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Effects of Increased Weights of Alternative Fuel Trucks on Pavement and Bridges

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Effects of Increased Weights of Alternative Fuel Trucks on Pavement and Bridges

November 2020

ITS UC DAVIS
INSTITUTE OF TRANSPORTATION STUDIES

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16. Abstract
California's truck fleet composition is shifting to include more natural gas vehicles (NGVs), electric vehicles (EVs), and fuel cell vehicles (FCVs), and it will shift more quickly to meet state greenhouse gas (GHG) emission goals. These alternative fuel trucks (AFTs) may introduce heavier axle loads, which may increase pavement damage and GHG emissions from work to maintain pavements. This project aimed to provide conceptual-level estimates of the effects of vehicle fleet changes on road and bridge infrastructure. Three AFT implementation scenarios were analyzed using typical Calif. state and local pavement structures, and a federal study's results were used to assess the effects on bridges. This study found that more NGV, EV, and FC trucks are expected among short-haul and medium-duty vehicles than among long-haul vehicles, for which range issues arise with EVs and FCs. But the estimates predicted that by 2050, alternative fuels would power 25–70% of long-haul and 40–95% of short-haul and medium-duty trucks. AFT implementation is expected to be focused in the 11 counties with the greatest freight traffic—primarily urban counties along major freight corridors. Results from the implementation scenarios suggest that introducing heavier AFTs will only result in minimal additional pavement damage, with its extent dependent on the pavement structure and AFT implementation scenario. Although allowing weight increases of up to 2,000 lbs. is unlikely to cause major issues on more modern bridges, the effects of truck concentrations at those new limits on inadequate bridges needs more careful evaluation. The study's most aggressive market penetration scenario yielded an approximate net reduction in annual well-to-wheel truck propulsion emissions of 1,200–2,700 kT per year of CO_2-e by 2030, and 6,300–34,000 kT by 2050 versus current truck technologies. Negligible effects on GHG emissions from pavement maintenance and rehabilitation resulted from AFT implementation.

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Trucks, electric vehicles, emissions, alternate fuels, greenhouse gasses, pavement distress, pavement performance, highway bridges, life cycle analysis

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Disclaimer

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November 2020

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Table of Contents

Table of Contents

List of Tables

List of Figures

Glossary

AADT	Average Annual Daily Traffic
AADTT	Average Annual Daily Truck Traffic
AB	aggregate base
AFT	alternative fuel truck
AASHTO	American Association of State Highway and Transportation Officials
BAU	business as usual
BEV	battery electric vehicle
Caltrans	California Department of Transportation
CTB	cement-treated base
CSTDM	California Statewide Travel Demand Model
CTSWL	Comprehensive Truck Size & Weight Limits
DOT	Department of Transportation
EV	electric vehicles
FCV	fuel cell vehicle
FHWA	Federal Highway Administration
GHG	greenhouse gas
GVW	gross vehicle weight
HMA	hot mix asphalt
ICE	internal combustion engine
LCA	life cycle assessment
LCCA	life cycle cost assessment
ME	mechanistic-empirical
M&R	maintenance and rehabilitation
NBI	National Bridge Inventory
NGV	natural gas vehicle

NHS	National Highway System
PCC	Portland cement concrete
RF	rating factor
RHMA	rubberized hot mix asphalt
RHMA-G	rubberized hot mix asphalt
RHMA-O	rubberized hot mix asphalt open-graded
TTM	Transportation Transitions Model
UC ITS	University of California Institute of Transportation Studies
UCPRC	University of California Pavement Research Center
VMT	vehicle miles traveled
WIM	weigh-in-motion
ZEV	zero emission vehicle

Executive Summary

Executive Summary

The composition of California's truck fleet is currently shifting from a conventional one consisting of mainly gasoline and diesel vehicles to one that includes more natural gas vehicles (NGVs), electric vehicles (EVs), and fuel cell vehicles (FCVs). This shift will occur with increasing speed to meet the state's greenhouse gas (GHG) emission goals.

However, these alternative fuel trucks (AFTs) may introduce heavier axle loads than current ones. These heavier loads can increase damage to the pavements they use and bring about an unintended consequence: increased GHG emissions resulting from either the necessary construction of stronger pavements or from the increased maintenance and rehabilitation (M&R) activities needed to keep those pavements in functional condition. Specifically, despite the similar engine weights of NGVs and conventional vehicles, NGV fuel tanks typically outweigh their conventional counterparts by 500 lbs. (250 kg) for a medium-duty truck and by 2,000 lbs. (1,000 kg) for a long-haul tractor. And although EVs and FCVs typically have lighter motors than conventional vehicles, their batteries typically outweigh those in current propulsion systems.

On September 20, 2018, then-Governor Jerry Brown signed California Assembly Bill 2061 (AB 2061) into law. This law allowed a 2,000 lb. weight limit increase in the gross vehicle weight (GVW) for near-zero-emission vehicles and zero-emission vehicles, while maintaining the current weight limits on individual axle types. The bill also included a request that the University of California Institute of Transportation Studies (UC ITS) conduct a study to evaluate the new law's environmental implications as well as its potential implications for transportation infrastructure.

Initial discussions regarding the study were held in February 2019 between legislative staff and ITS researchers from the UC Irvine, UC Los Angeles, and UC Davis campuses. On May 20, 2019, the Davis researchers submitted a proposal to perform the requested study, and prepared the scope definition, budget, and a formal proposal. After these were reviewed, they were signed on September 18, 2019. This report presents the study's results.

The goal of this project was to provide the California Legislature and other policy makers with conceptual-level estimates of the effects of vehicle fleet changes on road and bridge infrastructure. Evaluation of the effects of vehicle weight requirements on road safety was not part of the scope of this project. Road roughness can increase the fuel use of gasoline and diesel trucks by at most approximately six percent for the roughest roads, and if funds are available for scheduled maintenance should be less than about 3 percent. Road roughness was not considered because the effects were considered small compared to those of other factors, and because there is no information available regarding the effects of roughness on alternative fuel trucks.

The study followed these steps:

1. It estimated the additional weight of new technology vehicles relative to a conventional 2020 model year diesel truck considering three alternative pathways for implementation.
2. The study estimated the growth in truck travel and provided an estimate of where the increased travel attributable to the new technology trucks would occur.
3. The study assessed the impacts of axle load changes due to changes in vehicle technology and increased truck travel on bridge deterioration and its costs. This was done using the best available information, which came from the national Comprehensive Truck Size & Weight Limits (CTSWL) study performed by the US DOT as part of the

MAP-21 legislation. A mechanistic analysis approach for assessing bridge damage is not available.

4. The study estimated the changes in truck axle load spectra (distributions of axle loads for steering single, single, tandem, and tridem axle types) resulting from the estimates of the new technology vehicles' additional weight and implementation pathways.
5. The study assessed the impacts of axle load changes on pavement deterioration and the costs due to changes in vehicle technology using the updated axle load spectra estimates from Steps 1 and 2. The impacts of truck travel growth were also assessed.
6. An overall summary of the results was prepared.

Step 1 is presented in Chapter 2; Step 2, in Chapter 3; Step 3, in Chapter 4; Step 5, in Chapter 6; and Step 6, in Chapter 7.

Based on the conclusions of the project, which have been drawn from currently available information, the following are the study's conceptual-level, first-order findings addressing the objectives of the project:

- Objective: Provide estimates of the effects on freight logistics of an increased number of NGV, FC, and BEV trucks.
    - Answer: The increased numbers of NGV, EV, and FC trucks are expected to occur mainly in the short-haul and medium-duty types because of the range issues that exist for EV and FC long-haul trucks. However, depending on the implementation scenario, by 2050 an estimated 25 to 70 percent of long-haul trucks are predicted to be powered by alternative fuels. Further, depending on the scenario, by 2050 a predicted 40 to 95 percent of the short-haul and medium-duty trucks in the truck fleet will be powered by alternative fuel technologies. Implementation of alternative fuel trucks is expected to be focused in the 11 counties that already have the greatest freight traffic; these counties are primarily urban and along major freight corridors. The potential for truckers to increase their payloads when alternative propulsion systems become lighter after 2030 was not considered important because most implementation is occurring in short-haul and medium-duty trucks, which rarely operate near current axle load limits, and AB 2061 does not increase axle load limits.
- Objective: Provide an estimate of the additional damage to local- and state-government pavements caused by all trucks operating with an additional gross weight of 500 to 2,000 lbs.
    - Answer: Based on results from the implementation scenarios analyzed, introducing the heavier alternative fuel trucks is expected to only result in minimal additional damage to local- and state-government-owned pavements. The extent of the additional damage will range and vary according to the pavement structure and to the AFT implementation scenario. Two trends contribute to this conclusion. First, the technologies for EV and FC trucks are expected to remain heavier than current trucks between now and around 2030, but between that date and 2050, the weights of those technologies are expected to decrease as the technologies are improved. Second, the extent of implementation of these technologies is small to 2030 but is expected to increase rapidly after that, and they are expected to hold large market shares by 2050. Together, these two trends result in limited damage because the technologies' market penetration is minimal between 2020 and 2030, while they are heavy, and then their weights decrease as they penetrate further into the market. The NG technology cannot become lighter, but it is not expected to have significant market penetration. The study showed that using specific technologies at very high levels before their expected weight reductions can result in increased damage levels, as was shown in the examination of a waste facility access road. The somewhat increased damage levels that are expected on waste facility roads if diesel trucks are replaced with NG trucks can likely be compensated for by increasing those specific roads' structural capacity at costs by not more than about 20 percent of current costs, even for the cases where damage is greatest. The overall finding that

    increased gross vehicle weight limits will minimally affect pavement damage is in accordance with existing research and information. Specifically (i) pavement damage is especially driven by the heaviest axle loads, not by gross vehicle weights; and (ii) AB 2061 does not change axle weight limits and very few axles are currently at or above the current axle load limits.

- Objective: Provide an estimate of the weight restriction problems for local- and state-government bridges caused by all trucks operating with additional gross vehicle weight of 500 to 2,000 lbs.
    - Answer: This objective was difficult to complete well, even at the first-order conceptual level, because of a lack of bridge damage models—the same issue identified in the most recent national study. Although allowing weight increases of up to 2,000 lbs. is unlikely to cause major issues for trucks on more modern bridges, the effects of concentrations of trucks at those new legal limits on bridges that are already inadequate, and which are mostly owned by local governments, should be evaluated more carefully on a case-by-case basis. Because of the inability to adequately model bridge damage from increased gross vehicle weights, the US Department of Transportation recommends that they not be increased.
- Objective: Provide an estimate of the change in GHG emissions resulting from implementing vehicle fleet changes that consider well-to-wheel vehicle emissions and pavement maintenance and rehabilitation.
    - Answer: The study's most aggressive market penetration scenario yielded a net reduction in well-to-wheel truck propulsion emissions of approximately 2,700 kT of CO_2-e by 2030 and 34,000 kT by 2050 compared to keeping the current truck technologies. Its least aggressive scenario yielded a net reduction of approximately 1,200 kT by 2030 and 6,300 kT by 2050 compared to keeping the current truck technologies. These estimates consider expected growth in the truck fleet. For an order of magnitude comparison, in 2016 the emissions from the entire transportation sector were about 175,000 kT, which is 41 percent of the statewide total for the entire economy. None of the scenarios considered changes in GHG emissions from vehicle manufacture. Pavement-related emissions increases were estimated to be 70 to 900 times less than reductions from changes to truck operations.

The following recommendations are made based on the results of this study:

- Overall recommendation: To achieve large reductions in GHG emissions while still considering changes in costs, move ahead with the implementation of alternative fuel trucks but also monitor changes in pavement and bridge damage.
- Continue to periodically improve data and models for AFT implementation and GHG emissions related to truck use, and measurement of AFT weight change trends and projections and axle load spectra changes.
- Develop models for the effects of road roughness on AFT energy use and propulsion system life.
- Develop improved models for GHG emissions from truck manufacture, including changes in vehicle propulsion systems and other changes to the overall truck and trailer intended to reduce weight.
- In future modeling scenarios, include the potential effects on GHG emissions of implementing semi-autonomous and autonomous truck operations.
- Develop improved models for bridge deterioration as a function of truck axle loads.

Contents

1. Introduction

1.1 Background

The composition of California's truck fleet is currently shifting from a conventional one consisting mainly of gasoline and diesel vehicles to one that includes more natural gas vehicles (NGVs), electric vehicles (EVs), and fuel cell vehicles (FCVs). This shift will occur with increasing speed to meet the state's greenhouse gas (GHG) emission goals. However, these alternative fuel trucks may introduce heavier axle loads than current ones. These heavier loads can increase damage to the pavements they use and bring about an unintended consequence: increased GHG emissions resulting from either the necessary construction of stronger pavements or from the increased maintenance and rehabilitation (M&R) activities needed to keep those pavements in functional condition. Specifically, despite the similar engine weights of NGV and conventional vehicles, NGV fuel tanks typically outweigh their conventional counterparts by 500 lbs. (250 kg) for a medium-duty truck and by 2,000 lbs. (1,000 kg) for a long-haul tractor *(1)*. And although EVs and FCVs typically have lighter motors than conventional vehicles, their batteries typically outweigh those in current propulsion systems.

On September 20, 2018, then-Governor Jerry Brown signed California Assembly Bill 2061 (AB 2061) into law. This law allowed a 2,000 lb. weight limit increase in the gross vehicle weight (GVW) for near-zero-emission vehicles and zero-emission vehicles, while maintaining the current weight limits on individual axle types. The bill also included a request that the University of California Institute of Transportation Studies (UC ITS) conduct a study to evaluate the new law's environmental implications as well as its potential implications for transportation infrastructure.

On February 28, 2019, researchers from the University of California Institute of Transportation Studies (UC ITS) at the Irvine, Los Angeles, and Davis campuses met to discuss questions about the scope of the requested research that the Irvine and Los Angeles researchers could pose to Randy Chinn (Chief Consultant, Senate Transportation Committee) and David Sforza (Consultant, Assembly Transportation Committee) at a meeting later that day. Some clarification was obtained as a result of the meeting.

On May 20, 2019, the Davis researchers submitted a proposal to perform the requested study, and prepared the scope definition, budget, and a formal proposal. After these were reviewed, they were signed on September 18, 2019. This report presents the study's results.

The goal of this project was to provide the California Legislature and other policy makers with conceptual-level estimates of the effects of vehicle fleet changes on road and bridge infrastructure. These estimates can then be used as part of the policy development process to consider the costs and environmental impacts of changing the proportion of conventional and alternative-fuel trucks on the state's roadways. Using currently available information, this research study completed the following objectives at a first-order level:

- Provide estimates of the effects on freight logistics of an increased number of NGV, FCV, and BEV trucks.
- Provide an estimate of the additional damage to local- and state-government pavements caused by all trucks operating with an additional gross weight of 500 to 2,000 lbs.
- Provide an estimate of the weight restriction problems for local and state government bridges caused by all trucks operating with additional gross vehicle weight of 500 to 2,000 lbs.

- Provide an estimate of the change in GHG emissions resulting from implementing vehicle fleet changes that consider well-to-wheel vehicle emissions and pavement maintenance and rehabilitation.

Road safety impacts of changing gross vehicle weight limits were not in the scope of this project. Road roughness can increase the fuel use of gasoline and diesel trucks by at most approximately six percent for the roughest roads, and, if funds are available for scheduled maintenance, this figure should be less than about 3 percent. Road roughness was not considered because the effects were considered small compared to those of other factors, and because there is no information available regarding the effects of roughness on alternative fuel trucks.

1.2 Research Approach

The study followed these steps:

1. It estimated the additional weight of new technology vehicles relative to a conventional 2020 model year diesel truck considering three alternative pathways for implementation.
    a. The new technology vehicles included battery electric, fuel cell, and natural gas trucks.
    b. The truck types considered were long-haul tractor, short-haul tractor, and medium-duty urban (e.g., a box delivery truck).
    c. Two time periods were considered—10 and 30 years from the year 2020—to capture the effects of the estimated changes in vehicle technology in the years 2030 and 2050, which are also related to important legislative milestones for GHG emissions reductions.
2. The study estimated the growth in truck travel and provided an estimate of where the increased travel attributable to the new technology trucks would occur.
    a. Projections for 2015, 2020, 2035, and 2040 were taken from the *California Statewide Travel Demand Model* (CSTDM), using a baseline year of 2010 (the last update).
    b. Estimates were made for changes in light-, medium-, and heavy-duty truck miles traveled (note that truck-type definitions in the CSTDM are different from the definitions used in the rest of this study).
    c. Estimates were made for road types with different speed limits; the study used these limits to indicate whether a road was a freeway, highway or county road, city collector, or city residential street.
3. The study assessed the impacts of axle load changes due to changes in vehicle technology and of increased truck travel on bridge deterioration and its costs. This was done using the best available information, which came from the national Comprehensive Truck Size & Weight Limits (CTSWL) study performed by the US DOT as part of the MAP-21 legislation. A mechanistic analysis approach for assessing bridge damage was not available.
4. The study estimated the changes in truck axle load spectra (distributions of axle loads for steering single, single, tandem, and tridem axle types) resulting from the estimates of the new technology vehicles' additional weight and implementation pathways.
    a. Data from Caltrans Weigh-in-Motion (WIM) stations were used, with the last update made in 2018 serving as the baseline.
    b. Axle load spectra for each of the state highway network's five typical spectra—as identified earlier by the University of California Pavement Research Center (UCPRC) for use in Caltrans pavement management and

    pavement design procedures—were updated to consider the pathways for implementation of the alternative fuel trucks.
    c. Spectra for city collector roads and county roads were assumed from state highway segments that perform the same functions.
    d. Spectra for residential streets were developed under the assumption that the only heavy vehicles that use them are waste collection and package delivery trucks.
5. The study assessed the impacts of axle load changes on pavement deterioration and the costs due to changes in vehicle technology using the updated axle load spectra estimates from Steps 1 and 2. The impacts of truck travel growth were also assessed.
    a. A mechanistic analysis approach was used for assessing pavement damage.
    b. A conceptual-level estimate of increased pavement costs from the new, heavier vehicles was performed by analyzing the incremental pavement damage for each year after implementation of these vehicles, starting from a baseline of 2020 to 2050 for representative scenarios.
    c. Six representative pavement scenarios were evaluated for the baseline axle load spectra of 2020 and the estimated changes in axle load spectra in 2030 and 2050, with two or three different typical axle load spectra evaluated for each pavement scenario based on the alternative pathways to implementation of the alternative fuel trucks.
    d. Results for the entire period of 2020 to 2050 were interpolated from the results from 2020, 2030, and 2050.
6. An overall summary of the results was prepared.

Step 1 is presented in Chapter 2; Step 2, in Chapter 3; Step 3, in Chapter 4; Step 5, in Chapter 6; and Step 6, in Chapter 7.

2. Alternative Vehicle Weights and Pathways for Implementation

2.1 Additional Weight of New Technology Vehicles

In this part of the study, which corresponds to Step 1 of the research approach described in Section 1.2, the additional weight of new technology vehicles was estimated relative to a conventional 2020 model year (MY) diesel truck. The new technology vehicles include battery electric, fuel cell, and natural gas trucks. The truck types considered are long-haul tractor, short-haul tractor, and medium-duty urban (e.g., a box delivery truck). Results are considered for two future endpoints: the years 2030 and 2050.

The estimated additional-weight calculations were made by subtracting the weight of the diesel components that will be absent from the new technology trucks and adding the weight of the new technology truck component replacements. The 2020 MY diesel component weights were kept constant for all calculations, but since new diesel technologies will evolve, the weight of these components was estimated for both 2030 MY and 2050 MY.

2.1.1 Diesel Component Weights

The four diesel components removed from the new technology trucks were the engine, the fuel tank, the exhaust after-treatment system, and the diesel-exhaust fluid tank. It was assumed that these components are identical for both long-haul and short-haul tractors. Using truck component data sheets, Mareev et al. estimated the weight of these components in heavy-duty trucks to be roughly 1,700 kg *(2)*. The diesel engine for heavy-duty trucks was taken to be the Cummins X15, which weighs 1,430 kg *(3)*. The assumed medium-duty, urban truck diesel engine was the Ford 6.8L V-10, which weighs 284 kg *(4)*.

To determine the weight of the four diesel components to be removed from the medium-duty urban truck, it was noted that the ratio of the heavy-duty engine to the heavy-duty removed components is 0.84 (1,430/1,700). It was assumed that this ratio will be slightly smaller for the medium-duty truck, and the value taken was roughly 0.75. Using this 0.75 ratio to calculate the total weight of the four diesel components removed from the medium-duty truck yielded a value of 379 kg. Table 2.1 summarizes the diesel component weights.

Table 2.1. Diesel Component Weights for Long-Haul, Short-Haul, and Medium-Duty Urban Trucks

Truck Type	Engine Weight (kg)	Four Components Removed (kg)*
Long-haul tractor	1,430	1,700
Short-haul tractor	1,430	1,700
Medium-duty urban	284	379

* The engine, fuel tank, exhaust after-treatment system, and diesel-exhaust fluid tank.

2.1.2 Battery Electric Truck Component Weights

Estimating the additional weight for a battery electric truck required determining the weights of the battery pack and the power electronics. The battery pack weight depends on the pack energy, which varies depending on the assumed vehicle range, vehicle energy usage, and pack energy density. It was assumed that 2050 MY battery electric long-haul trucks will have a 500-mile range. It was also assumed that the 2030 MY trucks would have a shorter, 300-mile range due to their higher cost and the lower pack energy density. Short-haul trucks were assumed to have a range of 150 miles in 2030 and 200 miles in 2050.

Pack energy was estimated using the Advisor dynamic vehicle simulation on standard driving cycles. The pack energy for a 2030 MY truck with a range of 500 miles was 1,134 kWh. The 2030 MY truck pack energy was then scaled to 680 kWh for 300 miles. The simulation estimated short-haul truck pack energy to be 350 kWh in 2030 *(5)*. To determine the battery pack weight a battery cell energy density of 250 Wh/kg was assumed in 2030 and 400 Wh/kg in 2050, and it was assumed that the ratio of the pack weight to the cell weight was 1.35 *(6)*. Finally, the efficiency improvement for long-haul trucks from 2030 to 2050 was estimated to be a factor of 1.2, and the efficiency improvement for short-haul trucks to be a factor of 1.16 *(7)*. The 2050 pack energies were then 945 kWh (long haul) and 402 kWh (short haul).

A 150-mile range was assumed for the medium-duty urban truck in both 2030 and 2050. Using the dynamic vehicle simulation, the pack energy was estimated to be 150 kWh in 2030. The efficiency improvement factor from 2030 to 2050 for medium-duty urban trucks was estimated to be 1.18. The 2050 pack energy was then 127 kWh *(7)*. Table 2.2 gives a summary of the battery electric component assumptions for trucks.

