and vulnerability to factors that jeopardize 3PLs' abilities to deliver the expected service. The factors that could seriously jeopardize 3PLs' abilities to deliver the expected service are related to transport infrastructure, communication infrastructure, economic volatility, environmental regulation, and geopolitical unrest. Given California's heavy dependence on road infrastructure, even short-term delays or capacity constrictions caused by congestion or construction could be detrimental to the 3PL industry, not just the large-scale disruptions caused by, for example, terrorist attacks or earthquakes. The implementation of ever-stricter environmental regulation also places severe financial and operational burdens on Company B and other asset-based motor carriers.

Supply chain network design is also significantly affected by transport infrastructure and regulation. Supply chain network design has been defined by Klibi et al. *[2]* as the "strategic decisions on the number, location, capacity and mission of production-distribution facilities in a company, or of a set of collaborating companies, in order to provide goods to a predetermined, but possibly evolving, customer base. It also involves decisions related to the selection of suppliers, subcontractors and 3PLs, and to the offers to make to product-markets." During supply chain network design, a number of value drivers have to be balanced among many diverse supply chain organizations. These value drivers are related to revenue (customer service, product, market coverage), cost (product cost, logistics cost, overheads), and capital expenditures (network investments, value of current assets). Transport infrastructure and regulation affect revenue by impacting customer service, product availability, and potential market coverage. In addition, transport costs are the greatest drivers of logistics costs and are heavily influenced by the design, location and performance of infrastructure as well as the cost of adhering to regulations. Lastly, infrastructure and regulation affect decisions regarding facility location (capital expenditures).

The Spread of Economic Sectors in California and Implications for Road Infrastructure and Regulation

Ten of the economic sectors identified by the United State Census Bureau are considered goods movement-dependent economic sectors, namely:

- Mining;
- Utilities;
- Agriculture, Forestry and Fishing;
- Manufacturing;
- Transportation and Warehousing;
- Retail Trade;
- Wholesale Trade;
- Waste Management;
- Health Care and Social Assistance, and
- Accommodation and Food Services

The supply chain design and vulnerability factors relevant within each of these economic sectors varies greatly and thus the manner in which road infrastructure and regulation affects each of these sectors also varies. The Agriculture, Forestry and Fishing and Transport and Warehousing sectors have been discussed in this pilot study based on the case study findings. Analysis of the other eight sectors is beyond the scope of this pilot study. It is critical for Caltrans to be aware of which sectors are present in which counties and the size of those sectors. Having this awareness could alert Caltrans to the potential impact of certain road infrastructure and regulation decisions on the various sectors present and spur collaboration with private industry to mitigate potential negative effects.

Analysis of these economic sectors within the 58 Californian counties was based on the economic values reported by the United States Census Bureau's American Fact Finder tool. (Economic contribution was considered instead of tons transported to ascertain a better picture of the potential economic impact of supply chains in these sectors.) Los Angeles, Orange, Santa Clara, Alameda and San Diego are the five most prominent counties, with wholesale trade, retail trade and manufacturing contributing most to these counties' economic well-being. Individual county analyses for all 58 counties are presented in the technical appendices.

CONCLUSIONS AND WAY FORWARD

This study has shown through desktop studies, qualitative analysis, and case studies that road infrastructure and regulation, as managed by Caltrans, has a marked impact on supply chain operations and strategies. This is one instance where public sector decision making greatly influences private sector decision making. The analysis has shown that, in this instance, the reciprocal influence of private sector decision making on public sector decision making is not as significant. Given the critical role that supply chains play in the economic well-being and quality of life in California and the dependence of these supply chains on road infrastructure and regulation, it is imperative that the public sector (Caltrans) and private sector are engage throughout the planning and construction of road infrastructure as well as during the drafting and implementation of policy. There have been a few successful efforts in this regard, for example in the recent establishment of the California Freight Advisory Committee and in the deliberate and interactive inclusion of the private sector stakeholders during drafting of the San Joaquin Valley (SJV) Interregional Good Movement Plan.

The first step in more meaningful engagement between Caltrans and the private sector is an adequate understanding of how and when road infrastructure and regulation influence supply chains. In this pilot study, it has been identified that road infrastructure and regulation have a direct effect on supply chain vulnerability and design, and that private companies make decisions that take these two elements into consideration. However, supply chain vulnerability and design are different for each economic goods movement-dependent sector and therefore a blanket approach would not suffice.

This pilot study presented the methodology for a sector-by-sector analysis that can inform Caltrans regarding the intricacies and considerations of supply chain vulnerability and design in different sectors. The scope of the pilot study was limited in the following terms:

- Only two of the ten identified goods movement-dependent sectors were analyzed, namely the Agriculture, Forestry and Fishing sector and the Transportation and Warehousing sector, and
- Case studies were only conducted at one company in each of the sectors mentioned above.

In order for this study to be comprehensive enough to form part of routine Caltrans decision making regarding road infrastructure and regulation, its scope needs to be expanded to cover all goods movement-dependent sectors and it also needs to be deepened by conducting a representative ensemble of case studies in each sector.