Table 2.2. Component Assumptions for Battery Electric Trucks

Model Year	2030	2050
Long-haul range (miles)	300	500
Long-haul battery energy (kWh)	680	945
Long-haul efficiency improvement 2030 to 2050		1.2
Short-haul range (miles)	150	200
Short-haul battery energy (kWh)	350	402
Short-haul efficiency improvement 2030 to 2050		1.16
Medium-duty urban range (miles)	150	150
Medium-duty urban battery energy (kWh)	150	127
Medium-duty urban efficiency improvement 2030 to 2050		1.18

The final battery pack weights were calculated from the pack energy and battery energy density. Mareev et al. estimated the power electronics' weight for heavy-duty trucks to be 450 kg *(2)*. The weight of the power electronics for the medium-duty urban truck was estimated to be roughly 50 percent of that of the heavy-duty trucks based on the ratio of motor power. A summary of the battery electric truck weights is given in Table 2.3, where the total extra weight is the sum of the battery and power electronics weights minus the weights of the diesel component removed.

Table 2.3. Summary of Battery Electric Truck Weights

Truck type/MY	Battery weight (kg)	Power electronics weight (kg)	Total extra truck weight (kg)	Total extra truck weight (lbs)
Long-haul 2030	3,672	450	2,422	5,328
Long-haul 2050	3,189	450	1,939	4,267
Short-haul 2030	1,890	450	640	1,408
Short-haul 2050	1,358	450	108	237
Medium-duty urban 2030	810	225	656	1,444
Medium-duty urban 2050	429	225	275	606

2.1.3 Fuel Cell Truck Component Weights

It was assumed that fuel cell trucks will be hybrids, with both fuel cells and battery packs. Therefore, to estimate the additional weight for fuel cell trucks, the weight of the fuel cell, battery pack, power electronics, and hydrogen storage had to be determined. It was assumed that the range of long-haul fuel cell trucks is 500 miles in both 2030 and 2050. Similarly, the range of short-haul and medium-duty urban fuel cell trucks was assumed to be 150 miles in both 2030 and 2050.

Dynamic vehicle simulation was used to determine the fuel cell power and the hydrogen weight stored for each truck type *(6)*. The fuel cell system power densities were assumed to be 0.256 kW/kg in 2030 *(6)* and assumed to almost double, 0.5 kW/kg, in 2050. The hydrogen storage densities were assumed to be 0.057 kg H_2/kg system in 2030 and to meet the DOE goal of 0.075 kg H_2/kg in 2050 *(6)*. Table 2.4 shows the fuel cell truck assumptions and calculated parameters.

Table 2.4. Fuel Cell Truck Assumptions and Parameters

Parameter	Value
Long-haul	
Range (miles)	500
Fuel cell power (kW)	250
Battery pack (kWh)	40
Hydrogen storage (kg)	62
Short-haul	
Range (miles)	150
Fuel cell power (kW)	250
Battery pack (kWh)	20
Hydrogen storage (kg)	25
Medium-duty urban	
Range (miles)	150
Fuel cell power (kW)	125
Battery pack (kWh)	6
Hydrogen storage (kg)	8.5

The final battery pack weights were calculated from the pack energy and battery energy density. The fuel cell weights were calculated from the fuel cell power and power densities. The hydrogen storage weights were calculated from the hydrogen kilograms stored and the storage densities. The battery pack parameters and the power electronics weights were the same as those for battery electric trucks. A summary of the battery electric truck weights is given in Table 2.5, where the total extra weight in pounds is the sum of the battery, fuel cell, hydrogen storage, and power electronics weights minus the weight of the diesel components removed.

Table 2.5. Summary of Fuel Cell Truck Weights

Truck Type/MY	Fuel Cell Weight (kg)	Power Electronics Weight (kg)	Hydrogen Storage Weight (kg)	Battery Weight (kg)	Total Extra Truck Weight (lbs)
Long-haul					
2030	977	450	1,088	216	2,267
2050	500	450	827	135	466
Short-haul					
2030	977	450	439	108	601
2050	500	450	333	68	-768
Medium-duty urban					
2030	488	225	149	32	1,136
2050	250	225	113	20	506

2.1.4 Natural Gas Truck Component Weights

The natural gas truck additional weights were assumed to be 227, 455, and 909 kg (500, 1,000, 2,000 lbs) for long-haul trucks, short-haul trucks, and medium-duty urban trucks, respectively *(1)*.

2.1.5 Weight Distribution on Vehicle Axles

The final part of the additional weight analysis was to determine where the component weights will fall with respect to the vehicle axles. Components weights were assumed to be over the front axle (that is, under the hood) or between the front and next axle (that is, behind the cab or on the frame rail). The engine and power electronics were assumed to be placed under the hood. All fuel storage (diesel, hydrogen, or natural gas) were assumed to be placed behind the cab or on the frame rail. Batteries for battery electric trucks were assumed to be stored behind the cab or on the frame rail, but for fuel cell trucks they were assumed to be stored under the hood. The fuel cell was assumed to be stored behind the cab in 2030 MY trucks and under the hood in 2050 MY trucks. Table 2.6 shows the weight changes under the hood and behind the cab for the new technology vehicles compared to 2020 MY diesel trucks.

Table 2.6. Weight Changes on New Technology Trucks Compared to MT 2020 Diesel Trucks

	Long-Haul: 2030	Long-Haul: 2050	Short-Haul: 2030	Short-Haul: 2050	Medium-Duty Urban: 2030	Medium-Duty Urban: 2050
Battery electric						
Under hood	-2,156	-2,156	-2,156	-2,156	-130	-130
Behind cab	7,484	6,423	3,564	2,393	1,574	736
Fuel Cell						
Under hood	-1,681	-759	-1,918	-908	-59	465
Behind cab	3,947	1,225	2,519	139	1,194	41
Natural gas						
Under hood	0	0	0	0	0	0
Behind cab	2,000	2,000	1,000	1,000	500	500

Note: All weights in pounds.

2.2 Vehicle Stock

The Transportation Transitions Model (TTM) was used to estimate the number of new technology trucks projected to be using California roads in 2030 and 2050. The TTM is a stock turnover model with inputs of truck technology sales shares year by year from the present through 2050 *(7)*. The TTM divides trucks into eight categories: long-haul, short-haul, medium-duty urban, transit bus, other bus, medium-duty vocational, heavy-duty vocational, and heavy-duty pickups and vans. The model can input scenarios of new technology sales shares and output the stock for all technology types and truck types.

To estimate the number of battery electric, fuel cell, and natural gas long-haul, short-haul, and medium-duty urban trucks in the years 2030 and 2050, market penetration scenarios were created for each technology for those truck types. Three scenarios were created for new technology implementation: baseline, low, and high market penetration. The baseline scenario is based on a proposed California Air Resources Board Advanced Clean Truck Regulation *(8)*. The regulation would require significant California market penetration of zero emission vehicles (ZEVs)—that is, vehicles that produce no emissions while they operate, although there may be significant emissions in creating the propulsion energy. In the baseline scenario established by the proposed regulation following TTM, essentially 15 percent of the total of long-haul and short-haul trucks, and 50 percent of all the medium-duty urban trucks sold in 2030 would be ZEVs. In the baseline scenario, long-haul truck ZEV sales reach 80 percent in 2050, with 10 percent being battery electric and 90 percent being fuel cell. The baseline scenario also has short-haul and medium-duty urban trucks reaching 100 percent ZEV sales in 2050.

The percentage of ZEVs sold that are fuel cell or battery electric varies with truck type and year. In 2030, short-haul ZEVs would make up 95 percent of the mandated sales, with fuel cell trucks constituting 5 percent of the short-haul truck sales. Natural gas vehicles would have a significant market share for medium-duty urban trucks through 2030 but it tapers to zero by 2050. NG trucks are expected to make up a small percentage of short-haul trucks in 2030 and none in 2050. There are no NG long-haul trucks.

The low market penetration scenario has half as many ZEVs in the total stock of trucks, considering year-to-year sales, as the baseline scenario. The high market penetration scenario has 1.5 times the baseline scenario's ZEVs in the truck stock in 2030. In 2050, where short-haul and medium-duty urban ZEVs make up nearly all of the baseline scenario truck stock, the high penetration scenario has nearly all of the total truck stock divided between fuel cell and battery electric ZEVs, with a small percentage that are natural gas in the medium-duty urban trucks.

Table 2.7 shows the number of trucks for each truck type and scenario for the years 2020, 2030, and 2050. The total number indicates the total stock for all the technologies for that truck type. Long-haul trucks are Class 8 tractor-trailer combination trucks (referring to FHWA truck classifications) that typically travel long daily distances and do not return to base to refuel. Short-haul trucks are Class 7–8 tractor-trailer combination trucks that typically travel in local or regional areas and return to base to refuel. Medium-duty urban trucks are Class 4–6 unitary trucks that typically make local deliveries of freight. Examples would be step vans and box trucks.

The trucks considered in the VMT and fleet measurements in this chapter, which come from California Air Resource Board's (ARB) EMFAC 2014 data (9) (a database of EMission FACtors), were used in the rest of this report to calculate greenhouse gas emissions and truck axle loads. The VMT for long-haul trucks in the EMFAC data are commensurate with the heavy-duty vehicles included in the California Statewide Travel Demand Model (CSTDM) data discussed in Chapter 3. The short-haul trucks and medium-duty trucks considered in this chapter that come from EMFAC do not map well to the medium-duty and light-duty trucks considered in CSTDM; the short-haul and medium-duty trucks from EMFAC considered in this chapter appear to not include all classes of medium-duty trucks and none of the light-duty trucks considered in CSTDM.

Additional truck fleet and VMT data collection methods and databases are being developed for California, such as those described by Khan et al. (10). It was beyond the scope of this project to reconcile differences between truck and truck VMT databases. For the purposes of this study, lack of consideration of light-duty trucks is not important since they cause very little damage to pavements because of their light axle loads, even when they are converted to alternative fuels. This study focused on the three types of trucks identified in the EMFAC data that cause most pavement damage.

Table 2.7. Truck Stock by Truck Type, Year, and Scenario

Truck Scenario	2020 Total	2030 Total	2030 BEV	2030 FC	2030 NG	2050 Total	2050 BEV	2050 FC	2050 NG
LH 1	148,000	156,000	255	255	0	181,000	13,785	124,065	0
LH 2	148,000	156,000	170	170	0	181,000	9,190	82,710	0
LH 3	148,000	156,000	85	85	0	181,000	4,595	41,355	0
SH 1	44,000	48,000	4,845	242	495	56,000	24,080	31,920	0
SH 2	44,000	48,000	3,230	162	330	56,000	18,900	25,100	0
SH 3	44,000	48,000	1,615	81	165	56,000	9,450	12,550	0
MD 1	302,000	347,000	37,350	7,410	37,650	426,000	202,740	199,470	22,890
MD 2	302,000	347,000	24,900	4,940	25,100	426,000	186,000	183,000	21,000
MD 3	302,000	347,000	12,450	2,470	12,550	426,000	93,000	91,500	10,500

Note: BEV = battery electric; FC = fuel cell; NG = natural gas; LH = long haul; SH = short haul; MD = medium-duty urban; 1 = high market penetration scenario; 2 = baseline scenario; 3 = low market penetration scenario

2.3 Vehicle Cost

Vehicle costs were estimated by summing the cost of the vehicle glider (tractor without the power train components of engine and transmission) and various components. The components for battery electric and fuel cell trucks, such as batteries, motors, fuel cells, and hydrogen storage were sized for each technology and multiplied by a component cost factor (for example, $/kWh of battery or $/kW of fuel cell system). Truck component sizes for these technologies were determined using the Advisor dynamic vehicle model *(6)*.

Two components of interest are fuel cells and batteries, as costs for both have declined significantly over time and are expected to continue to decrease through volume sales. Battery cost projections vary, with Bloomberg New Energy Futures projecting dramatic increases through 2030 *(11),* while The International Council on Clean Transportation (ICCT) projects smaller increases *(12);* this current study used costs roughly midway between those other studies and extrapolated them through 2050. These costs are the cost of equipment only paid by the original equipment manufacturer (OEM) to the battery manufacturers. To arrive at a final component cost in the vehicle, an integration cost factor of 1.4 was assumed.

The cost of fuel cells was taken from an analysis by Strategic Analysis *(13)*. The analysis estimated fuel cell costs as a function of volume sales. In each of the ZEV scenarios the volume sales costs were compared to expected sales to determine costs as a function of year. The truck numbers only included volume sales up to 1,000 units/yr. Costs for higher volumes were extrapolated using ratios of volume sales costs for light-duty vehicles (LDVs). These costs include internal markups for components but do not include final OEM integration. The integration cost factor was assumed to be 1.4.

Table 2.8 shows projected truck costs for diesel, battery electric, fuel cell, and natural gas trucks in years 2030 and 2050.

Table 2.8. Vehicle Costs

	2030 Long-Haul	2030 Short-Haul	2030 Medium-Duty-Urban	2050 Long-Haul	2050 Short-Haul	2050 Medium-Duty-Urban
Diesel	\$148,000	\$130,000	\$58,000	\$154,000	\$135,000	\$59,000
BEV	\$215,000	\$163,000	\$63,000	\$227,000	\$158,000	\$55,000
FC	\$220,000	\$189,000	\$72,000	\$185,000	\$157,000	\$60,000
NG	\$183,000	\$163,000	\$69,000	\$166,000	\$143,000	\$66,000

Note: LH = long-haul; SH = short-haul; MD = medium-duty urban; BEV = battery electric; FC = fuel cell; NG = natural gas

2.4 Vehicle Carbon Emissions from Fuel Production and Consumption

Introducing ZEVs into the California truck fleet will reduce well-to-wheel vehicle propulsion carbon emissions. Battery electric and fuel cell trucks have zero tailpipe emissions and can have very low upstream emissions (emissions from the production and distribution of the fuel), depending on how the fuels are produced. The emissions for each scenario and each truck type included in this study were calculated using the TTM. The TTM calculates carbon emissions for all truck types based on assumptions made for fuel carbon intensity (g CO_2-e/MJ).

The differences in emissions from differences in vehicle production were not considered in the model.

In the analysis, it was assumed that electricity has a carbon intensity roughly 75 percent lower than diesel fuel in 2030, and that hydrogen has a carbon intensity roughly 33 percent lower than diesel fuel. In 2030, although the majority of electricity comes from renewable fuels, most hydrogen is assumed to still be reformed from natural gas. It was assumed that by 2050 both electricity and hydrogen have zero carbon intensity because they come from 100 percent renewable energy sources. It was also assumed that the diesel fuel’s carbon intensity would not change appreciably from 2020 values based on the assumption that the role of biofuel production remained constant in these scenarios.

The assumed vehicle miles traveled (VMT) for long-haul, short-haul, and medium-duty urban trucks varied with vehicle age and is given in Table 2.9. The yearly vehicle miles traveled (VMT) data come from the California Air Resource Board’s (ARB) EMFAC 2014 data (9). VMT is a function of truck age and decreases from year to year for each generation of trucks. The long-haul data include both in-state and out-of-state trucks. Out-of-state trucks may travel only a portion of the listed VMT in California, but all the VMT contributes to greenhouse gas emissions.

Table 2.9. Yearly VMT per Truck for Long-Haul, Short-Haul, and Medium-Duty Urban Trucks

Age in Years	Long Haul (miles)	Short Haul (miles)	Medium-Duty Urban (miles)
Age 0	116,560	60,031	29,905
Age 1	116,512	59,491	29,988
Age 2	113,023	59,965	29,677
Age 3	107,242	57,331	29,223
Age 4	100,330	54,412	28,377
Age 5	92,005	49,752	27,090
Age 6	84,023	45,616	25,520
Age 7	76,641	42,424	23,853
Age 8	69,639	39,428	22,321
Age 9	63,163	36,485	21,099
Age 10	57,425	33,785	20,005
Age 11	52,667	31,725	18,808
Age 12	48,707	29,904	17,677
Age 13	45,093	27,802	16,290
Age 14	41,824	25,384	14,891
Age 15	38,504	22,701	13,104
Age 16	38,137	21,031	12,784
Age 17	37,719	19,222	12,416
Age 18	37,275	17,080	12,021
Age 19	36,830	16,161	11,516
Age 20	36,361	13,827	10,938

The carbon emissions were calculated for four scenarios: business as usual (BAU), the baseline ZEV market penetration (baseline), high ZEV market penetration (high), and low ZEV market penetration (low). Table 2.10 shows the total carbon emissions for each scenario for the sum of long-haul, short-haul, and medium-duty urban trucks in kT CO_2-e along with the percentage reduction from the BAU scenario. The BAU scenario itself reduces carbon emissions from 2020 because the fuel economy of diesel vehicles increases significantly.

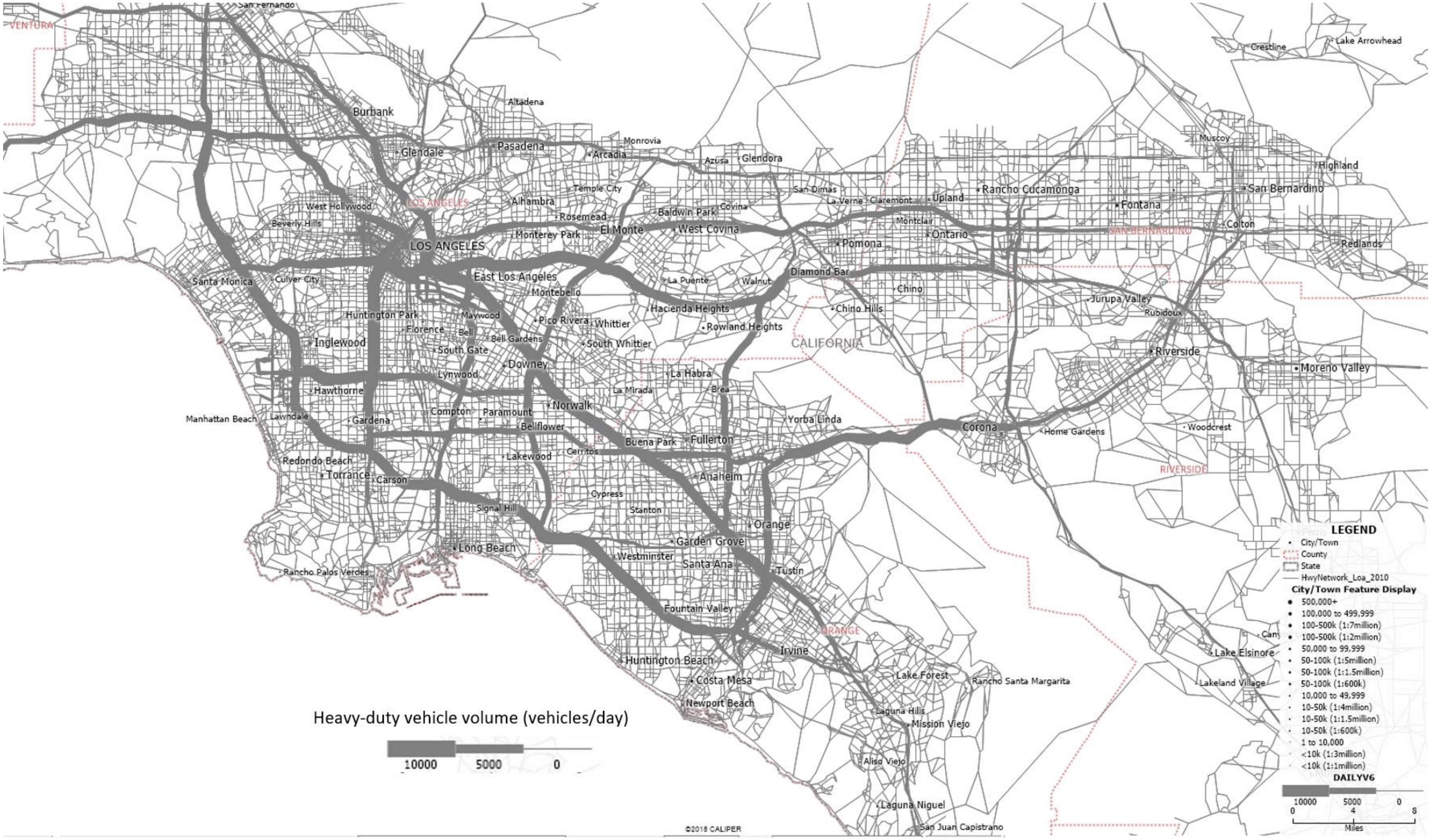
Table 2.10. Carbon Emissions (in kT CO2-e) for the Four Scenarios: BAU, Baseline, High, and Low Market Penetration

Scenario	2020 Total	2030 Total	2030 % Reduction	2050 Total	2050 % Reduction
BAU	39,600	34,900	NA	29,200	NA
Baseline	39,600	33,100	5	8,700	70
High	39,600	32,500	7	3,800	87
Low	39,600	33,860	3	24,700	16

3. Estimating Freight Flows in California 2020–2040

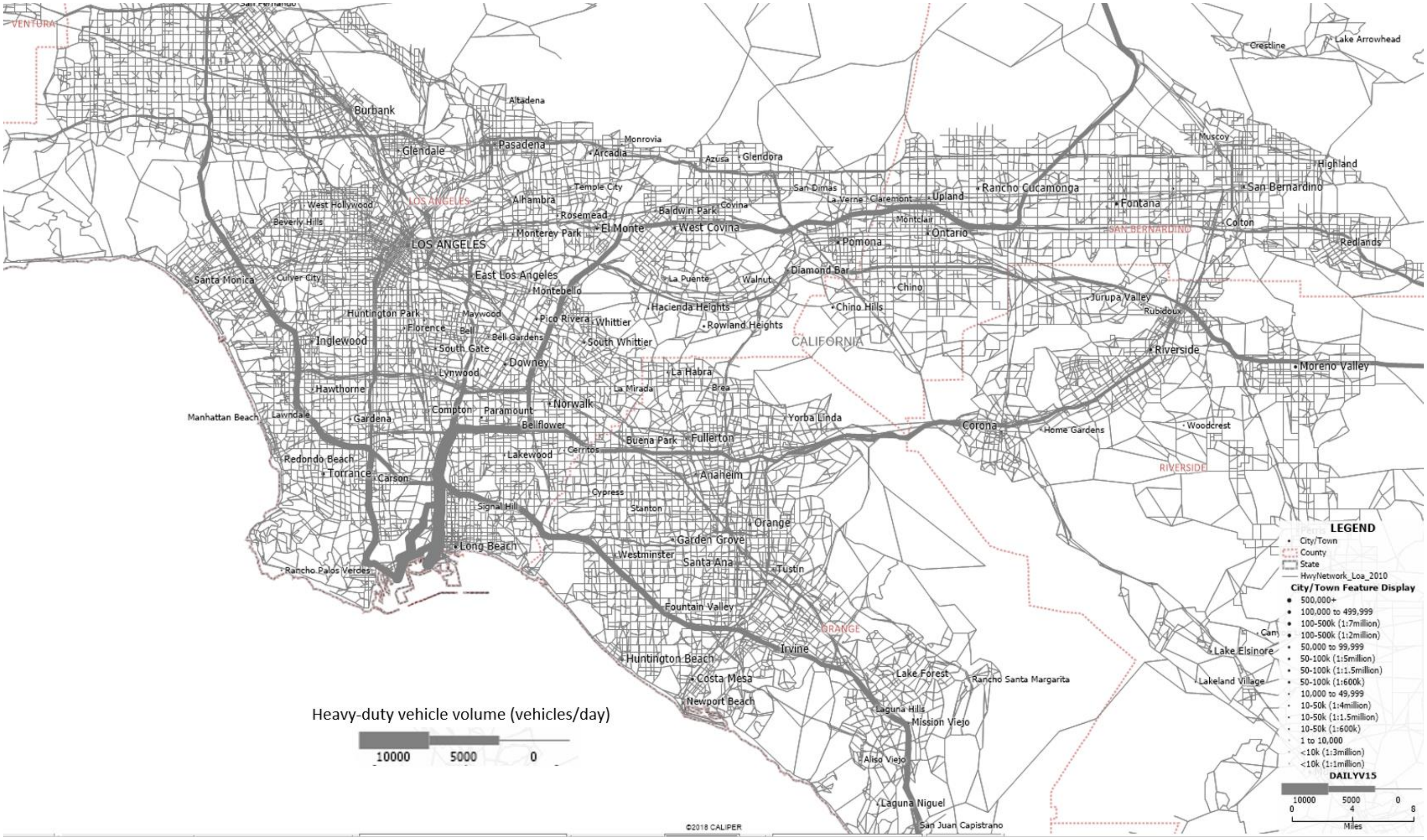
Freight flows over much of the time horizon for this study, and their locations in the state, were estimated separately from the analysis in Chapter 2 and subsequent chapters on bridge and pavement damage. Results from the *California Statewide Travel Demand Model* (CSTDM) were used to estimate the freight flows on the state's entire road transportation network *(14)*, which is Step 2 in the research approach outlined in Section 1.2.

The California Department of Transportation (Caltrans) has calibrated the CSTDM to generate travel demand estimates for future travel scenarios (for example, 2010, 2015, 2020, 2035, and 2040). The CSTDM is managed, maintained, and updated by Caltrans to perform inter-regional travel analyses, and to support the California Transportation Plan (CTP), modal plans, and other system planning efforts. Caltrans also uses the CSTDM to evaluate greenhouse gas (GHG) footprints and measure VMT. The final output of the model considers three types of trucks: light, medium, and heavy duty. There is a distinction made in the model between short- and long-distance travel, as well as travel to external zones. The model estimates the flows over each link of a simplified road network. While the model estimates the flows for different time periods throughout the day, average daily flows were used for this report. As an example of the model output, Figure 3.1 shows the flows of heavy-duty trucks in Southern California for short- and long-distance trips, and trips external to the region.



a. Short-distance heavy-duty vehicle flow

b. Long-distance heavy-duty vehicle flow



c. External heavy-duty vehicle flow

Figure 3.1. Examples of heavy-duty vehicle flows in Southern California. The thickness of the grey lines indicates the volume of heavy-duty vehicle flow in number of vehicles per day.

The flows from these outputs were used to estimate the change in daily flows in 2015, 2020, 2035, and 2040, with 2040 being the maximum future projection that the model was capable of producing. The projected flows were then used to evaluate the impacts on infrastructure by considering the estimated axle load spectra, and to distribute the forecasted percentages of zero-emission vehicles as part of these flows. The CSTDM considers signalized speed limits to classify the road types present, and in this study these signalized speed limits (for passenger vehicles) were used to classify the road types considered in the analysis (for example, freeway/highway, county road, collector, local/residential street).

Table 3.1 shows the total estimated VMT for the 2010 base year over the different road types, with heavy-duty trucks traveling about 50 million miles per day, and medium- and light-duty vehicles traveling about 32 and 25 million miles per day, respectively. These estimates are higher than the estimated 2020 base year VMT values included in Chapter 2 (Table 2.7 and Table 2.9), which are approximately 47, 25, and 7 million miles per day for long-haul, medium-duty urban, and short-haul trucks, respectively. The estimated daily VMT for heavy-duty trucks corresponds well with the estimate of long-haul truck daily VMT amount in Chapter 2. However, results for the medium-duty urban versus medium-duty and short-haul versus light-duty categories differ because the methodologies used here and in Chapter 2 categorize the vehicles differently.

The distribution is quite different for each vehicle type across the different road types. Although light- and medium-duty trucks dominate the local and arterial roads, heavy-duty trucks travel over 20 percent more than the combined travel of light- and medium-duty trucks on highways/freeways. The faster growth of light-duty truck VMT than medium-duty truck VMT is due in part to the expected faster growth of residential last-mile-type deliveries compared with the current use of medium-duty trucks for last-mile hauling to retail stores.

Table 3.1 also shows the percent change of the vehicle types over the different roads for future years compared to the base year. Light-duty truck VMT is expected to grow at a faster rate than the other vehicle types on local and arterial roads. However, the CSTDM results show a significant increase in the VMT of heavy-duty trucks on county roads and freeways/highways. For illustration purposes, Table 3.2 shows the share of VMT on the different road types for each truck type. These results indicate only minor changes in the truck type distributions on each road type across the years considered.

To estimate where the zero-emissions vehicles are expected to penetrate in the state, future changes in VMT were estimated using the model for different counties. The results presented in Table 3.3 show that 11 out of 58 (19 percent) of the counties are expected to receive about 75 percent of the truck VMT in the state, with these percentages not changing in each of the years considered. It would be expected that the market penetration of the zero-emission vehicles in the state would follow a similar distribution.

Table 3.1. Daily VMT in the Base Year in Millions, and Percent Change in Each Future Planning Scenario

Speed Limit (mph)	Corres-ponding Road Type	Base Year (2010) Light	Base Year (2010) Med.	Base Year (2010) Heavy	Light 2015	Light 2020	Light 2030	Light 2040	Med. 2015	Med. 2020	Med. 2035	Med. 2040	Heavy 2015	Heavy 2020	Heavy 2035	Heavy 2040
≤30	Local/ Residential	3.43	3.31	2.64	14%	23%	36%	40%	9%	16%	20%	23%	7%	16%	29%	36%
>30, ≤45	Collector	6.45	7.03	6.03	9%	18%	39%	44%	8%	15%	30%	36%	6%	14%	34%	43%
>45, ≤60	County Road	4.40	6.37	9.96	15%	26%	53%	62%	17%	26%	47%	56%	14%	24%	54%	64%
>60	Freeway/ Highway	10.29	15.72	31.46	6%	16%	39%	43%	6%	15%	35%	39%	7%	18%	52%	62%
Total		24.56	32.43	50.08	10%	19%	41%	46%	9%	17%	35%	40%	8%	19%	49%	

Table 3.2. Percentage of VMT for the Different Road Types for Each Truck Type

Road Type Speed Limit (mph)	2010 Light	2010 Med.	2010 Heavy	2015 Light	2015 Med.	2015 Heavy	2020 Light	2020 Med.	2020 Heavy	2035 Light	2035 Med.	2035 Heavy	2040 Light	2040 Med.	2040 Heavy
≤30	14%	10%	5%	15%	10%	5%	14%	10%	5%	13%	9%	5%	13%	9%	5%
>30, ≤45	26%	22%	12%	26%	21%	12%	26%	21%	12%	26%	21%	11%	26%	21%	11%
>45, ≤60	18%	20%	20%	19%	21%	21%	19%	21%	21%	19%	21%	21%	20%	22%	21%
>60	42%	48%	63%	41%	47%	62%	41%	48%	62%	41%	49%	64%	41%	48%	64%

Table 3.3. Distribution of VMT in 11 Counties with Heaviest VMT (accounting for 75% of Total State VMT)

County	2010 Light	2010 Med	2010 Heavy	2015 Light	2015 Med	2015 Heavy	2020 Light	2020 Med	2020 Heavy	2035 Light	2035 Med	2035 Heavy	2040 Light	2040 Med	2040 Heavy
Los Angeles	27%	25%	22%	24%	22%	19%	24%	21%	19%	22%	20%	18%	22%	19%	18%
San Bernardino	5%	10%	7%	5%	10%	7%	5%	11%	7%	6%	12%	8%	6%	12%	8%
Riverside	5%	6%	7%	7%	7%	7%	7%	8%	8%	8%	9%	8%	8%	9%	8%
San Diego	8%	7%	6%	8%	7%	6%	8%	7%	6%	8%	7%	6%	8%	6%	6%
Orange	9%	8%	6%	9%	7%	6%	8%	7%	6%	8%	7%	6%	8%	7%	5%
Alameda	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	4%	5%	5%	5%
Kern	2%	2%	5%	2%	2%	6%	2%	3%	6%	3%	3%	6%	3%	3%	7%
Fresno	3%	2%	4%	3%	2%	4%	3%	2%	4%	3%	2%	4%	3%	2%	4%
Santa Clara	5%	4%	4%	6%	4%	4%	6%	4%	4%	5%	4%	3%	5%	4%	3%
Sacramento	4%	3%	2%	4%	3%	2%	4%	3%	2%	4%	3%	2%	4%	3%	2%
Contra Costa	2%	3%	2%	3%	3%	2%	3%	3%	2%	2%	3%	2%	2%	3%	2%
Total	75%	75%	69%	75%	74%	67%	75%	74%	68%	74%	74%	67%	73%	73%	67%

4. Effects of Increased Axle Loads on Bridges

This chapter presents a summary of a national study on the impacts of increased gross vehicle weights and axle loads on infrastructure costs, including the costs of bridges. This chapter completes Step 3 of the research approach outlined in Section 1.2.

4.1 State Bridge Inventory

The United States has approximately 614,000 bridges on the public roads subject to the National Bridge Inspection Standards mandated by Congress. About half of these bridges are owned by state governments and the other half by local governments. Generally, state governments own the larger and more heavily traveled bridges, such as those on the Interstate Highway System. Altogether, the federal government owns less than two percent of highway bridges, and those are primarily on federally owned land.

In California, the state owns approximately 12,400 of the 25,700 total bridges.

4.1.1 National Highway System

The National Highway System (NHS) consists of roadways important to the nation's economy, defense, and mobility, and includes the following roadway subsystems (note that a specific highway route may be in more than one subsystem):

- Interstate: The Eisenhower Interstate Highway System retains a separate identity within the NHS.
- Other Principal Arterials: These are highways in rural and urban areas that provide access between an arterial and a major port, airport, public transportation facility, or other intermodal transportation facility.
- Strategic Highway Network (STRAHNET): This is a network of highways important to the United States' strategic defense policy, and which provides defense access, continuity, and emergency capabilities for defense purposes.
- Major Strategic Highway Network Connectors: These are highways that provide access between major military installations and highways.
- Intermodal Connectors: These highways provide access between major intermodal facilities and the other four subsystems that make up the National Highway System.

The NHS includes the Interstate Highway System as well as other roads important to the nation's economy, defense, and mobility. The NHS was developed by the US DOT in cooperation with the states, local officials, and metropolitan planning organizations.

4.1.2 National Bridge Inventory (NBI)

In general, as part of the National Bridge Inventory (NBI), states are required to inspect every bridge once every two years and to report the findings for approximately 40 data items to the Federal Highway Administration (FHWA) *(15)*. The following bridge parts are inspected:

- Deck
- Superstructure

- Substructure

As part of the process, a field inspector assigns a “condition code” for each of the bridge’s three areas. The codes vary from 9 (Excellent Condition) to 1 (Imminent Failure Condition), but a value of 0 can also be assigned to a bridge component to indicate that the component is beyond corrective action.

Using the condition code given to a component, the FHWA assigns its condition as “Good,” “Fair,” or “Poor”:

- Good: A condition code of 7 or greater
- Fair: A condition code of 4, 5, or 6
- Poor: A condition code of less than 4

The FHWA may also categorize a bridge as “Structurally Deficient (SD).” A structurally deficient bridge is one with a Poor rating for its deck, superstructure, or substructure.

Every year the FHWA generates many online reports summarizing the overall condition of the nation’s bridges based on the Good, Fair, or Poor scale. The reports usually treat NHS bridges and non-NHS bridges separately, but all the reports identify structurally deficient bridges. The following are some excerpts from NBI reports for California for 2018:

- All bridges in California
    - There are approximately 25,700
    - Classified as:
        - Good: 14,800
        - Fair: 9,100
        - Poor: 1,800
        - Structurally deficient: 1,600 (2017)
- NHS bridges in California
    - There are approximately 10,800
    - Classified as:
        - Good: 7,200
        - Fair: 3,000
        - Poor: 500
        - Structurally deficient: 424 (2017)

Four out of five of the state’s structurally deficient bridges are in rural areas. These bridges tend to be small and relatively lightly traveled. On the other hand, while urban areas were found to have far fewer structurally deficient bridges, urban bridges were generally much larger and, therefore, more expensive to fix. Specifically, the 2018 NBI reports showed that almost 57 percent of the deck area (a measure of bridge size) of structurally deficient bridges are on urban bridges. Further, the reports showed that bridges on roads that carry heavy traffic loads, particularly bridges on the Interstate Highway System, are generally in better condition than those on more lightly traveled routes.

4.1.3 General Principles of Axle Load and Spacing Limits on Bridges

A “load rating” is also done on every bridge every 2 years as part of the NBI. Load rating a bridge is an office exercise that consists of performing a structural analysis using load-rating software (usually AASHTOWare’s Bridge Rating application, *ABrR* [which was originally called *VIRTIS*], and uses load and resistance factor design [LRFD] and load and resistance factor rating [LRFR] specifications) and using material and section properties for the current condition of the inspected bridge.

Two rating factors are computed for a bridge using the design live load *(live load* means the weight of vehicles or other objects using the bridge rather than the weight of the bridge itself):

- Inventory Rating (IR): this rating is based on a test that stresses a component to 55 percent of its yield stress, called Allowable Stress Design (ASD), or an associated reliability, beta, of 3.5 (Load Resistance Factor Design, LRFD/LRFR) and a Live Load Factor of 1.75 (Gamma-L in the rating equation below). A reliability of 3.5 represents the probability of failure 233 out of 1,000,000 load applications.
- Operating Rating (OR): this rating is based on a test that stresses a component to 75 percent of its yield stress or a beta of 2.5 and a Live Load Factor of 1.35. A reliability of 2.5 represents the probability of failure 6,210 times out of 1,000,000 load applications.

IR is associated with the number of trucks that can pass over the bridge on a regular or normal basis. OR is associated with the number trucks that might use the bridge on a one-time basis, sometimes with constraints—such as speed, restricted lane use, or whether a traffic stoppage is needed for the truck to pass on the bridge.

The general Load Rating equation for bridges is a Capacity/Live Load demand equation. If the ratio (rating factor [RF]) is greater than 1, then the so-called “item”—a structure response such as moment, shear or axial force for any structural member in the bridge due to the design live load or a state’s live load-rating vehicle—has enough capacity to resist a live load. If the ratio is less than 1, that structure response is deemed inadequate, which typically means the bridge will require frequent monitoring, repairs or strengthening, or load posting (that is, placing restrictions on the sizes of truck that may use the bridge).

The live load-rating vehicle is usually American Association of State Highway and Transportation Officials’ (AASHTO’s) legal load or it can be the state’s legal live load. For example, a bridge rating engineer could compare the flexural capacity of a superstructure at mid-span to the positive moment produced by the rating vehicle. Alternatively, a rating engineer could check the shear capacity close to a support to the live load shear at that location.

An increase of gross vehicle weight (GVW) of up to 2,000 lbs. for trucks also requires that a bridge satisfy the Federal Bridge Gross Weight Formula, which is also known as Bridge Formula B. The purpose of the federal bridge weight formula is to protect bridges on the interstate system by controlling the number and spacing of truck axles. The weight of groups of two or more axles must be checked against the bridge formula to ensure that they meet federal weight limit requirements and that the allowable gross vehicle weight and axle weights are correlated with the spacing and number of axles to prevent severe overstressing of highway bridges.

A plot of Bridge Formula B is shown in Figure 4.1 for axle groups of 2, 3, 4, and 5 closely spaced axles. The plot reflects rounding to the nearest 500 lbs. per federal guidelines, and constraint rules like the ones that state that no single axle can have more than 20,000 lbs. and that tandem axle groups (two closely spaced axles) cannot weigh more than 34,000 lbs., which are also the California legal load limits.

Compliance with bridge formula weight limits may require axle weights lower than the standard Interstate Highway System weight limits of 20,000 lbs. for a single axle and 34,000 lbs. for a tandem axle set. It may also require a gross weight lower than the standard 80,000-lb. Interstate Highway System limit. The weight allowed under the bridge formula can be increased to these limits by adding axles or positioning them farther apart. Since states may retain higher bridge formula weight limits than were in effect in 1975 (that is, bridge formula weight limits that have been grandfathered in), some states may have higher limits than others.

In summary, if a zero-emission vehicle (ZEV) truck has a total GVW of 82,000 lbs.—surpassing the 80,000-lb limit because of electrification (consistent with AB 2061)—it must also comply with Formula B. If any axle group (every group of two or more axles must be checked) exceeds the maximum per Formula B, then weight would either need to be redistributed across the truck or its axle spacing would need to be increased.

4.2 US DOT (FHWA) Comprehensive Truck and Weight Limits Study (April 2016)

4.2.1 Overview

AB 2061 as enacted allows near-zero and zero-emission vehicles to exceed the current federal maximum gross vehicle weight (GVW) of 80,000 lbs. by 2,000 pounds when they travel on public roads, highways, and bridges.

Many factors contribute to bridge damage, but increased truck loads are known to be a major one. As a result, the effects of allowing increased truck weights and sizes have been heavily researched over the last several decades.

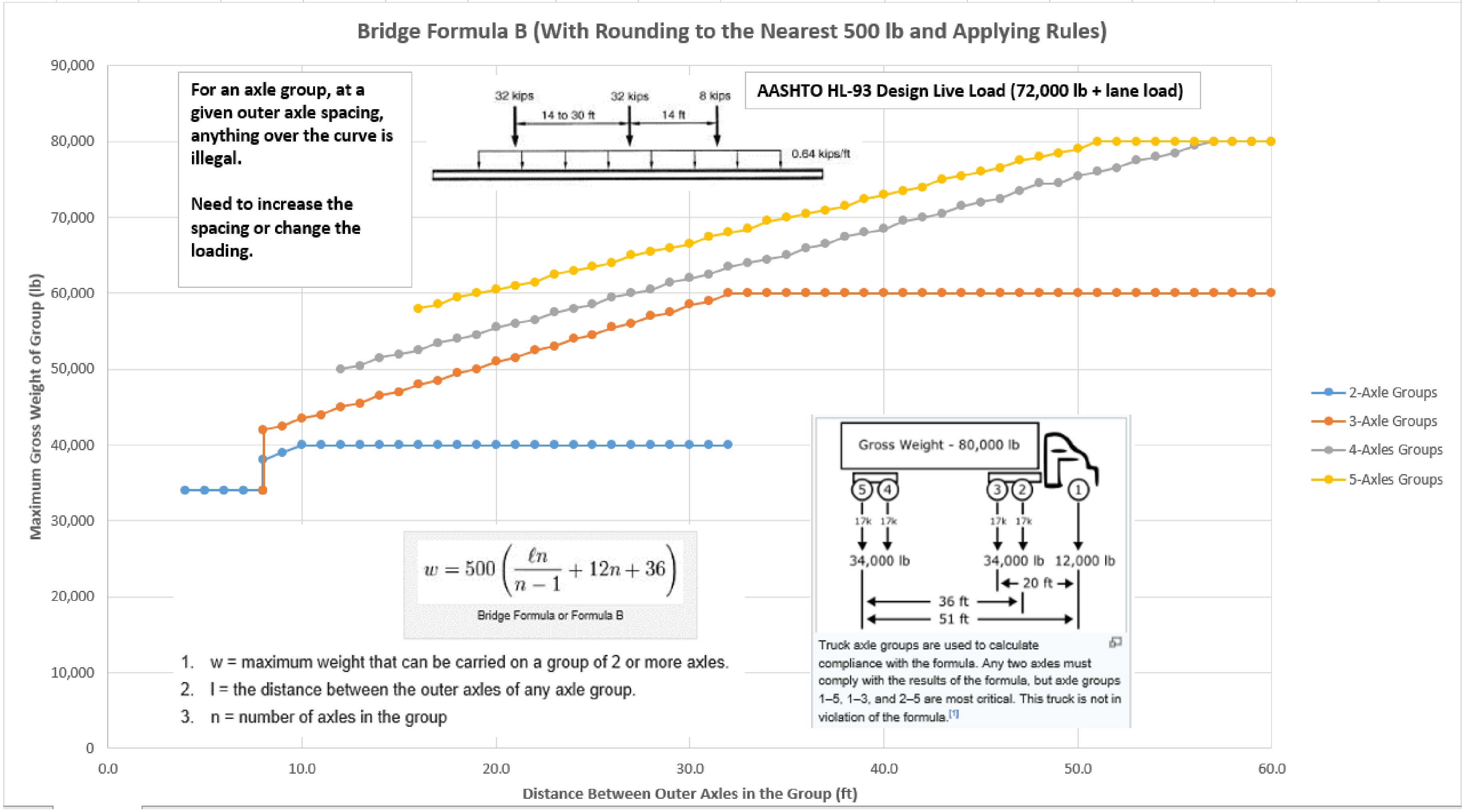
The Moving Ahead for Progress in the 21st Century Act (MAP-21) required the US DOT to conduct a Comprehensive Truck Size and Weight Limits Study (CTSWLS). This study used state-of-the-art analysis and modeling approaches to determine the impacts of several truck size and weight configurations on pavements, bridges, safety, and other areas. The study was designed to ensure that best practices are followed in each area, and, as its final report was prepared, an independent Transportation Research Board panel of experts provided critical reviews of its components. Published in 2016, the report has since been cited in many subsequent reports.

4.2.2 Summary of the CTSWLS

The following is a summary of the MAP-21 (2016) CTSWLS.

MAP-21 (the Moving Ahead for Progress in the 21st Century Act) directed the US DOT, in conjunction with states and other federal agencies, to perform the following tasks (partial list):

- Evaluate the impacts to infrastructure in states where vehicles are allowed to operate at a size and weight exceeding the federal limits, compared to vehicles not operating in excess, for the following characteristics:
    - Cost and benefits of the impacts in dollars;
    - Percentage of trucks operating in excess of the federal limits; and,
    - Ability of each state to recover the costs or the benefits incurred.
- Evaluate the frequency of violations in excess of federal size and weight provisions, and the cost of enforcement and effectiveness of the enforcement methods
- Assess and compare the impacts of vehicles in excess of federal limits to those not in excess on bridges, including impacts from number of bridge loadings



For an axle group, at a given outer axle spacing, anything over the curve is illegal.

Need to increase the spacing or change the loading.

$$w = 500\left(\frac{\ell n}{n-1} + 12n + 36\right)$$

1. w = maximum weight that can be carried on a group of 2 or more axles.
2. l = the distance between the outer axles of any axle group.
3. n = number of axles in the group

Truck axle groups are used to calculate compliance with the formula. Any two axles must comply with the results of the formula, but axle groups 1–5, 1–3, and 2–5 are most critical. This truck is not in violation of the formula.[1]

Figure 4.1. Graphical representation of Federal Bridge Formula B (Adapted from Federal Highway Administration *(16)*).

The study was organized around five core technical areas:

- Highway safety and truck crash rates, vehicle performance (stability and control), and inspection and violation patterns
- Shifts in goods movement among truck types and between modes
- Pavement service life
- Highway bridge performance
- Truck size and weight enforcement programs

This summary covers the highway bridge performance area.

An extensive literature survey was done that was subjected to peer review by the National Academy of Sciences and included extensive outreach and transparency. The study accounted for the shift of truck traffic to other modes of transportation, including use of the FHWA's Freight Analysis Framework, a more refined data set for assigning vehicles to freight corridors, and more advanced models to assess truck impacts on pavements and bridges. The Freight Analysis Framework information was applied at the county level to allow analysis of certain configurations on limited highway networks. The Freight Analysis Framework data were used in the Intermodal Transportation and Inventory Costing Model to estimate modal shifts that were then used to estimate changes in truck Vehicle Miles Traveled (VMT) by configuration and weight group.

The study included bridge analyses that evaluated truck size and weight enforcement programs and the effects of truck sizes and weights on bridge deterioration. To do this, the study used six truck configuration scenarios and a control vehicle.

The consultants who collected data and performed the structural analysis for the bridge analyses used *AASHTOWare Bridge Rating ABrR,* (formerly *VIRTIS,* which uses LRFD/LRFR). The consultants assumed superstructure flexure and shear rating factors <1.0 to determine the need for strengthening, rehabilitation, or replacement. To do this they used the 11 most common bridge types from the NBI, which represents 96 percent of all the bridges in the US. They also evaluated a range of bridge ages, conditions, and span lengths. A total of 490 National Highway System bridges from 11 states were rated. The bridges in the set evaluated included no local bridges.

A cost analysis was performed that looked at the effects of increased truck and axle loads on annual bridge capital costs based on 2011 dollars and included both the state and federal shares of costs, including costs of design, construction, and inspection.

A nine-step, one-time cost methodology was used for the cost analysis:

1. Determine the distribution of span lengths in the sample database as percentages separately for Interstate bridges and other NHS bridges.
2. Calculate the costs of bridge rehabilitation for each span length interval per ft^2 (calculated value = $235/$ft^2$) and include the following agency cost elements:
    a. Construction
    b. Design (8 percent to 20 percent depending on the project size)
    c. Construction inspection- and design-related assistance (13 percent)
    d. Work zone traffic control
    e. Substructure rehabilitation
    f. Mobilization (4 percent)

    g. Other costs, including
        i. Railing and transitions
        ii. Joints and approach pavements
        iii. Striping, grooving, sealing the deck, etc.

3. Determine the percentage of bridges rated less than 1.0 in the structural analysis process for each alternative truck configuration scenario for each span interval.
4. Determine the total number of Interstate bridges and other NHS bridges in the NBI.
5. Estimate the actual number of bridges in each span interval using the distributions observed in the sample database.
6. Determine the projected number of bridges with rating factor <1.0 for each configuration scenario by multiplying the percentage of bridges rated less than 1.0, calculated in Step 3, by the number of bridges in each span interval, calculated in Step 5.
7. Determine the cost of bridge rehabilitations for each span interval for each truck type, separating Interstate bridges from other bridges on the NHS, by multiplying the cost calculated for a single bridge for that span interval by the projected number of bridges with rating factor <1.0 for each truck scenario.
8. Add the costs from each span interval to determine the total costs for each scenario.
9. Calculate the change in cost for each scenario. The change in cost is the difference in the cost of rehabilitations due to an alternative truck configuration and that from the related control vehicle.

The projected one-time costs for all the bridges in the NHS (88,945 state bridges; no local bridges) from the cost analysis for the scenario most relevant to AB 2061—a change in truck gross vehicle weights from 80,000 lbs. to 88,000 lbs.—resulted in an estimated one-time cost increase of $0.4 billion. This is the cost for bridge strengthening and replacement for all of the bridges in the NHS. Although this scenario is for a greater load increase than AB 2061 allows, it is the closest that could be found in the study, and no other relevant studies were found. However, at the end of this chapter calculations to adjust the results for the change from an allowable truck GVW limit of 88,000 lbs. to an 82,000-lb. GVW limit are performed using a reasonable assumption.

This cost calculation included an assumption that larger loads on trucks would result in a reduction of truck VMT by 0.6 percent.

In addition to agency costs, the study also evaluated impacts to safety. Although no data regarding increases or decreases in the number of crashes could be found, two findings revealed by the literature were: that increased truck weights resulted in longer stopping distances but did not affect vehicle tracking; and that although there were slightly higher rates of citations for brake violations with heavier vehicles, vehicle weight or configuration were not predominant factors when predicting violations.

The MAP-21 report has the following main recommendation:

> At the conclusion of the technical reports, the Department believed that the current model and data limitations were so profound that the results could not accurately be extrapolated to confidently predict national impacts. Subsequent public input and peer review has not altered that view. As such, the Department stresses that no changes in the relevant federal truck size and weight laws and regulations should be made until these limitations

> are overcome. Despite recent congressional action approving additional size and weight exceptions and waivers on a piecemeal and nationwide basis, DOT recommends a thoughtful approach to future policy making.

The following were the study's conclusions and recommendations *(15, 17):*

- The US DOT recommended to Congress to not make changes in the relevant federal truck size and weight laws and regulations until the limitations in the ability to analyze those factors are overcome. Despite recent congressional action approving additional size and weight exceptions and waivers on a piecemeal and nationwide basis, the DOT recommended taking a thoughtful approach to future policy making.
- At this time, another study effort, with more time and more money, would not yield more reliable results. To make a genuine, measurable improvement in the knowledge needed for these study areas, a more robust study effort should start with the design of a research program that can establish data sources and models to advance the state of practice. Not all of this is within the purview or capacity of US DOT. Even recent gains in long-term transportation program reauthorizations have not sufficiently advanced the state of research and data to enable the US DOT to say when or even whether it will be in a position to collect and analyze better data and apply it to improved policy determinations and regulatory strategies.
- Changes made by Congress regarding the size and weight of vehicles allowed on the nation's Interstate Highway System are matters of policy. The work performed and the findings produced in this US DOT-sponsored study can inform the debate on these matters but do not provide definitive evidence or direction to support any specific new change of direction in the areas of truck size and weight limitations. This work has helped identify the areas in which there is a need to know more, and that new technologies for data collection and sharing can offer improved mechanisms for growing that knowledge.

4.3 Cost to Strengthen and Replace Bridges Due to a 2,000-Pound Truck Weight Increase

The MAP-21 study provided an estimate of $0.4 billion for the one-time costs to strengthen and replace bridges due to a 5-axle, 88,000 lb. truck (Scenario 1 of the CTSWLS) across all states. The following is a top-down first-order calculation that translates that national-level cost to California alone.

- The MAP-21 study assumed that bridges with a rating factor (either flexure or shear) less than 1.0 will require rehabilitation.
- For this current study, it was assumed that the bridges in the structurally deficient category are those that had rating factors less than 1.0.
- California has 6.2 percent of all the bridges in the US that are structurally deficient and 3.9 percent of all the structurally deficient NHS bridges. It was assumed for this study that 4.5 percent of the bridges are structurally deficient. Bridges on the NHS system are longer and more costly to rehabilitate than non-NHS bridges.
- It was also assumed for this study that the 82,000-lb. GVW limit produces half (allowing for some illegal trucks over the 82,000-lb. limit) as many ratings less than 1.0 than the 88,000-lb. truck scenario (a conservative estimate).
- The estimated cost is then: 4.5% × 0.5 × $400 million = $9 million in 2011 dollars.
- This cost estimate does not include any increases in annual maintenance costs due to the heavier trucks.

- A one-time cost estimation is the most precise estimate that could be made because of the lack of models and data, and because bridges have very long design lives.

5. Estimation of Changes in Axle Load Distributions

This chapter presents the process and results of adjusting current axle load spectra to reflect projected alternative fuel truck market penetration and the associated vehicle weight increases presented in Chapter 2. This work is Step 4 in the research approach outlined in Section 1.2.

5.1 Weigh-in-Motion (WIM) Spectra Groups

An *axle load spectra* is a table that shows the distribution of axle types (steering, single, tandem, tridem) and the axle loads occurring within each type in a population of trucks. Axle load spectra are used in mechanistic-empirical (ME) pavement simulation and design to characterize truck loading. Along with the total number of trucks passing over a pavement, axle load spectra answer the question “What proportion of axle type X with axle load Y within that number of trucks will this pavement be subjected to?” by showing the frequency of all axle types and axle loads. The damage caused by the number of passes of each axle load of a given axle type is simulated separately in ME design. This is repeated for each axle type, and the results are then summed to determine the total damage to the pavement caused by all loads of all axle types. The amount of each distress, such as cracking, is calculated from the total damage.

The California Department of Transportation (Caltrans) operates 132 Weigh-in-Motion (WIM) stations at key highway locations. These WIM stations collect, process, and store data on truck traffic—including truck classifications, speeds, gross vehicle weights (GVW), and axle loads *(18)*. The University of California Pavement Research Center (UCPRC) periodically obtains these data to update the axle load spectra used in the Caltrans pavement management system’s performance models and in Caltrans’s concrete and asphalt pavement project-level simulation and design programs.

To generate traffic inputs for pavement design and pavement management, in 2018 the UCPRC took axle load distributions from all the WIM stations for the 11-year period from 2004 to 2015 and grouped the axle load spectra into five representative ones. The most appropriate spectra of these five representative spectra were then assigned to every postmile on the state highway network based on predictive variables such as truck traffic level, percentage of trucks in the traffic stream, and the relative proportions of long-haul versus shorter-haul trucks (medium-duty trucks and short-haul tractor-trailers) in the stream. Locations with a preponderance of long-haul trucks and routes that have more trucks and a higher percentage of trucks tend to have heavier, more damaging spectra, because long-haul trucks tend to operate with partial loads or full loads in both highway directions. Heavier spectra also tend to occur more in rural areas, where there is less short-haul traffic. Shorter-haul trucks tend to return empty more often, operate with less-than-full loads, and operate more in urban areas with higher traffic and higher total truck traffic, but with trucks making up lower percentages of the total traffic.

The potential for truckers to increase their payloads when alternative propulsion systems become lighter after 2030 was not considered important because the most implementation is occurring in short-haul and medium-duty trucks, few of which operate near current axle load limits, and because AB 2061 does not increase axle load limits.

A combination of clustering and cut-tree analysis was used to create a decision tree for classifying the WIM data into the five “typical” spectra (2) *(19)*. Spectra 1 (the plural, *spectra,* is used because each of the five includes spectra for all four axle types), the lightest axle load spectra, was found on WIM sites on rural and inter-regional highway routes that carry few trucks in Caltrans Districts 1, 3, 4, 5, 6, 7, 8, 10, and 11 (note that District 9 has no WIM site). Spectra 2 and 3, the medium axle load spectra, included WIM sites on urban and intra-regional highway sections in Districts 3, 4, 5, 6, 7, 8, 10, 11, and 12. Spectra 2 and 3 occurred on most highway segments in urban areas. The heavier Spectra 4 was observed around the state, mostly on the primary truck routes between cities. Spectra 5, also a heavier axle load spectra, also mostly occurred on primary truck routes between cities, such as Interstate 5 in Districts 2, 3, 6, and 10 and Interstates 10 and 40 in District 8; and lower traffic volume routes where trucks make-up a higher percentage of the traffic , such as US 97 and US 395 in Districts 2 and 9, and State Route 58 in Districts 6 and 8. All of these are major inter-regional corridors where the large majority of the trucks travel loaded in both trip directions. Figure 5.1 shows a map of the state with the spectra assigned to each state highway network segment indicated by color. Figure 5.2 shows the load distributions within each axle type for each of the five spectra. The lines showing *counted as single* in the figure are the summation of all the axle types with multiple axles (tandems have two axles, tridems have three) counted as multiple single axles. The farther the *counted as single* summation is to the right, the heavier and more exponentially damaging the spectra.

Figure 5.1. Map of the spectra assigned to each segment of the state highway network.

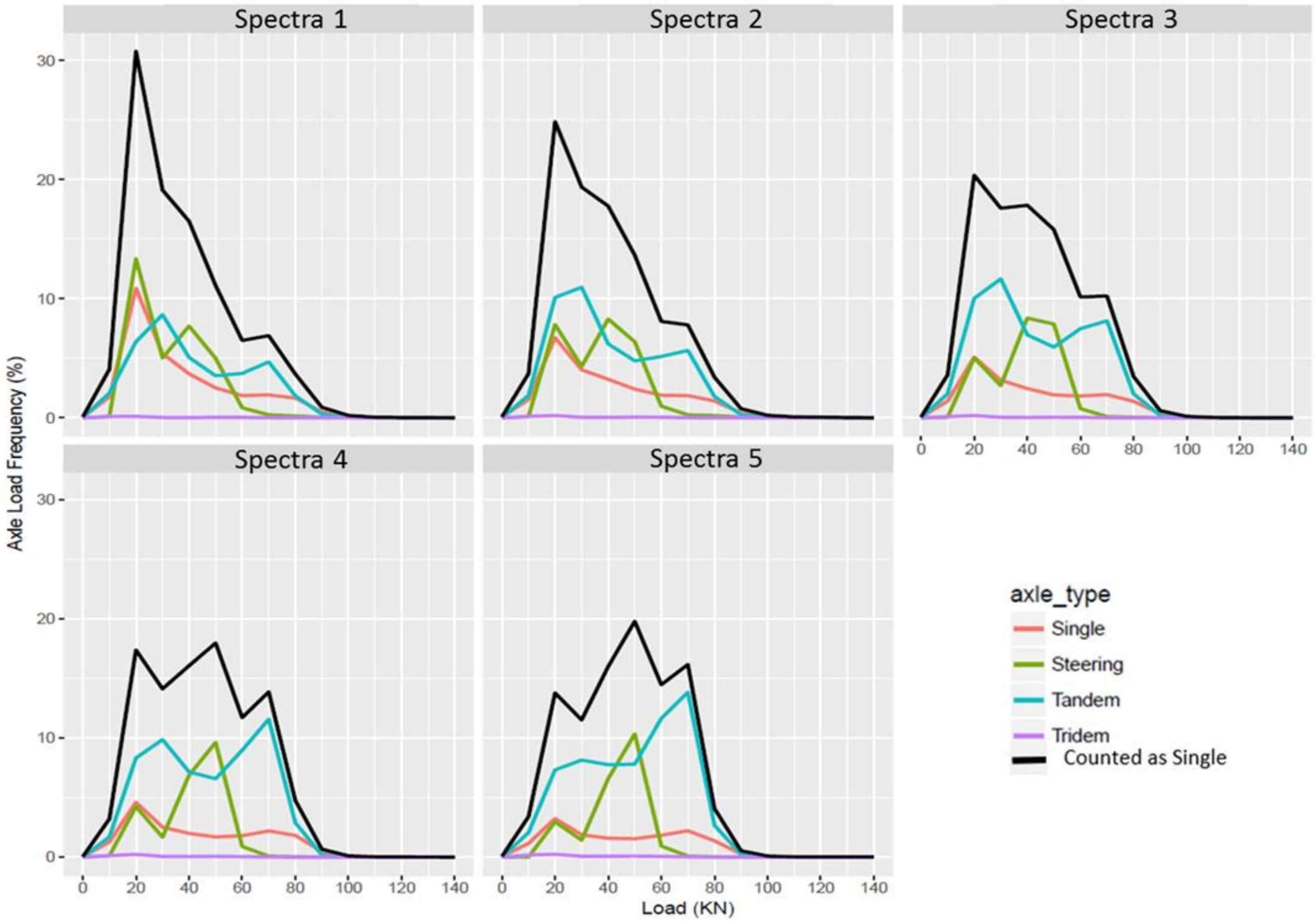


Figure 5.2. Five representative axle load distributions. Note: Tandem axles are shown as two single axles and tridem axles as three singles. Counted as Single is the summation of all axle types when counted as singles.

5.2 Gross Vehicle Weight

The distributions of gross vehicle weights (GVWs) on five WIM axle load spectra groups (Figure 5.3) were investigated to measure the current pattern of GVW for each axle load spectra. The GVWs over the California limit (80,000 lbs.) were found most in Spectra 4 and 5 (the two heaviest axle load spectra), and GVWs over the California limit were found rarely in Spectra 1 and 2 (the lightest and the second lightest axle load spectra). The percentages of GVWs over California limit were 0.4, 0.9, 0.3, 2.0, and 1.6 percent for Spectra 1, 2, 3, 4 and 5, respectively.

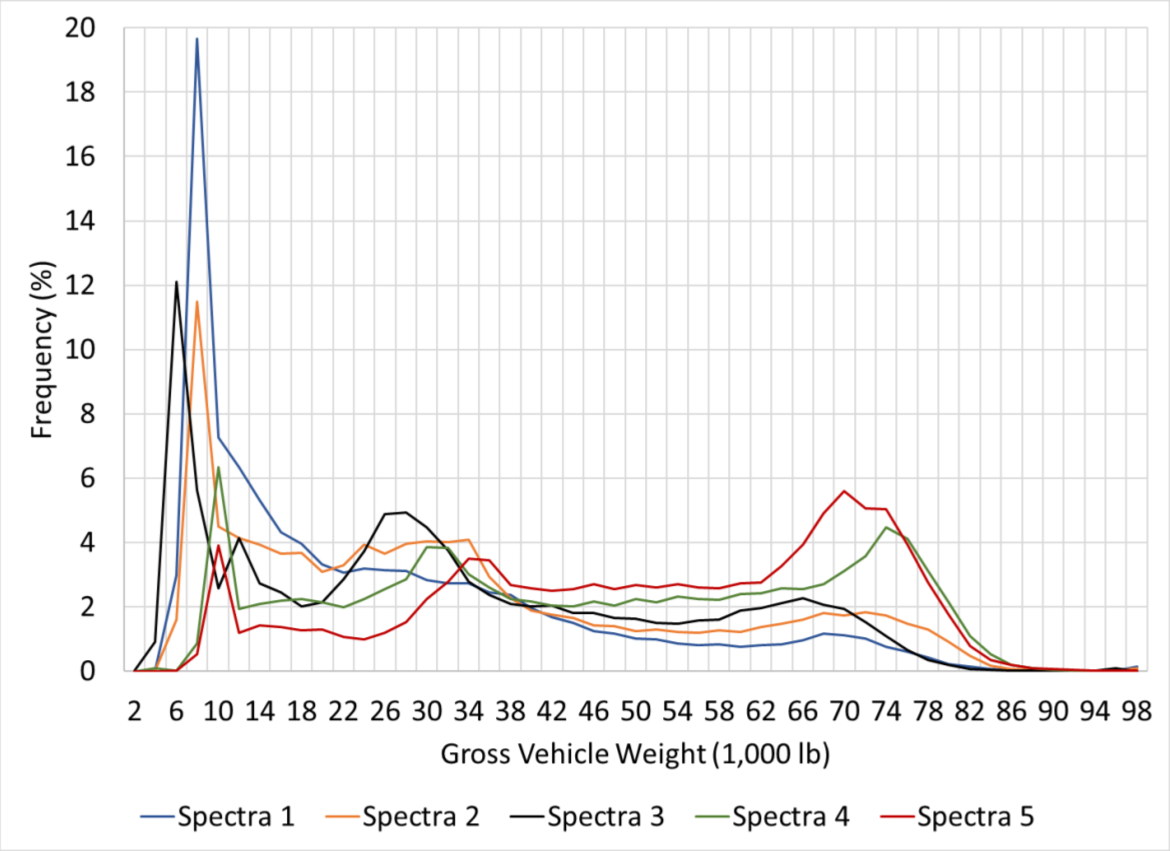


Figure 5.3. Distribution of gross vehicle weights (GVW) for the representative WIM axle load spectra groups.

5.3 Estimating Axle Load Spectra for Alternative Fuel Trucks

5.3.1 Assumptions and Processes Used for the Estimation

The assumptions made to calculate axle load spectra changes caused by increases in the market share of alternative truck technologies were based on Table 2.6 and Table 2.7.

- Axle weight limits are not being changed and current WIM spectra indicate that few axles are currently at or above the current axle load limits.
- For conventional trucks, the weight of both the internal combustion engine (ICE) and the under-the-hood transmission is loaded on the steering axle.
- For battery electric (BEV) and fuel cell (FCV) trucks, the engine and transmission have been removed from the engine space under the hood, and the battery or fuel cell has been installed behind the cabin.
- For BEV trucks, the weight of the batteries is evenly loaded on the steering axle and the next axle (single axle for medium-duty trucks and tandem axle for long-haul and short-haul trucks) *(20)*
- If a third or fourth axle is present, the axle loads of all three vehicle types are unaffected by the change in fuel type.

- The percentages of trucks of different types in different scenarios for the pathways to alternative fuel trucks identified in Chapter 2 were used to estimate changes to current axle load spectra 1 through 5:
    - Three truck types: short-haul (with a range less than 150 miles), medium-duty (with a range between 150 and 300 miles), and long-haul trucks (with a range exceeding 300 miles).
    - Three alternative truck technologies: BEV, FCV, and natural gas (NGV) trucks.
    - Three scenarios for market change: Scenario 1 (aggressive market share), Scenario 2 (moderate market share), and Scenario 3 (conservative market share).

The estimated proportions of truck types within each axle load spectra are shown in Table 5.1.

Table 5.1. Proportions of Truck Types in Five WIM Spectra

WIM Spectra	Long-Haul Trucks	Short-Haul Trucks	Medium-Duty Trucks	Sum
Spectra 1	10.0%	10.0%	80.0%	100%
Spectra 2	10.0%	10.0%	80.0%	100%
Spectra 3	30.0%	10.0%	60.0%	100%
Spectra 4	42.5%	5.0%	52.5%	100%
Spectra 5	50.0%	10.0%	40.0%	100%
All	28.5%	9.0%	62.5%	100%

Revised spectra for the years 2030 and 2050 were prepared for *Pavement ME,* the damage simulation program Caltrans uses for concrete pavement, and *CalME,* the damage simulation program Caltrans uses for asphalt pavement. Eight steps were required for this process:

1. Calculate the percentage of the truck fleet that uses alternative fuels. Starting from the 2020 baseline truck fleet information, future market share proportion estimates for each alternative truck technology (battery electric, fuel cell, and natural gas) were applied to each truck type (short-haul, medium-duty, and long-haul trucks) for the three scenarios (aggressive, moderate, and conservative market shares) in years 2030 and 2050 (see Table 5.2).
2. Determine the percentage of each axle type occurring in each truck type. Short-haul trucks were assumed to consist of a tractor with one steering single axle and one single axle, and both had weight adjustments for different fuel types in 2030 and 2050. The single or tandem axle at the back of the trailer was unchanged. Medium-duty trucks, which had weight adjustments for different fuel types in each year, were assumed to have a steering single axle and a back axle. It was assumed that 25 percent of the back axles were singles and 75 percent were tandems. Long-haul trucks were assumed to consist of a tractor with one steering single axle and one tandem axle on the tractor, and both had weight adjustments for different fuel types in each year. The tandem axle at the back of the trailer was unchanged.
3. Calculate the assumed average weight change on each of the axles affected by the fuel type change for the three truck types. These are shown in Table 5.3, Table 5.4, and Table 5.5, for battery electric, fuel cell, and natural gas, respectively.

4. Determine the approximate average percentage of the three truck types for each of the three scenarios. Do this for each of the five WIM spectra using the information shown in Table 5.1. The results of this step are shown in Table 5.6.
5. Calculate adjustment factors for the axle load spectra for the three alternative-fuel-truck market penetration scenarios. This was done in the following steps:
    a. Calculate each axle type percentage for each fuel type, including internal combustion engines, for each truck type in each spectra. The tridem axle spectra will not change in *Pavement ME* or *CalME* because that spectra is based on loads at the back of the trailer on short-haul and long-haul trucks, which do not change with fuel changes. Calculate an adjustment factor for each load range in each axle load spectra for each scenario and each year. This was done separately for *CalM*E (for asphalt pavement simulation) and *Pavement ME* (for concrete pavement simulation) because their input data are organized differently.
        i. For *CalME*, a preliminary adjustment factor is the ratio of an axle type's average weight increase to the load range in the spectra weighted by the percentages from Step 5a. For example, if in 2030 the long-haul steering single axle average change in weight for battery electric trucks is 1,586 lbs., the load range step in the spectra is 2,250 lbs., and long-haul BEV steering single axles make up 0.016 percent of the steering single axles in Spectra 1, then the adjustment factor is 0.00012. This was repeated for each fuel type in that truck type/axle type/spectra number combination, and they were then summed as a weighted average across all fuel types to calculate the final adjustment factor for each load range in each spectra.
        ii. *Pavement ME* has different load ranges in the spectra than *CalME.* It does not separate steering single and single axles, and it needs to have spectra tied to a truck class rather than using spectra directly. To simplify the adjustments to axle load spectra task, it was assumed that all the changes occurred in two predominant truck classes: it was assumed that all short-haul and long-haul tractor-trailers are Class 9 trucks and that all medium-duty trucks are Class 5. Final adjustment factors were then calculated for those two truck classes for input to *Pavement ME*.
6. Apply the adjustment factors to the axle load spectra. This was done by reducing the percentage of axles in the lightest load category in the axle load spectra using information from the preceding steps and proportionally increasing the number of axles in the heavier load categories. This was done for all axle types for *CalME* and for the two predominant truck types for *Pavement ME.*
7. Split the updated axle load spectra across the hours of the day. Each spectra consists of tables for each hour of a typical day because axle load distributions change hourly (trucks tend to run heavier at night because that is when long-haul truckers prefer to travel), and the interaction of axle load with pavement temperature is important for both concrete and asphalt pavements. For concrete pavements, the temperature difference between the top and bottom of a concrete slab causes stresses that interact with the load stresses caused by the axles, which together damage the concrete and lead to cracking. The case for asphalt pavements is different: the asphalt's stiffness is highly temperature dependent and the magnitude of the tensile strains in the asphalt and resultant pavement damage depend on the interaction of the asphalt stiffness and the axle loads.
8. Produce the final input files for each of the two pavement simulation programs. *Pavement ME* requires consideration of monthly differences in axle load spectra. *CalME* can also consider monthly changes, but—based on a previous analysis that showed insignificant differences between months in California *(21)*—it was assumed that they were the same across all months.

Table 5.2. Alternative Fuel Truck Proportions of the Truck Fleet by Truck Type for Three Scenarios

Scenario	Truck Type	2030 Battery Electric	2030 Fuel Cell	2030 Natural Gas	2050 Battery Electric	2050 Fuel Cell	2050 Natural Gas
Scenario 1	Short-haul	10.1%	0.5%	1.0%	43.0%	57.0%	0.0%
Scenario 1	Medium-duty	10.8%	2.1%	10.9%	47.6%	46.8%	5.4%
Scenario 1	Long-haul	0.2%	0.2%	0.0%	7.6%	68.5%	0.0%
Scenario 2	Short-haul	6.7%	0.3%	0.7%	33.8%	44.8%	0.0%
Scenario 2	Medium-duty	7.2%	1.4%	7.2%	43.7%	43.0%	4.9%
Scenario 2	Long-haul	0.1%	0.1%	0.0%	5.1%	45.7%	0.0%
Scenario 3	Short-haul	3.4%	0.2%	0.3%	16.9%	22.4%	0.0%
Scenario 3	Medium-duty	3.6%	0.7%	3.6%	21.8%	21.5%	2.5%
Scenario 3	Long-haul	0.1%	0.1%	0.0%	2.5%	22.9%	0.0%

Note: 1 = high market share scenario; 2 = baseline market share scenario; 3 = low market share scenario

Table 5.3. Weight Change (lbs.) over Axle Position by Vehicle Type for Years 2030 and 2050 for Battery Electric Vehicles

		2030 Long-Haul	2030 Short-Haul	2030 Medium-Duty	2030 Long-Haul	2030 Short-haul	2030 Medium-Duty
By body position	Hood	-2,156	-2,156	-130	-2,156	-2,156	-130
	Behind cab	7,484	3,564	1,574	6,423	2,393	736
By axle position	Steering	1,586	-374	657	1,055	-959	238
	Front single or tandem	3,742	1,782	787	3,211	1,197	368
	Rear single	0	0	Not applicable	0	0	Not applicable
	Rear tandem	0	0	Not applicable	0	0	Not applicable

Table 5.4. Weight Change (lbs.) over Axle Position by Vehicle Type for Year 2030 and 2050 for Fuel Cell Vehicles

		2030 Long-Haul	**2030 Short-Haul**	**2030 Medium-Duty**	**2030 Long-Haul**	**2030 Short-Haul**	**2030 Medium-Duty**
By body position	Hood	-1,681	-1,918	-59	-1,859	-2,008	-85
By body	Behind cab	3,947	2,519	1,194	2,325	1,239	591
By axle position	Steering	293	-659	538	-697	-1,388	210
	Front single or tandem	1,974	1,260	597	1,162	620	296
	Rear single	0	0	Not applicable	0	0	Not applicable
	Rear tandem	0	0	Not applicable	0	0	Not applicable

Table 5.5. Weight Change (lbs.) over Axle Position by Vehicle Type for Year 2030 and 2050 for Natural Gas Vehicles

		2030 Long-Haul	**2030 Short-Haul**	**2030 Medium-Duty**	**2030 Long-Haul**	**2030 Short-Haul**	**2030 Medium-Duty**
By Body Position	Hood	0	0	0	0	0	0
	Behind cab	2,000	1,000	500	2,000	1,000	500
By Axle Position	Steering	1,000	500	250	1,000	500	250
	Front single or tandem	1,000	500	250	1,000	500	250
	Rear single	0	0	Not applicable	0	0	Not applicable
	Rear tandem	0	0	Not applicable	0	0	Not applicable

Table 5.6. Proportions in Total Truck Fleet of Internal Combustion Engine (ICE) and Alternative Fuel Truck (AFT) Technologies by Truck Type and WIM Spectra in 2030 and 2050 for Three Scenarios

Scenario	WIM Spectra	2030 ICE All Truck Types	2030 AFT Short-Haul Trucks	2030 AFT Medium-Duty Trucks	2030 AFT Long-Haul Trucks	2050 ICE All Truck Types	2050 AFT Short-Haul Trucks	2050 AFT Medium-Duty Trucks	2050 AFT Long-Haul Trucks
1	Spectra 1	83.9%	1.6%	12.9%	1.6%	6.6%	9.3%	74.7%	9.3%
1	Spectra 2	83.9%	1.6%	12.9%	1.6%	6.6%	9.3%	74.7%	9.3%
1	Spectra 3	83.9%	1.6%	9.6%	4.8%	6.6%	9.3%	56.0%	28.0%
1	Spectra 4	83.9%	0.8%	8.4%	6.8%	6.6%	4.7%	49.0%	39.7%
1	Spectra 5	83.9%	1.6%	6.4%	8.0%	6.6%	9.3%	37.3%	46.7%
2	Spectra 1	89.3%	1.1%	8.6%	1.1%	20.7%	7.9%	63.5%	7.9%
2	Spectra 2	89.3%	1.1%	8.6%	1.1%	20.7%	7.9%	63.5%	7.9%
2	Spectra 3	89.3%	1.1%	6.4%	3.2%	20.7%	7.9%	47.6%	23.8%
2	Spectra 4	89.3%	0.5%	5.6%	4.6%	20.7%	4.0%	41.6%	33.7%
2	Spectra 5	89.3%	1.1%	4.3%	5.4%	20.7%	7.9%	31.7%	39.7%
3	Spectra 1	94.6%	0.5%	4.3%	0.5%	60.3%	4.0%	31.7%	4.0%
3	Spectra 2	94.6%	0.5%	4.3%	0.5%	60.3%	4.0%	31.7%	4.0%
3	Spectra 3	95.7%	0.5%	3.2%	0.5%	60.3%	4.0%	23.8%	11.9%
3	Spectra 4	94.6%	0.3%	2.8%	2.3%	60.3%	2.0%	20.8%	16.9%
3	Spectra 5	94.6%	0.5%	2.1%	2.7%	60.3%	4.0%	15.9%	19.8%

Note: 1 = high market share scenario; 2 = baseline market share scenario; 3 = low market share scenario; AFT = BEV, FCV, NGV combined.

5.3.2 Axle Load Spectra for Concrete Pavement Simulation

The axle load distributions for concrete pavements in the five WIM spectra for the three scenarios were calculated using the input format of *Pavement ME*. This simulation program requires the axle load distribution of each axle type (single, tandem, tridem, and quadrum) for each truck class for each month for each WIM spectra. The steering and single axles were combined as *Pavement ME* uses a single input file for both of these. Based on the assumptions described in the previous section, the adjustment factors for axle load change generated for each axle type for the five WIM spectra and three scenarios are shown in Table 5.7.

The adjustment factors reflect the proportion of each technology (ICE, BEV, FCV, and NGV) in 2030 and 2050, and the axle load changes for the first two axles for the vehicle types considered. A positive adjustment factor indicates an increase in loads in the spectra, and similarly a negative adjustment factor indicates a decrease. As described in the eight-step process to create the adjusted spectra, additional factors contributing to an increase or decrease in the adjusted spectra are the proportion of trucks changed to alternative fuels within a truck type, the proportion of that truck type in the spectra, and the axle types on those trucks.

As mentioned previously, the adjustment factors were applied to the two dominant truck classes observed in California: Truck Class 5 for medium-duty trucks and Truck Class 9 for long-haul and short-haul trucks (both are semi-tractor trailer combinations). These two classes were selected rather than all 10 truck classes to reduce the complexity and amount of work needed to update the spectra. In Truck Classes 5 and 9 the lightest load category was reduced by the product of the 2020 percentage of axles in that category times the adjustment factor shown in the table, and that same percentage of axles was increased proportionally in the heavier load categories.

As an example, Figure 5.4 shows the single axle load distributions of Truck Class 5 for Spectra 1 for Scenario 1 in the years 2020, 2030, and 2050. Compared to 2020, the proportion of axle loads in the lightest category, 2,000 to 3,000 lbs., is slightly lower in 2030 and 2050, and the proportion of axle loads in the heavier categories is slightly higher due to the additional axle load for batteries, fuel cells, and natural gas tanks. However, the differences are in fact nearly impossible to see in Figure 5.4 because they are so small. They are small because the trailer axles that make up a large portion of the single axles are unchanged by changes in fuel technology in both 2030 and 2050. Other contributing factors to the small differences are the very small proportion of trucks with alternative fuel technologies in 2030, and the weight reductions of battery electric and fuel cell technologies in 2050 (as shown in Table 5.2 and Table 5.3), when the percentage of AFTs is greater (as shown in Table 5.6). The negative adjustment factors in 2050 shown in Table 5.7 occurred because the combined proportions of BEV and FCV have actually lightened the overall spectra for Class 9 (short-haul and long-haul tractor-trailers) single axles.

Table 5.7. Axle Load Adjustment Factors for Concrete Pavement Simulations Using *Pavement ME*

WIM	Axle Type	Year 2030						Year 2050					
		Scenario 1		Scenario 2		Scenario 3		Scenario 1		Scenario 2		Scenario 3	
		Class 5	Class 9	Class 5	Class 9	Class 5	Class 9	Class 5	Class 9	Class 5	Class 9	Class 5	Class 9
Spectra 1	Single	0.112	0.019	0.075	0.013	0.037	0.006	0.245	-0.055	0.225	-0.027	0.113	-0.013
	Tandem	0.019	0.001	0.012	0.001	0.001	0.001	0.005	0.026	0.045	0.017	0.023	0.009
Spectra 2	Single	0.082	0.016	0.055	0.011	0.027	0.005	0.243	-0.073	0.200	-0.053	0.100	-0.026
	Tandem	0.019	0.001	0.012	0.001	0.006	0.001	0.049	0.026	0.045	0.017	0.023	0.009
Spectra 3	Single	0.084	0.016	0.056	0.011	0.028	0.005	0.184	-0.153	0.169	-0.106	0.084	-0.053
	Tandem	0.028	0.001	0.019	0.001	0.009	0.001	0.074	0.078	0.068	0.052	0.034	0.026
Spectra 4	Single	0.045	0.001	0.030	0.006	0.015	0.003	0.102	-0.186	0.094	-0.126	0.047	-0.063
	Tandem	0.025	0.001	0.016	0.001	0.008	0.001	0.064	0.111	0.060	0.074	0.030	0.037
Spectra 5	Single	0.034	0.017	0.023	0.011	0.011	0.006	0.078	-0.232	0.071	-0.156	0.036	-0.079
	Tandem	0.001	0.001	0.006	0.001	0.003	0.001	0.025	0.130	0.023	0.087	0.011	0.043

Note: positive numbers indicate axle load increases within the spectra, and negative numbers indicate axle load decreases.

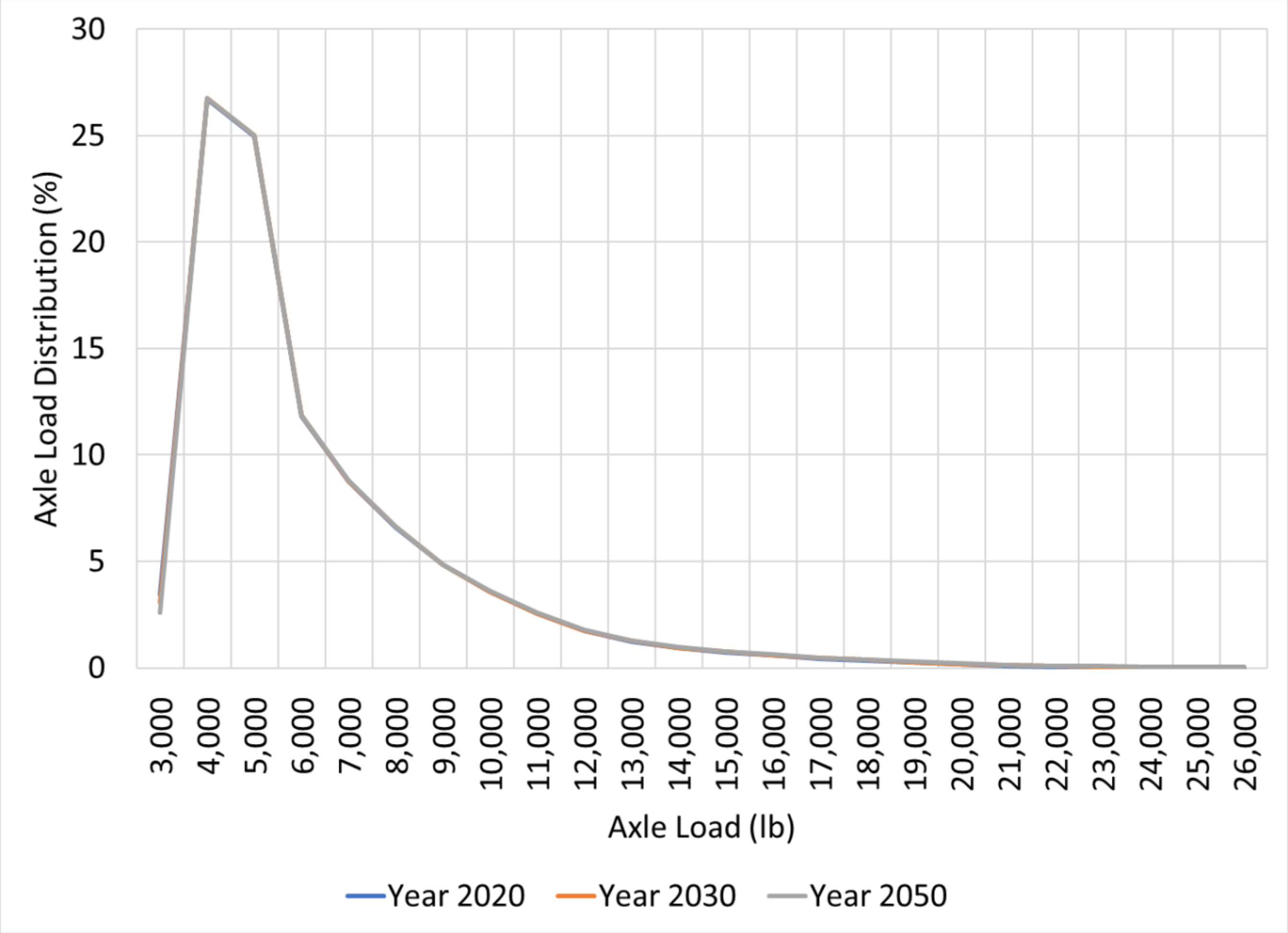


Figure 5.4. Single axle load distributions of Truck Class 5 for Spectra 1 for Scenario 1. Notes: 1. The legal limit in California is 20,000 lbs. 2. The figure has three curves that are nearly identical.

Figure 5.5 shows the tandem axle load distributions of Truck Class 9 for Spectra 5 for Scenario 1 in years 2020, 2030, and 2050. The results are comparable to those of the single axles and for the same reasons. As was seen in Figure 5.4, the differences in the axle load distributions shown in Figure 5.5 are so small as to be indistinguishable.

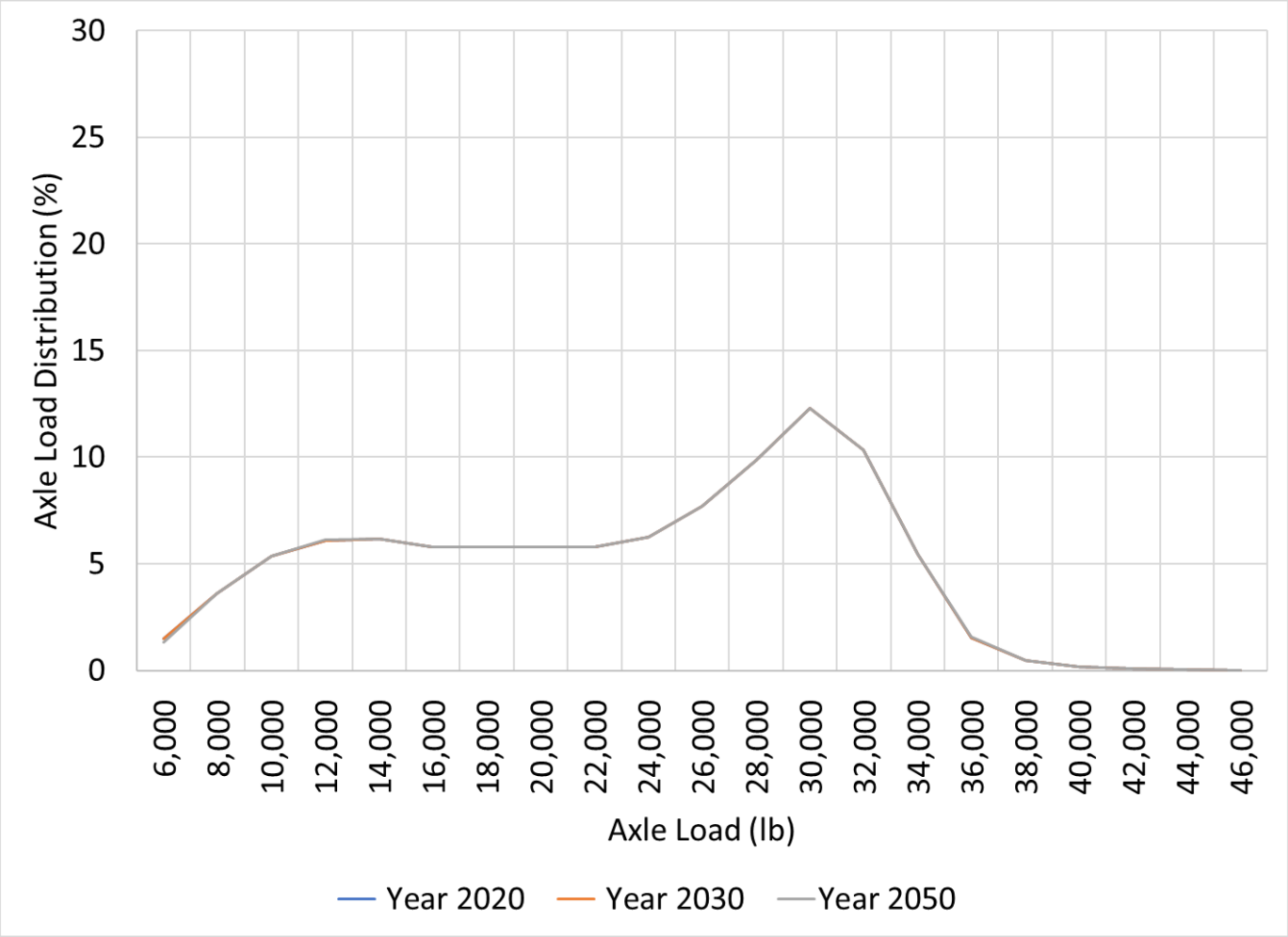


Figure 5.5. Tandem axle load distributions of Truck Class 9 for Spectra 5 for Scenario 1. Notes: 1. The legal limit in California is 34,000 lbs. The figure has three curves that are nearly identical.

5.3.3 Axle Load Spectra for Asphalt Pavement Simulation

Another set of axle load distributions of the five WIM spectra were calculated for asphalt pavement in the input format of *CalME*. This simulation program requires the hourly axle load distribution of each axle type (steering, single, tandem, and tridem) for each WIM spectra. The axle load distribution of each axle type and the hourly truck distribution for each WIM spectra were extracted from the Caltrans WIM database *(18)*. Figure 5.6 shows the average statewide hourly truck distribution of each WIM spectra. It can be seen that locations with the spectra dominated by long-haul trucks (4 and 5) tend to have a greater percentage of operations between midnight and 10 a.m. than locations with spectra dominated by medium-duty trucks (1, 2, 3), which tend to have more operations than the heavier spectra between noon and 9 p.m. All truck operations in the state are heavier in the afternoon and evening than between midnight and noon.

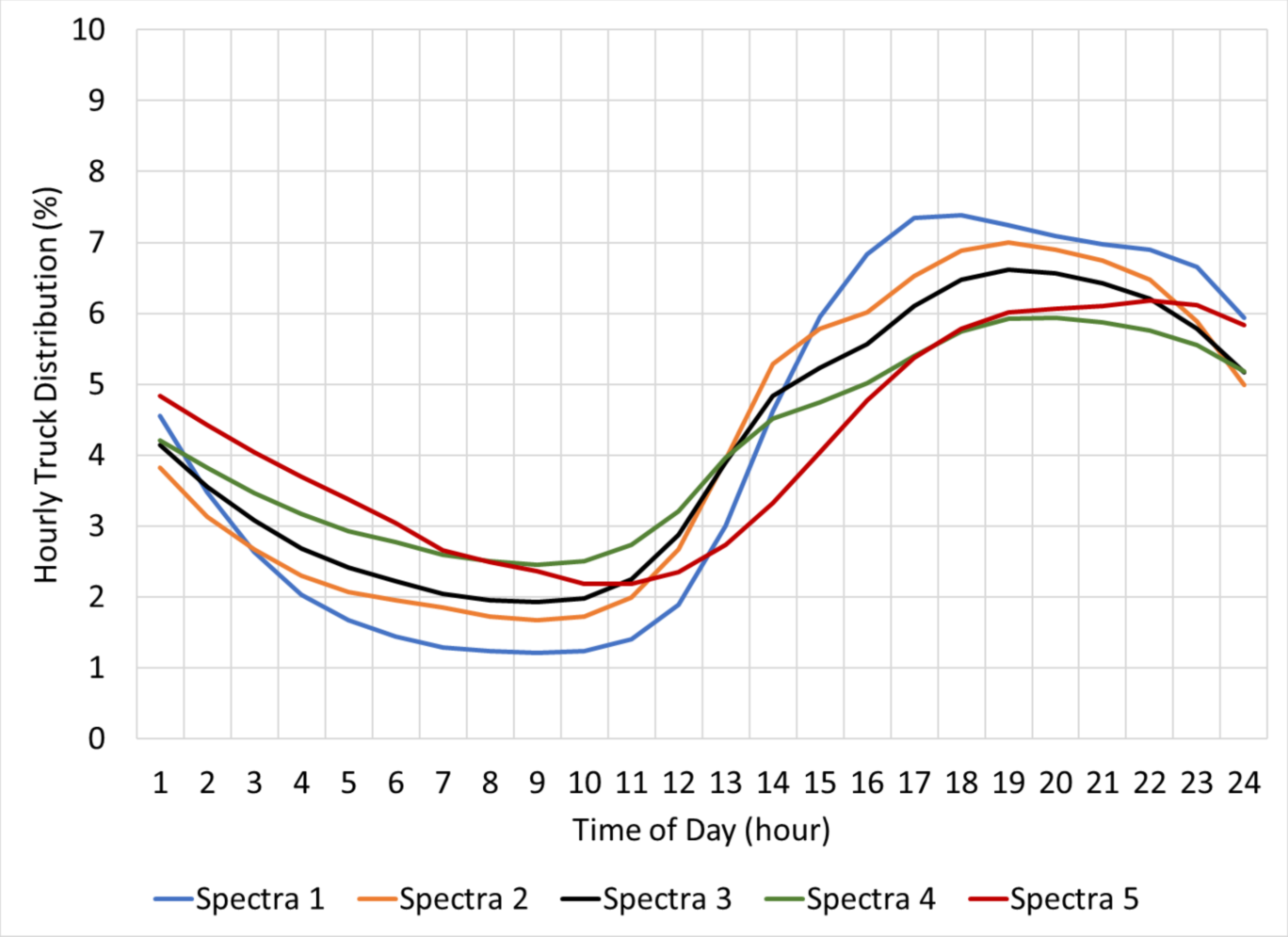


Figure 5.6. Average statewide hourly truck distributions for the five WIM spectra.

Table 5.8 shows the axle load adjustment factors for *CalME* for the asphalt pavement analysis developed following the earlier eight-step process, and Figure 5.7 and Figure 5.8 show the axle load spectra for steering single axles and tandem axles, respectively. As with the previous spectra shown in Figure 5.4 and Figure 5.5, the differences in the spectra caused by market penetration and technology changes for AFT are so small as to be indistinguishable from current spectra. As noted earlier, *CalME* does not require the spectra to be tied to specific truck classes. The trends shown previously for *Pavement ME* are the same because these are the same data, although they are now organized by axle type alone rather than by axle type for the two truck classes.

Table 5.8. Axle Load Adjustment Factors for Asphalt Pavement for Proportion of Axles Changing Spectra Load Range

			Year 2030			Year 2050	
Spectra	**Axle Type**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 1**	**Scenario 2**	**Scenario 3**
	Steering	0.040	0.026	0.013	0.017	0.031	0.016
Spectra 1	Single	0.042	0.028	0.014	0.126	0.110	0.055
	Tandem	0.006	0.004	0.002	0.026	0.021	0.011
	Steering	0.025	0.016	0.008	0.008	0.008	0.004
Spectra 21	Single	0.042	0.028	0.014	0.126	0.110	0.055
	Tandem	0.006	0.004	0.002	0.026	0.021	0.011
	Steering	0.029	0.019	0.010	-0.047	-0.022	-0.011
Spectra 3	Single	0.033	0.022	0.011	0.104	0.090	0.045
	Tandem	0.004	0.003	0.001	0.046	0.033	0.017
	Steering	0.026	0.017	0.009	-0.049	-0.023	-0.011
Spectra 4	Single	0.026	0.017	0.009	0.077	0.068	0.034
	Tandem	0.004	0.003	0.001	0.059	0.042	0.021
	Steering	0.019	0.013	0.006	-0.102	-0.064	-0.032
Spectra 5	Single	0.025	0.017	0.008	0.082	0.070	0.035
	Tandem	0.003	0.002	0.001	0.065	0.045	0.023

Note: Positive numbers indicate axle load increases, and negative numbers indicate axle load decreases.

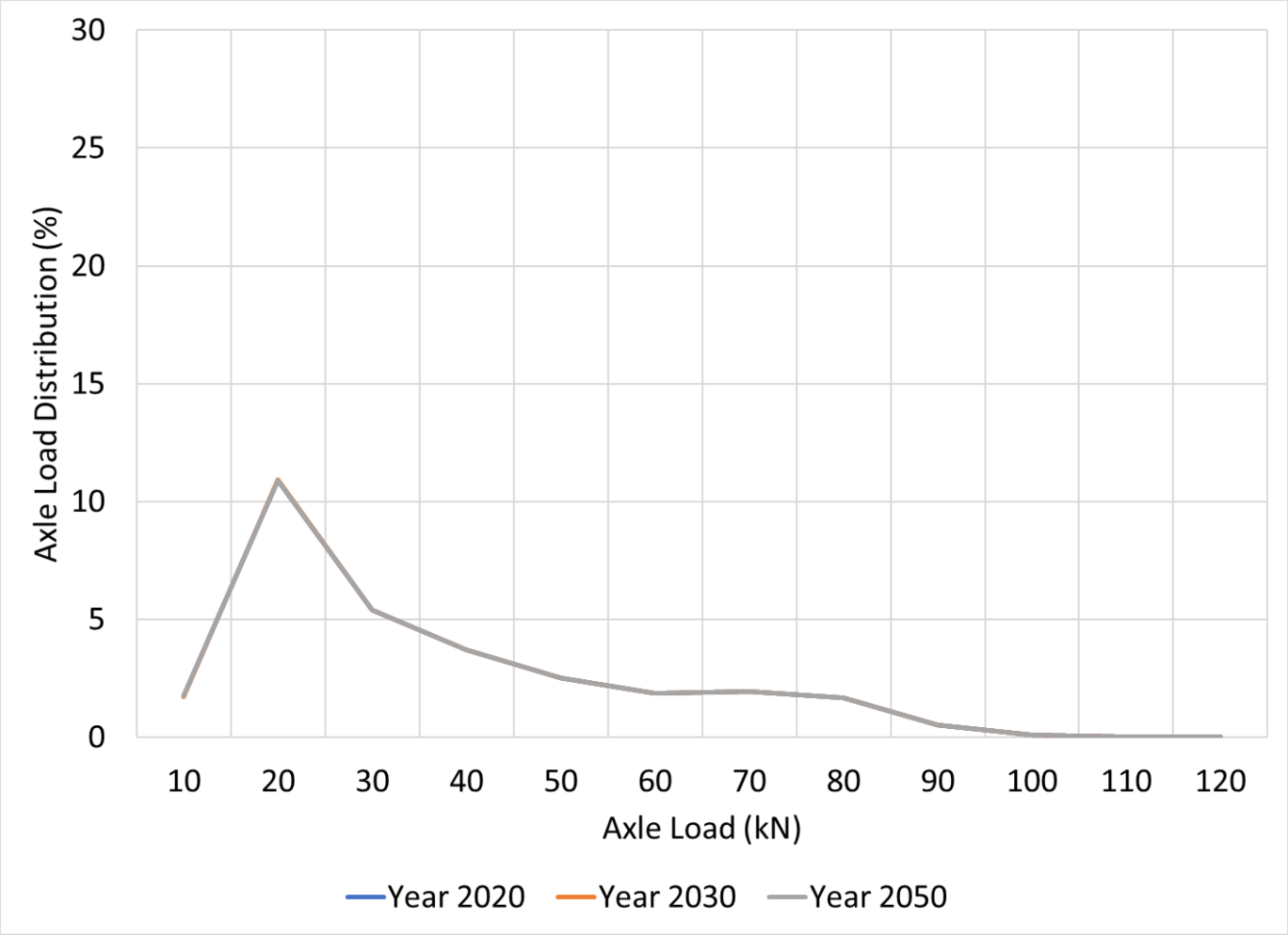


Figure 5.7. Axle load distributions of steering axles for Spectra 1 for Years 2020, 2030, and 2050. Note: The figure has three curves that are nearly identical.

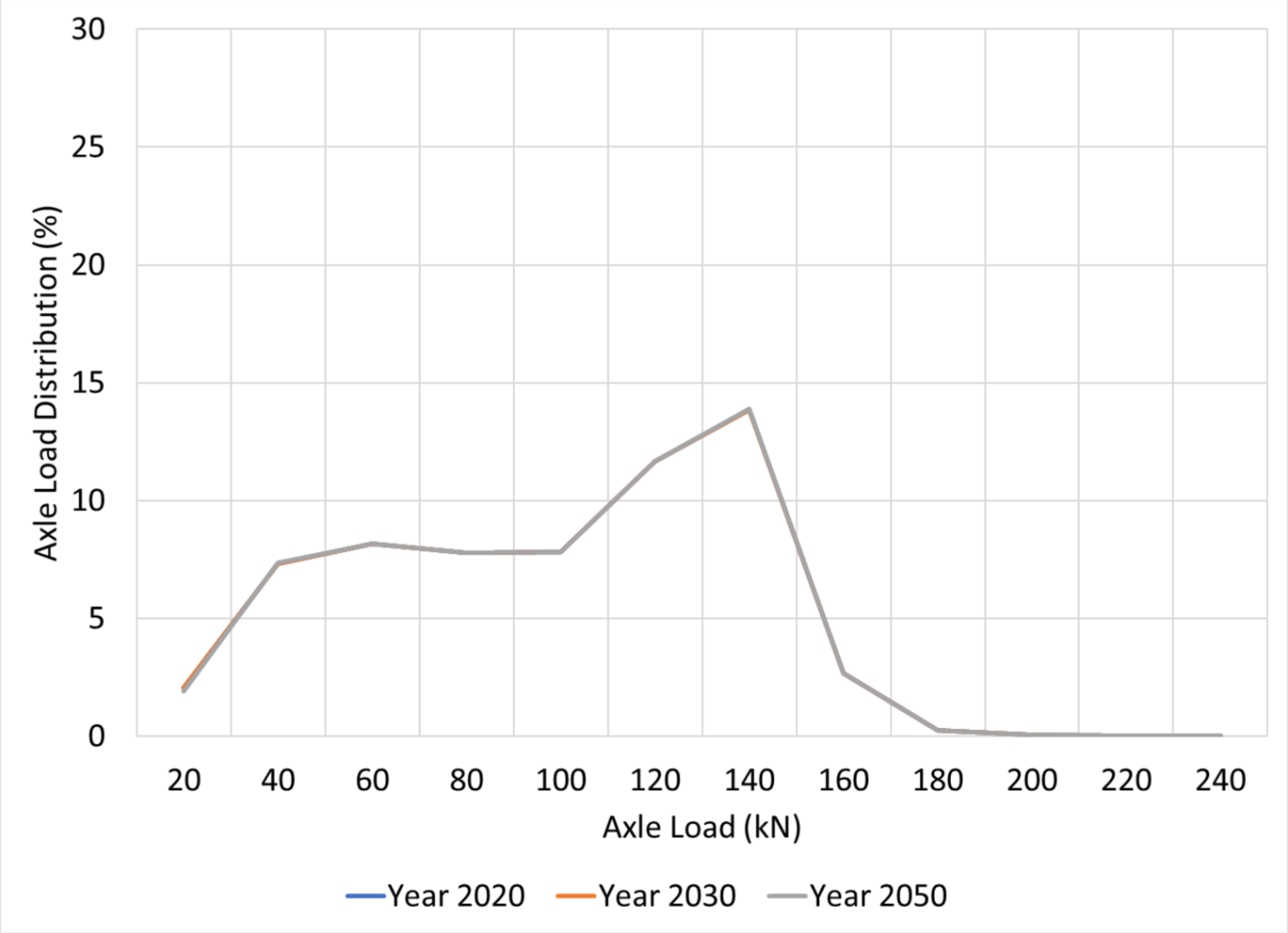


Figure 5.8. Axle load distributions of tandem axles for Spectra 5 for Years 2020, 2030, and 2050. Note: The figure has three curves that are nearly identical.

5.4 Garbage Truck Impact Analysis

An analysis was made of the effects of converting a typical garbage truck from diesel to natural gas (NG). The scope of the analysis included three scenarios in terms of the street types that the NG garbage trucks would be operating on: arriving full on the road into the waste-handling facility, leaving the facility empty, and operating partially loaded on residential streets. The latter distribution was centered around the trucks being half full to allow interpolation between the full case—considered equivalent to the trucks' content on the last street traversed on the run before they left for the waste handling facility—and the empty one—considered equivalent to their load on the first street they traversed on the run.

5.4.1 Assumptions

Axle loads

The business as usual (BAU) scenario assumed that a diesel-powered garbage truck consists of a steering axle and a tandem axle, and that the truck's gross vehicle weight is 28,000 lbs. when empty, 37,000 lbs. when half loaded, and 46,000 lbs. when fully loaded. These assumptions were based on a review of typical garbage truck specifications from a number of Internet sources and are intended to provide support to a first-order analysis of the effects of the fuel technology change. Performing a detailed analysis of all the garbage truck types operating in California would be very difficult for several reasons: first, because commercial operators' truck-load information is proprietary and closely held; second, an enormous effort would be required to collect this kind of information across a state so large. These factors combined rendered that type of detailed analysis impossible within the project's scope and budget.

Because California's tandem axle load limit is 34,000 lbs., this analysis assumed that when a diesel-powered garbage truck is fully loaded the weight of its garbage is 18,000 lbs. An NG vehicle's additional weight is the greater weight of its fuel tank compared to a diesel fuel tank. Two NG scenarios were considered in the analysis: one in which NG garbage trucks are intended to travel on shorter routes with an extra 500-lb. weight, and another in which NG trucks travel on longer routes with an extra 2,000-lb. weight. Because the fuel tank is expected to sit behind and potentially under the cabin, it was assumed that the steering axle (front) carries 75 percent of the extra load and the tandem (rear) axle carries 25 percent. Table 5.9 shows the steering and the tandem axle loads for the diesel-powered garbage trucks and the two cases with NG-powered garbage trucks.

Table 5.9. Axle Loads for Load Conditions and Axle Types for the Garbage Truck Alternatives

Load Condition	Axle Type	Axle Load (lb.) for Diesel-Powered Garbage Trucks	Axle Load (lb.) for Natural Gas-Powered Garbage Trucks (Extra 500 lb.)	Axle Load (lb.) for Natural Gas-Powered Garbage Trucks (Extra 2,000 lb.)
Empty	Steering	12,000	12,375	13,500
Empty	Tandem	16,000	16,125	16,500
Empty	All Axles	28,000	28,500	30,000
Half loaded	Steering	12,000	12,375	13,500
Half loaded	Tandem	16,000	25,125	25,500
Half loaded	All Axles	37,000	37,500	39,000
Fully loaded	Steering	12,000	12,375	13,500
Fully loaded	Tandem	34,000	34,125	34,500
Fully loaded	All Axles	46,000	46,500	48,000

Vehicle Hourly Distribution

These assumptions were made for all the scenarios: for the waste facility's outbound road, it was assumed that the traffic from 50 percent of the empty trucks using the road for their initial run was distributed equally between 5 a.m. and 7 a.m., and that 50 percent of the empty-truck traffic for subsequent runs was distributed equally from between 7 a.m. and 2 p.m. For the waste facility's inbound road, it was assumed that 100 percent of the fully loaded garbage truck passes were distributed equally between 8 a.m. and 4 p.m. The hourly distributions of different axle load spectra are important because of the interactions of pavement temperature and axle loads affecting damage and distress development for both asphalt and concrete pavements.

For simplicity, on residential streets it was assumed that there is one garbage truck pass per day at noon, with a 25 percent probability that the truck would be empty, a 50 percent probability that the truck would be half-loaded, and a 25 percent probability that it would be fully loaded. Table 5.10 shows the assumed hourly distributions of garbage truck passes on each road type.

Table 5.10. Hourly Distribution of Garbage Truck Passes on Each Road Type

Hour	Outbound Road from a Waste Facility	Inbound Road to a Waste Facility	Residential Street
12 AM – 5 AM	0.0%	0.0%	0.0%
5 AM – 6 AM	25.0%	0.0%	0.0%
6 AM – 7 AM	25.0%	0.0%	0.0%
7 AM – 8 AM	7.1%	0.0%	0.0%
8 AM – 9 AM	7.1%	12.5%	0.0%
9 AM – 10 AM	7.1%	12.5%	0.0%
10 AM – 11 AM	7.1%	12.5%	0.0%
11 AM – 12 PM	7.1%	12.5%	0.0%
12 PM – 1 PM	7.1%	12.5%	100.0%
1 PM – 2 PM	7.1%	12.5%	0.0%
2 PM – 3 PM	0.0%	12.5%	0.0%
3 PM – 4 PM	0.0%	12.5%	0.0%
4 PM – 12 AM	0.0%	0.0%	0.0%
Total	100.0%	100.0%	100.0%

5.4.2 Axle Load Distributions

Axle load distributions for each axle for the three road cases (residential street, and waste facility inbound and outbound directions) were generated for use with *CalME*. The three garbage truck types were (1) diesel-powered, (2) NG-powered with an extra 500 lbs., and (3) NG-powered with an extra 2,000 lbs. The three road cases considered were (1) an outbound road from a waste facility with empty trucks, (2) an inbound road to a waste facility with full trucks, and (3) a residential street with half-full trucks.

For all the distributions, the percentages of axles in each load range category had to be manipulated to produce the average weight change shown in Table 5.5 for NG vehicles.

6. Impact of Increased Truck Weights on Pavement Damage, Costs, and Environmental Impacts

6.1 Introduction

This part of the study produced a first-order quantification of the environmental and cost consequences that the proposed weight limit increases for alternative fuel trucks (AFTs) would have on California's state- and local-government-owned pavement infrastructure. These consequences were evaluated under different AFT market penetration scenarios. Because higher damage rates result in more frequent maintenance and rehabilitation (M&R) activities, which in turn increase construction activity and consume more materials, the study quantified and expressed these changes in terms of the change in greenhouse gas (GHG) emissions within the study's analysis period. This work is Step 5 in the research approach outlined in Section 1.2.

The study's methodologies included life cycle assessment to determine GHG impacts, and life cycle cost analysis to determine cost impacts. Life cycle assessment is a methodology widely used to quantify the full life cycle environmental impacts of a product or service, and studies have shown that its application in transportation infrastructure management has gained increased attention from federal, state, and local government agencies *(22, 23, 24)*. Life cycle cost analysis is a standard Caltrans procedure used to compare rehabilitation alternatives, and it is also used by most other states.

6.2 Goal, Scope and Assumptions

6.2.1 Goal and Scope

The goal of this study was to quantify the greenhouse gas emission impacts and agency costs attributable to the change in damage to California's publicly owned pavement infrastructure caused by proposed weight limit increases for alternative fuel trucks. The study examined this by considering different market penetration scenarios for those trucks. The transportation infrastructure considered included all the state and local government-owned pavements in California.

The assumed analysis period was 30 years (2020 to 2050) and the system boundaries included the following life cycle stages: *material production, transportation to site,* and *construction activities.* The system boundary did not include the *use stage* and the routine maintenance activities within that period. For the *end-of-life stage*, the study assumed that the old materials were removed (concrete) or milled (asphalt) and transported to a plant for recycling. The cut-off method was applied for allocating the end-of-life impacts, meaning that all the impacts of removal or milling, transport to the plant, and recycling were assumed to be assigned to the downstream project. The material transportation distance for the initial construction was assumed to be 50 miles.

6.2.2 Modeling Approach and Assumptions

A flowchart of the analysis procedure and the modeling approach used for this study is shown in Figure 6.1. How data were collected for the items in the figure's upper-left and –middle boxes—AFT and market penetration data and axle load spectra data—are discussed in Chapters 2 and 4, respectively. The distributions of axle types and axle loads for each truck type were also explained in Chapter 5. Transportation network data were collected from the Caltrans pavement management system for the pavements managed by the state. The pavement damage estimation was performed separately for asphalt and concrete pavement using two software programs: *CalME (25)* was used for the analysis of asphalt pavements and AASHTO *Pavement ME (26)* was used for concrete pavements. The life cycle inventory and life cycle impact assessment data needed for the life cycle assessment were taken from the UCPRC Life Cycle Inventory Database *(27)*.

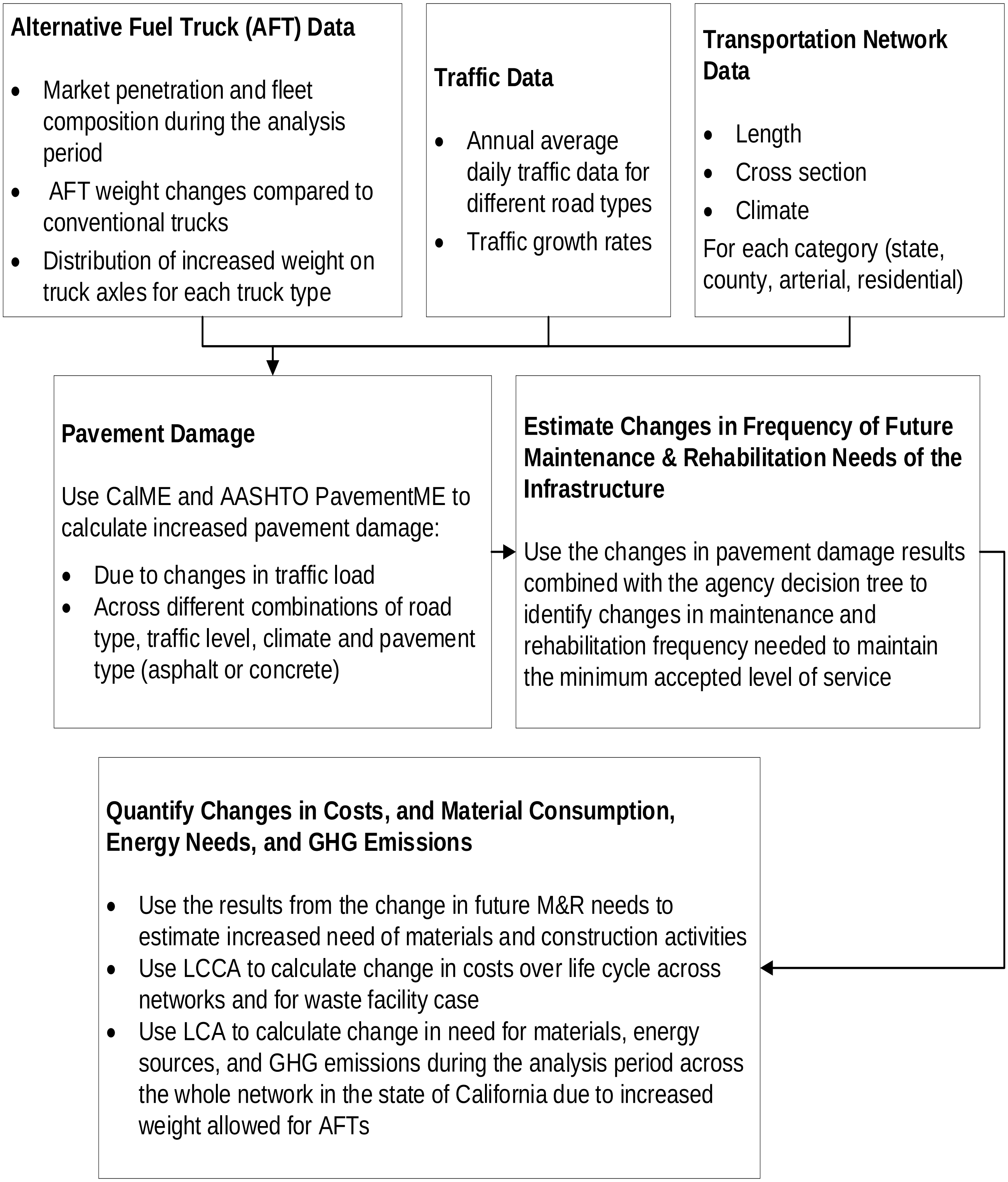


Figure 6.1. Flowchart of the analysis procedure undertaken in this study. (LCCA is life cycle cost analysis; LCA is life cycle analysis)

The pavement damage module was run under seven cases: the business as usual case (BAU, based on 2020 data), and three AFT market penetration cases repeated for the years 2030 and 2050. For each WIM spectra, the BAU pavement layer cross section was designed to provide a 20-year service life for the state highway cases and an approximately 12-year service life for the local government cases. The pavement cross section was then analyzed under the other six cases to calculate the change in pavement life attributable to the axle load changes. It was assumed that the same treatment would be applied at the end of the service life for each case.

An example pavement cross section was selected for each case to provide a first-order representation of the entire state for that road and pavement type.

State-Owned Pavement Example Sections

The locations of the example pavement locations for the state highway network are shown in Table 6.1, along with traffic and climate region information.

Each of these is currently an asphalt pavement. Analyzing the pavement damage under the changed axle load spectra required the creation of pavements with typical rehabilitation treatments to be placed on the existing asphalt pavements; therefore a typical rehabilitation asphalt overlay with an approximate 20-year design life was placed on the existing pavement cross-section found in the Caltrans pavement management system database. The pavement structures analyzed for each WIM spectra are shown in Table 6.2. The asphalt overlay materials used in the damage simulations met state specifications.

For the Spectra 1 and 2 analyses, the structural overlay thicknesses were too thin to also include a structural rubberized hot mix asphalt-gap graded (RHMA-G) surface, so it was assumed that a non-structural RHMA-open-graded (RHMA-O) surfacing would be used to meet the Caltrans rubberized asphalt surface policy. The RHMA-O layer is not shown in Table 6.2. For the Spectra 4 analysis, the existing asphalt layer (old hot mix asphalt [HMA]) thickness was adjusted slightly to produce a 20-year design life for the section’s traffic and climate region. The existing asphalt pavement was assumed to have 35 percent of its wheelpath cracked prior to placement of the overlay. These pavements were designed to provide 95 percent between-project reliability, and the simulation was run to find the average time to cracking of the entire section for the designs. The question the analysis sought to answer for the asphalt pavements was: How much did the changes in axle load distribution change the lives of typical rehabilitation treatments?

Table 6.1. Example Pavement Section Locations for the State Highway Network, Including Traffic and Climate Region Information

WIM Spectra	Route	County	Post-mile	Climate Region	One Direction AADT	One Direction AADTT	% Trucks	# of Lanes	% Trucks in the Design Lane	Traffic Growth Rate
1&2	101	Monterey	57.60	Central Coast	16,750	1,781	10.60%	2	86%	1.90%
3&4	10	Riverside	45.54	Desert	47,500	14,063	29.6%	3	69%	1.40%
5	5	Tehama	13.00	Inland Valley	14,500	3,087	21.3%	2	86%	1.40%

Note: AADT is Average Annual Daily Traffic; AADTT is Average Annual Daily Truck Traffic.

For rigid pavements, a one-directional Average Annual Daily Truck Traffic (AADTT) was assumed to be 12,000 and WIM Spectra 5 was assumed to design a 20-year service life, with the typical minimum portland cement concrete (PCC) thickness assumed to be the California historical minimum design of 9 inches.

Table 6.2. Historical Asphalt Pavement Cross Sections Considered for the Five WIM Spectra for the State-Owned Pavement Example Sections

WIM Spectra	Layer	Material Type from CalME Database	Thickness (feet)	Thickness (inches)
WIM 1	HMA Overlay	2020 Standard HMA Type A Mix with PG64-XX Binder and up to 15% RAP for non-PRS Projects	0.35	4.2
	Existing HMA	2020 Standard Old HMA for non-PRS Projects	0.40	4.8
	AB	2020 Standard AB-Class 2 for non-PRS Projects	0.40	4.8
	Subgrade	2020 Standard SM for non-PRS Projects	Infinite	Infinite
WIM 2	HMA Overlay	2020 Standard HMA Type A Mix with PG64-XX Binder and up to 15% RAP for non-PRS Projects	0.35	4.2
	Existing HMA	2020 Standard Old HMA for non-PRS Projects	0.40	4.8
	AB	2020 Standard AB-Class 2 for non-PRS Projects	0.40	4.8
	Subgrade	2020 Standard SM for non-PRS Projects	Infinite	Infinite

WIM Spectra	Layer	Material Type from CalME Database	Thickness (feet)	Thickness (inches)
WIM 3	RHMA Overlay	2020 Standard RHMA-G for non-PRS Projects	0.20	2.4
	HMA Overlay	2020 Standard HMA Type A Mix with PG64-XX Binder and up to 15% RAP for non-PRS Projects	0.50	6
	Existing HMA	2020 Standard Old HMA for non-PRS Projects	1.00	12
	CTB-Class B	2020 Standard CTB-Class B for non-PRS Projects	0.50	6
	Subgrade	2020 Standard CL for non-PRS Projects	Infinite	Infinite
WIM 4	RHMA Overlay	2020 Standard RHMA-G for non-PRS Projects	0.20	2.4
	HMA Overlay	2020 Standard HMA Type A Mix with PG64-XX Binder and up to 15% RAP for non-PRS Projects	0.50	6
	Existing HMA	2020 Standard Old HMA for non-PRS Projects	1.10	13.2
	CTB-Class B	2020 Standard CTB-Class B for non-PRS Projects	0.50	6
	Subgrade	2020 Standard low plasticity clay for non-PRS Projects	Infinite	Infinite
WIM 5	RHMA Overlay	2020 Standard RHMA-G for non-PRS Projects	0.20	2.4
	HMA Overlay	2020 Standard HMA Type A Mix with PG64-XX Binder and up to 15% RAP for non-PRS Projects	0.30	3.6
	HMA	2020 Standard Old HMA for non-PRS Projects	0.75	9
	AB	2020 Standard AB-Class 2 for non-PRS Projects	0.50	6
	Subgrade	2020 Standard low plasticity clay for non-PRS Projects	Infinite	Infinite

Note: HMA is hot mix asphalt; RHMA-G is rubberized hot mix asphalt gap-graded; AB is aggregate base; CTB is cement-treated base; PRS is performance-related specifications; RAP is recycled asphalt pavement.

To produce cross-sections that are similar to Caltrans concrete pavement designs from the 1980s, alternative concrete sections were designed using design criteria from that period for each of the examples’ existing asphalt sections shown in Table 6.1. These were intended to represent typical existing concrete pavement structures in the state network. Only the heavier WIM spectra—Spectra 3, 4, and 5—were analyzed for concrete pavement. Concrete pavements have historically had a minimum concrete thickness regardless of truck traffic, so it was therefore not expected that the estimated axle load distribution changes would affect concrete pavements for WIM Spectra 1 and 2. Consequently, these spectra were not analyzed.

The alternative concrete pavement structures, shown in Table 6.3, were designed to have an approximately 50 percent chance of having 15 percent cracked slabs in 20 years. Many existing older Caltrans concrete pavements have structures that are similar and were designed for 20 years of life but have provided much longer service. The intention behind developing these example pavement designs was to examine the effects of the changed axle load spectra on these older concrete pavements. Other than undergoing one or two grinding treatments for smoothness and periodic replacement of a small percentage of broken slabs, concrete pavements do not typically undergo repeated structural treatments after initial construction and remain in place until they are eventually replaced or subjected to a major rehabilitation. Therefore, the question posed for the concrete pavements in this study was: How much does the changed axle load distribution change the life of the original pavement? It must be emphasized that the example asphalt and concrete pavement sections used in this study were designed differently and cannot be compared with each other.

Table 6.3. Concrete Pavement Cross Sections for Each WIM Spectra

WIM Spectra	Layer	Thickness (ft)	Thickness (inches)
WIM 3	PCC	0.79	9.5
	CTB	0.50	6
	AB	1.00	12
	Subgrade	Infinite	Infinite
WIM 4	PCC	0.83	10
	CTB	0.50	6
	AB	1.00	12
	Subgrade	Infinite	Infinite
WIM 5	PCC	0.75	9
	CTB	0.50	6
	AB	1.00	12
	Subgrade	Infinite	Infinite

Note: PCC is portland cement concrete; CTB is cement-treated base (treated the same as lean concrete base in the design program); AB is aggregate base.

The Caltrans highway network consists of approximately 37,000 lane-miles (74 percent) of asphalt pavement and 13,000 lane-miles (26 percent) of concrete pavement *(28)*, totaling just under 50,000 lane-miles. Table 6.4 and Table 6.5 show the approximate breakdown by WIM spectra and pavement type (concrete, asphalt) of the state network centerline-miles, with the WIM spectra shown for the outside lane that carries the most trucks. These data are taken from the Caltrans pavement management system databases maintained by the UCPRC.

Table 6.4. Approximate Breakdown of State Highway Centerline-Miles by WIM Spectra and Pavement Type

WIM Spectra	HMA	PCC	Total	% of Total (Statewide)
1	1,716	888	2,603	20%
2	2,038	1,054	3,091	24%
3	2,466	1,276	3,742	29%
4	858	444	1,302	10%
5	1,501	777	2,278	18%

Note: HMA is hot mix asphalt; PCC is portland cement concrete.

Table 6.5. Approximate Breakdown of State Highway Centerline-Miles by Pavement Type Only

Statewide	HMA	PCC	Total
Center-line miles	8,578	4,438	13,016
% of Total	66%	34%	100%

Notes: HMA is hot mix asphalt; PCC is portland cement concrete.

Local Government-Owned Pavement Example Sections

Table 6.6 shows the county- and city-owned and functional-type breakdowns by lane-miles for paved roads from the 2018 California Statewide Local Streets and Roads Needs Assessment report *(29)*.

Table 6.6. Ownership and Functional Type Breakdown by Lane-Miles for Local Government Pavements *(29)*

Local Agency Type	Urban Major	Urban Minor	Rural Major	Rural Minor	Total
Cities	82,376	111,142	1,751	2,852	198,121
Counties	13,614	23,131	32,032	44,585	113,362
Total	95,990	134,273	33,783	47,437	

Example pavements were developed for the Rural Major, Urban Major, and Urban Minor categories. The Rural Minor category was assumed to be similar to the Urban Minor category in terms of the change in damage from the change in axle loads because both types are damaged primarily by exposure to the environment rather than by truck loads. Cross section details of the example Rural Major (County) road, Urban Major (City Arterial) street, and Urban Minor/Rural Minor (Residential) street, and the waste-hauling facility road are shown in Table 6.7.

The following assumptions were made for the functional road types:

- All local government roads were assumed to be asphalt because more than 95 percent of the local government lane-miles in the state are asphalt surfaced.
- The asphalt overlays were designed to last approximately 12 years for the Rural Major/County Road and Urban Major/City Arterial examples, but different traffic indexes were assumed for each. (Traffic index is a typical method for characterizing truck traffic used in historical Caltrans pavement design methods.)
- For the Rural Major/County Road, light truck traffic was assumed (a 20-year traffic index of 9); and for Urban Major/City arterials, very light truck traffic (a traffic index of 8) was assumed.
- The WIM Spectra 1 axle distribution typical of urban areas and lower truck-traffic–volume rural roads was also assumed for both road types.
- The existing asphalt pavement was assumed to have 35 percent of its wheelpath cracked prior to placement of the overlay. These pavements were designed to provide 95 percent between-project reliability to the 12-year design life.
- It was also assumed that the overlays were built with an asphalt material typically used by local governments.
- The question this analysis aimed to answer for these asphalt pavements was: How much does the changed axle load spectra change the life of typical rehabilitation treatments? This is the same question asked about the asphalt overlays on state highways.

The following assumptions were made for the residential streets:

- Residential streets were analyzed using their original structure, and the analysis only considered waste-hauling trucks that were converted to natural gas.
- The analysis used the axle load spectra for this case discussed in Chapter 5.
- It was assumed that one waste-hauling truck uses a residential street each week, and that this street type generally fails because of damage caused by exposure to the environment, not by once-a-week exposure to a waste-hauling truck. For this reason, instead of examining an overlay, the analysis examined the original pavement's change in life due to the change in the waste-hauling truck's axle loading.
- If a change in axle load distribution did not cause the pavement to fail in less than 20 years, this would indicate that the pavement would fail because of environmental exposure rather than truck loading.

The following assumptions were made for the waste facility road:

- The case for a pavement that leads into and out from a waste collection facility was only analyzed for waste-hauling trucks converted to natural gas, and the analysis used the axle load spectra changes for this case discussed in Chapter 5.
- The existing asphalt pavement was assumed to have 35 percent of its wheelpath cracked prior to placement of the overlay. An asphalt overlay was designed for a 12-year life assuming 95 percent between-project reliability, and the average time-to-cracking of 12 years was used for the designs.
- It was assumed that the overlay was built with an asphalt material typically used by local governments. It was assumed that 70 fully loaded waste-hauling trucks entered the waste facility each day and that the same number of identical vehicles exited it empty each day.

Table 6.7. Cross Section Details for County Roads, Arterials, and Residential Roads

Road Category	#	Type	Material	Thickness (feet)	Thickness (inches)
Rural Major (County Road)	1	HMA Overlay	WesTrack FMH with Phi 0.8	0.25	3
	2	Existing HMA	2020 Standard Old HMA for non-PRS Projects	0.50	6
	3	AB	2020 Standard AB-Class 2 for non-PRS Projects	0.80	9.6
	4	Subgrade	2020 Standard low plasticity clay for non-PRS Projects	Infinite	Infinite
Urban Major/City Arterial	1	HMA Overlay	WesTrack FMH with Phi 0.8	0.15	1.8
	2	Existing HMA	2020 Standard Old HMA for non-PRS Projects	0.30	3.6
	3	AB	2020 Standard AB-Class 2 for non-PRS Projects	0.80	9.6
	4	Subgrade	2020 Standard low plasticity clay for non-PRS Projects	Infinite	Infinite
Urban Minor, Rural Minor (Residential)	1	HMA	WesTrack FMH with Phi 0.8	0.25	3
	2	AB	2020 Standard AB-Class 2 for non-PRS Projects	0.50	6
	3	Subgrade	2020 Standard low plasticity clay for non-PRS Projects	Infinite	Infinite
Waste-hauling Facility	1	HMA Overlay	WesTrack FMH with Phi 0.8	0.5	6
	2	Existing HMA	2020 Standard Old HMA for non-PRS Projects	0.5	6
	3	AB	2020 Standard AB-Class 2 for non-PRS Projects	1.0	12
	4	Subgrade	2020 Standard low plasticity clay for non-PRS Projects	Infinite	Infinite

Note: HMA is hot mix asphalt; AB is aggregate base; CTB is cement treated base; FMH is fine mix with medium asphalt content and high air-voids from the FHWA WesTrack experimental test track.

6.3 Results

6.3.1 Pavement Performance

Table 6.8 shows the results of the *CalME* pavement cracking performance simulations for the state highway, Rural Major/County road, and Urban Major/City Arterial asphalt pavement cases. The table shows the change in service life of the asphalt example pavement sections for each change in axle load spectra and example pavement case for 2030 and 2050 axle loads versus the 2020 WIM spectra. The table also shows the weighted averages for the 2030 and 2050 results prorated for the 10 years from 2020 to 2030 and the 20 years from 2030 to 2050.

The results indicate that there is no discernible difference in expected pavement performance, with the calculated differences being so small that they are zero when rounded up to an appropriate number of significant digits. These results were anticipated based on the results from Chapters 2 and 5. The market penetrations of alternative fuel trucks are small up to 2030, when the new technologies are still relatively heavy; and the battery electric and fuel cell technologies are expected to be considerably lighter by 2050, when market penetrations are high. Pavement damage is also limited because it is especially driven by the heaviest axle loads, rather than gross vehicle weight. AB 2061 is not increasing axle weight limits and very few axles are currently at or above the current axle load limits where increases due to new propulsion technologies will be most damaging. In addition, on short-haul and long-haul, which are tractor-trailer combination vehicles, only the tractor axles will have axle load changes, and almost none of the loads on the many trailer axles in the spectra are expected to change, diluting the effects of axle load changes on overall pavement damage. Natural gas vehicles are not expected to make up much of the truck market in the three scenarios considered for the state highway network.

Table 6.8. Percent Change in Service Life vs. 2020 WIM Spectra for Asphalt Pavements for Each AFT Scenario and WIM Spectra for State-Owned Highways and Local Government-Owned County Roads and Arterials

Case	Year	Years to 5% Cracking	AFT Penetration Scenario	Years to 5% Cracking 2030 Spectra	Years to 5% Cracking 2050 Spectra	% Change in Life 2030 vs. 2020	% Change in Life 2050 vs. 2020	Weighted Average % Change in life vs. 2020
State Highway Spectra 1	2020	22.1	1	22.1	22.1	0%	0%	0%
State Highway Spectra 2	2020	20.5	1	20.5	20.5	0%	0%	0%
State Highway Spectra 3	2020	23.3	1	23.3	23.3	0%	0%	0%
State Highway Spectra 4	2020	21.5	1	21.5	21.5	0%	0%	0%
State Highway Spectra 5	2020	21.2	1	21.2	21.2	0%	0%	0%
Urban Major/Arterial	2020	11.2	1	11.2	11.2	0%	0%	0%
Rural Major/County	2020	13.1	1	13.1	13.1	0%	0%	0%
State Highway Spectra 1	2020	22.1	2	22.1	22.1	0%	0%	0%
State Highway Spectra 2	2020	20.5	2	20.5	20.5	0%	0%	0%
State Highway Spectra 3	2020	23.3	2	23.3	23.3	0%	0%	0%
State Highway Spectra 4	2020	21.5	2	21.5	21.5	0%	0%	0%
State Highway Spectra 5	2020	21.2	2	21.2	21.2	0%	0%	0%
Urban Major/Arterial	2020	11.2	2	11.2	11.2	0%	0%	0%
Rural Major/County	2020	13.1	2	13.1	13.1	0%	0%	0%
State Highway Spectra 1	2020	22.1	3	22.1	22.1	0%	0%	0%
State Highway Spectra 2	2020	20.5	3	20.5	20.5	0%	0%	0%
State Highway Spectra 3	2020	23.3	3	23.3	23.3	0%	0%	0%
State Highway Spectra 4	2020	21.5	3	21.5	21.5	0%	0%	0%
State Highway Spectra 5	2020	21.2	3	21.2	21.2	0%	0%	0%
Urban Major/Arterial	2020	11.2	3	11.2	11.2	0%	0%	0%
Rural Major/County	2020	13.1	3	13.1	13.1	0%	0%	0%

Note: For AFT scenarios, 1 is high market penetration scenario, 2 is baseline market penetration scenario, 3 is low market penetration scenario; see Chapter 2 for details.

The pavement cracking performance simulation results from *CalME* for Urban Minor/Residential streets showed that the change in axle loads for waste-hauling trucks converted to natural gas did not change the damage caused by the trucks much, and the truck-traffic–related cracking-life was still well above 20 years. This means that these pavements will continue to crack because of exposure to the environment rather than because of traffic.

The pavement cracking performance simulation results from *CalME* for the waste facility access road are shown in Table 6.9. The results indicate that the heavier, loaded trucks using the inbound lane would reduce the pavement cracking life by approximately 5 percent when the trucks are fitted with a 500-lb natural gas tank, and by approximately 13 percent when the trucks are fitted with a 2,000-lb natural-gas tank. The same trucks would not reduce the cracking-life of the outbound lane when they travel empty enough to change the cause of cracking from environmental exposure to truck loading.

Table 6.9. Service Life Change from CalME simulation for Waste Facility Access Road for Different Truck Types

Truck Type	Inbound-ICE	Inbound-NG-500	Inbound-NG-2000	Outbound-ICE	Outbound-NG-500	Outbound-NG-2000
Service Life	10.7	10.2	9.3	>40	>40	35.6
Percent Change vs. BAU (ICE)	0%	-5%	-13%	0%*	0%*	0%*

* Overlay will fail from environmental exposure many years prior to this.

Note: ICE is internal combustion engine, which is diesel for waste-hauling trucks; NG-500 is a 500-lb natural-gas tank for shorter-haul trucks; NG-2000 is a 2,000-lb natural-gas tank for longer-haul trucks.

Table 6.10 shows the percent changes in cracking-life obtained with *Pavement ME* for the concrete state highway pavements for the expected changes in axle load spectra in 2030 and 2050 compared to the 2020 baseline spectra. The expected pavement life changes are very small. Historically, concrete pavements are better at carrying heavy loads for longer periods than asphalt pavements, but they are also somewhat more sensitive to the few heaviest loads than asphalt pavements. The very small decreases in cracking shown in the table are likely due to interactions between the very small changes in the axle load spectra and climate, structure, and load position variables in the simulations, and can be considered to be noise.

The weighted averages for the changes in simulated cracking-life for the 2030 and 2050 results prorated for the time from 2020 to 2030 and from 2030 to 2050 are shown in Table 6.11. All the results indicate a less than one percent reduction in cracking-life, which is less than the uncertainty in the results from the assumptions made for the analyses. As for the asphalt pavement analyses, except for the waste facility access road, the negligible effects on concrete pavement cracking life can be expected based on the analyses of the axle load distributions in Chapter 5. The absence of any strong effects on cracking-life can be attributed to several factors. First, the new technologies have low market penetrations in 2030, the time they add the most weight. Second, the technologies have improved by 2050, when their market penetrations are high. And third, the effects of the alternative fuel technologies' increased weight have been diluted by the large numbers of axle loads on trailers and on the rear axles of medium-duty trucks that were unaffected or relatively unaffected by the changes in fuel technology.

Table 6.10. Percent Change in Cracking vs. 2020 WIM Spectra for Concrete Pavements for Each AFT Scenario and WIM Spectra for State-Owned Highways Based on Pavement ME

Case	Year	AFT Penetration Scenario	Age (years)	Age (months)	Percent of Slabs Cracked	% Change in Cracking vs. 2020 Data
State Highway Spectra 3	2020		19	226	15.16	
State Highway Spectra 3	2030	1	19	226	15.28	0.8%
State Highway Spectra 3	2030	2	19	226	15.18	0.1%
State Highway Spectra 3	2030	3	19	226	15.12	-0.3%
State Highway Spectra 3	2050	1	19	226	15.33	1.1%
State Highway Spectra 3	2050	2	19	226	15.33	1.1%
State Highway Spectra 3	2050	3	19	226	15.3	0.9%
State Highway Spectra 4	2020		24	288	15.03	
State Highway Spectra 4	2030	1	24	288	15.08	0.3%
State Highway Spectra 4	2030	2	24	288	15	-0.2%
State Highway Spectra 4	2030	3	24	288	14.98	-0.3%
State Highway Spectra 4	2050	1	24	288	15.14	0.7%
State Highway Spectra 4	2050	2	24	288	15.14	0.7%
State Highway Spectra 4	2050	3	24	288	15.12	0.6%
State Highway Spectra 5	2020		24	287	15.25	
State Highway Spectra 5	2030	1	24	287	15.31	0.4%
State Highway Spectra 5	2030	2	24	287	15.2	-0.3%
State Highway Spectra 5	2030	3	24	287	15.13	-0.8%
State Highway Spectra 5	2050	1	24	287	15.36	0.7%
State Highway Spectra 5	2050	2	24	287	15.36	0.7%
State Highway Spectra 5	2050	3	24	287	15.33	0.5%

Table 6.11. Percent Change in Service Life vs. 2020 WIM Spectra for State-Owned Concrete Pavements for Each AFT Scenario and WIM Spectra

Case	AFT Penetration Scenario	Weighted Average % Change in Service Life vs. 2020
State Highway Spectra 3	1	-1.0%
State Highway Spectra 4	1	-0.8%
State Highway Spectra 5	1	-0.5%
State Highway Spectra 3	2	-0.6%
State Highway Spectra 4	2	-0.4%
State Highway Spectra 5	2	-0.3%
State Highway Spectra 3	3	-0.6%
State Highway Spectra 4	3	-0.4%
State Highway Spectra 5	3	-0.1%

Overall, the analyses of the effects of increased axle loads from alternative fuel truck implementation based on pavement damage simulation indicated that none of the scenarios for implementation will result in significant increases in damage to pavements. The analyses also indicated that where there is complete implementation of an alternative fuel technology that increases all or a large portion of the axle loads, then the specific pavement should be analyzed to determine what the change in damage will be. This situation occurred in the case where only natural gas-fueled waste-hauling trucks arrived loaded at a waste facility (that is, there were no other trucks fueled by diesel or other fuel types), and they were the only ones used on the road.

6.3.2 Life Cycle Cost Analysis

State and Local Pavement Network Costs

A life cycle cost analysis for the potential range of costs resulting from the increase in damage caused by implementing alternative fuel trucks used a 10-year analysis period and constant 2018 dollars. Applying the pavement damage analyses shown earlier in this chapter, the range of damage was assumed to be between zero and one percent for both the state and local networks. Estimates of expected annual spending on pavements by California state and local governments over the 10-year period are shown in Table 6.12 and Table 6.13, respectively.

Table 6.12. California Transportation Asset Management Plan Estimate of Annual State Highway System Pavement Spending *(30)*

Annual Spending for Local Government-Owned Pavements	Pavement Rehabilitation, Preservation, and Maintenance ($ billion)
Pre-SB1	1.1
SB1	1.0
Total post-SB1	2.1

Note: SB1 is Senate Bill 1, Road Repair and Accountability Act of 2017; SB1 indicates funding provided by the bill, post-SB1 indicates expected spending after the bill.

Table 6.13. Local Streets and Roads Report and California Transportation Asset Management Plan Estimates of Annual Local Government Pavement Spending *(29, 30)*

Annual Spending for Local Government Pavement	Local Streets and Roads Report ($ billion)	California Transportation Asset Management Plan ($ billion)
Pre-SB1	2.09	1.98
SB1	0.94	1.35
Total post-SB1	3.08	3.33

Note: SB1 is Senate Bill 1, Road Repair and Accountability Act of 2017. SB1 indicates funding provided by the bill, post-SB1 indicates expected spending after the bill.

Based on these estimates, it is projected that the annual increase in costs in constant 2018 dollars for pavement damage will be between $0 and $21 million for the state highway network, and between $0 and $33 million for the local roads network. Cost increases for the local roads network, if there are any, are expected to be focused in the counties that currently have the highest vehicle miles traveled, as discussed in Chapter 4: Los Angeles, San Bernardino, Riverside, San Diego, Orange, Alameda, Kern, Fresno, Santa Clara, Sacramento, and Contra Costa.

Improved pavement construction quality, design, management, and materials over the next 10 to 30 years will easily compensate for the expected maximum one percent increase in cost from the alternative fuel trucks and the projected increased costs on both the state and local networks.

Waste Facility Costs

For the waste facility access road, the change in pavement cracking life from the conversion of waste-hauling trucks ranged from zero to about 15 percent, with the specific amount varying according to the pavement structure, the size of the natural gas fuel tanks used, and whether the trucks are loaded or unloaded. This will result in, at most, an approximate 18 percent increase (1/0.85) in life-cycle overlay costs, in constant dollars, if the same treatments are applied. If the pavements are given increased capacity with their next overlay, this increase in damage can be compensated for with slightly increased overlay thicknesses that would likely result in a less than 18 percent cost increase because of returns to scale for pavement construction costs.

6.3.3 Life Cycle Assessment of Environmental Impacts

Life cycle assessment (LCA) principles were used to calculate a first-order estimate of the greenhouse gas emission impacts of a maximum one percent increase in pavement damage across the state and local networks. They were calculated for each combination of road category, pavement type, and traffic level for the most aggressive alternative truck fuel scenario: a one percent increase in the amount of material required for construction of each base case for 2020 and current traffic.

This analysis used the UCPRC life cycle inventory to calculate the GHG emissions of cradle-to-gate material production (defined per kilogram of material based on the mix design; from resource extraction to leaving the factory gate), of transportation to the construction site (based on the total amount of materials in kg and assuming a 50-mile transport distance), and of the required construction activities based on lane-miles of road to be constructed. As stated earlier, the use stage is not included and the cut-off method was used for the end-of-life impacts (pulverization, transport to plant, and recycling impacts were all assigned to the downstream project that will use the recycled materials later). The GHG intensity of 10 cubic meters of material—including materials production, transport, and construction for HMA and PCC materials—is shown in Table 6.14.

The GHG increase results are shown in Table 6.15. This analysis assumed an annual one percent increase in materials use in the outside lanes of state highways (approximately 26,000 lane-miles (calculated as the double of total center-line miles in Table 6.4) and all lanes of local roads (Table 6.6). The results indicate that over the 30-year analysis period from 2020 to 2050, the total increase in GHG from the increased pavement treatments is about 1,147 kilotons (kT) CO_2-e. When this is divided by 30 years, the result is an approximate 38-kT per-year increase. This can be compared with the results from Table 2.10 in Chapter 2, which showed that the most aggressive alternative fuel truck replacement implementation scenario resulted in 7 percent and 87 percent reductions in truck GHG emissions across the state in 2030 and 2050, respectively, compared with the 2020 baseline of 39,600 kT CO_2-e, or approximately 2,400 kT and 34,000 kT CO_2-e less each of those years, respectively. Therefore, the reductions in vehicle emissions are approximately 60 and 900 times greater than the increases in pavement emissions for those two years, with other years expected to fall within that range.

It must be noted that the calculations shown above only consider the GHG reductions for the heavier, pavement-damaging trucks discussed in Chapter 2. The calculations do not consider the large numbers of additional lighter trucks discussed in Chapter 3. Introduction of these lighter trucks are expected to produce GHG reductions when they are converted to alternative fuels, but they will not produce any significant pavement damage—regardless of their fuel type. If the relative amount of GHG reductions attributable to those lighter trucks being converted to alternative fuel were compared with GHG increases due to increased pavement work, the benefits realized would be much greater than those calculated here.

Since the total length of the roads to waste facilities was unknown, Table 6.15 does not consider emissions from the increase in capacity of waste-hauling facility roads, although it will be insignificant compared with the results for the state and local networks.

Table 6.14. Global Warming Potential (GWP) of 1 lane-kilometer of Treatment with a Thickness of 1 cm (10 cubic meters of material) ***(27)***

Item	Life Cycle Stage	GWP [kg CO_2-e]
HMA	Material	4.67×10^3
HMA	Transport	5.54×10^2
HMA	Construction	3.49×10^2
PCC	Material	1.35×10^4
PCC	Transport	1.09×10^3
PCC	Construction	1.05×10^2

Table 6.15. Total Life Cycle (2020 to 2050) Pavement Treatment GHG Emissions for Treatment and Consequential Increase in Treatments Due to 1% Annual Increase in Pavement Damage from AFT Implementation

Road Type	WIM Spectra	Pavement Type	Material CO_2-e (kT) per Treatment	Transport CO_2-e (kT) per Treatment	Construction CO_2-e (kT) per Treatment	Total CO_2.e (kT) per Treatment	Average Number of Treatments in 30-Year Period 2020-2050	Increase in Total GHGs in Life Cycle for 1% Annual Increase in Damage from AFT (kT CO_2-e)
State	1	Asphalt	413	49	31	493	1.5	7
State	2	Asphalt	490	58	37	585	1.5	9
State	3	Asphalt	1,187	141	89	1,416	1.5	21
State	4	Asphalt	413	49	31	493	1.5	7
State	5	Asphalt	258	31	19	308	1.5	5
State	3	Concrete	658	154	15	827	1.5	12
State	4	Concrete	698	57	5	760	1.5	11
State	5	Concrete	1,157	94	9	1,260	1.5	19
County	1	Asphalt	36,990	1,518	955	39,463	2.5	987
Arterial	1	Asphalt	2,282	271	170	2,723	2.5	68
TOTAL			413	49	31	493		1,147

Note: One Treatment in Life Cycle x Lane-Miles with 2020 WIM Spectra.

7. Summary, Conclusions, and Recommendations

7.1 Summary

The study presented in this report was performed to provide the California Legislature and other policy makers with conceptual-level estimates, from 2020 to 2050, of the effects of vehicle fleet changes on road and bridge infrastructure, and the costs and greenhouse gas emissions related to those infrastructure effects. The study also compares the relative size of impacts on cost and GHG emissions stemming from ownership and operation of alternative fuel vehicles vs. those stemming from infrastructure changes that will be necessitated by the operation of those vehicles, which are heavier than internal combustion engine vehicles. Legislators and others can now consider these conceptual-level estimates for policy development.

To complete the study, weight-change and greenhouse-gas-reduction estimates were made for the heavier internal-combustion-engine truck types in current use (diesel-powered short-haul tractor-trailers and long-haul tractor-trailers, and medium-duty trucks powered by gasoline and diesel) after their conversion to the three alternative fuel types (battery electric, fuel cell, and natural gas) projected to be in use over the 2020 to 2050 analysis period. The study generated these estimates using models developed by the Institute of Transportation Studies at UC Davis (ITS-Davis); those estimates, which are attributable to vehicle fuel use, appeared in Chapter 2. In making the calculations, the study considered the baseline year of 2020 and the years 2030 and 2050 as milestones for the analyses and inferred the results for the years between 2030 and 2050 from those milestone years. Once the calculations were completed, they revealed a significant difference between the VMT estimate based on EMFAC2014 presented in Chapter 2 and the VMT estimate based on the California Statewide Travel Demand Model (CSTDM) discussed in Chapter 3. The source of the VMT difference was attributed to a difference between the scope of the data in the EMFAC2014 and the scope of the CSTDM. The latter is likely a more comprehensive estimate of statewide truck VMT because it appears to include additional medium-duty truck types, and it also includes light-duty trucks, which are not included in the EMFAC2014 data.

Three market penetration scenarios were created for implementation of these new technologies: baseline, low, and high. The baseline scenario was based on the California Air Resources Board Advanced Clean Truck proposed regulation *(31)*. In this scenario, sales in 2050 of zero emission vehicle (ZEV) short-haul and medium-duty urban trucks reach 100 percent market penetration, and sales of long-haul trucks reach 80 percent; further, in this scenario 10 percent of the vehicles are powered by battery electric and 90 percent are powered by fuel cells. The low market penetration scenario has half the number of ZEVs in the total truck stock—considering year-to-year sales—than the baseline scenario. The high market penetration scenario had 1.5 times the baseline scenario's number of ZEVs in the truck stock in 2030.

Well-to-wheel (complete fuel cycle) greenhouse gas emissions reductions for the entire fleet in 2030 and 2050 were calculated and compared with 2020, and included consideration of changes in the numbers of vehicles on the road and the miles they would travel in 2030 and 2050, as well as the truck types. The differences in emissions from differences in vehicle production, including production of the propulsion systems, were not considered in the model. Changes in the cost per truck, in constant dollars, were also estimated.

Chapter 3 presents the results of the estimation of freight flows on the entire state road transportation network. To estimate where the zero emission vehicles would be distributed in the state, future changes in vehicles miles traveled

(VMT) were estimated for different counties using the *California Statewide Travel Demand Model* (CSTDM). The results showed that 11 out 58 (19 percent) of the state's counties are expected to receive about 75 percent of the state's truck VMT, with these percentages staying unchanged in each of the years considered. It was reasonable to expect that the market penetration of ZEVs in the state would follow a similar distribution.

Chapter 4 presents a summary of a national study on the expected damage and resultant costs from allowing heavier vehicles to use highway bridges, and extrapolation of the results to the California bridge system. The results provide a first-order estimate of the cost of a 2,000-lb axle load increase on California's approximately 12,400 state-owned and 13,300 locally-owned bridges, based on results extrapolated from the national FHWA Comprehensive Truck Size and Weight Limits (CTSW) study that examined the effects of increased axle loads on bridge damage and repair costs.

Chapter 5 presents the process and results of using the AFT market penetration scenarios and AFT weight changes from Chapter 2 to create new axle load spectra that consider AFT axle weights and market penetration together. Axle weight changes on the three truck types and for the three alternative fuel truck (AFT) market penetration scenarios were used to adjust truck axle load spectra from 2020 (using 2018 data) and to create the spectra projected for 2030 and 2050. The baseline axle load spectra data came from the Caltrans Weigh-In-Motion (WIM) system that measures axle loads and truck types on the state's highways. UCPRC uses these same data: (a) to periodically update the Caltrans pavement management system's truck load data; and (b) for the software programs *CalME* and *Pavement ME,* which are used to design Caltrans's asphalt- and concrete-surfaced highways, respectively. To make use of the axle load spectra data for this study, they were prepared in those programs' input formats to simulate asphalt and concrete pavement damage. These programs' simulations include consideration of hourly truck flows for urban and rural areas.

The resulting axle load spectra estimates for 2030 and 2050 showed very small increases in axle loads for each year. This occurred because of low market penetrations in 2030, when battery electric and fuel cell technologies were estimated to increase axle loads, and because of technological improvements by 2050 that reduced the axle loads of alternative fuel trucks when their market penetration was much higher. The potential for truckers to increase their payloads when alternative propulsion systems become lighter after 2030 was not considered important because most of the implementation is occurring in short-haul and medium-duty trucks, few of which operate near current axle load limits, and because AB 2061 does not increase axle load limits.

Axle load spectra were also prepared for a scenario with waste-hauling trucks converted to natural gas from diesel. In the scenario, current waste-hauling trucks had increased weights of 500 and 2,000 lbs. when converted to natural gas. The simulations included empty, full, and half-loaded trucks on residential streets, empty trucks leaving a waste-handling facility, and full trucks arriving at the facility.

Chapter 6 presented the results of pavement damage simulations for example pavements for the following cases:

- State highways with asphalt surfaces and five different baseline typical axle load spectra, compared with the estimated spectra for 2030 and 2050 under the three alternative fuel truck (AFT) market penetration scenarios
- State highways with concrete surfaces and the three heaviest baseline typical axle load spectra, compared with estimated spectra for 2030 and 2050 for the three AFT market penetration scenarios
- Asphalt-surfaced Urban Major/Arterial streets with a typical baseline axle load spectra, compared with estimated spectra for 2030 and 2050 for the three AFT market penetration scenarios

- Asphalt-surfaced Rural Major/County road with a typical baseline axle load spectra, compared with estimated spectra for 2030 and 2050 for the three AFT market penetration scenarios
- Asphalt-surfaced residential street assuming a baseline waste hauling truck, compared with 500 and 2,000 lb. increases after conversion to natural gas
- Asphalt-surfaced waste facility access road assuming a baseline waste hauling truck, compared with 500 and 2,000 lb. increases after conversion to natural gas

The asphalt-surface pavement simulations were performed using *CalME* and the concrete-surface pavement simulations were performed using *Pavement ME*, which are the respective software programs used by Caltrans. The example asphalt and concrete pavement sections were designed differently and cannot be compared with each other. Damage to the asphalt sections was evaluated by examining the damage to their rehabilitation overlays; this approach was taken because the periodic application of overlays is the typical method used to restore asphalt pavement performance. Unlike asphalt pavements, once a concrete pavement is built, it typically does not require much maintenance or rehabilitation until it reaches the end of its life, when it is then partly reconstructed; consequently, the concrete sections in this part of the study were evaluated by examining the damage to the lives of existing concrete pavements.

7.2 Conclusions

The following conclusions were drawn from the results of the entire study:

- From Chapter 2, Alternative Vehicle Weights and Pathways for Implementation:
    - Compared with 2020 conventional trucks, the additional weight for battery electric trucks will be greater in 2030 than in 2050; short-haul and medium-duty trucks are estimated to have very small weight increases by 2050 compared to conventional 2020 trucks, while long-haul truck weights are estimated to have increased in 2050 compared with 2020, but not by as much as in 2030.
    - Weight increases for 2030 fuel cell trucks are expected to be smaller than those for battery electric trucks, and by 2050 both fuel cell and battery electric fuel systems show significant reductions for all truck types, including long-haul trucks; by 2050, short-haul trucks are actually expected to be lighter than in 2020.
    - In addition to weight reductions for battery electric trucks from 2030 to 2050, truck ranges are also expected to increase, contributing to market penetration.
    - Natural gas vehicle weights are expected to increase by 500 to 2,000 lbs. and to remain constant because the weight of the new, heavier fuel tanks will not change over time; this range of increase is about half of that of 2030 battery electric trucks and similar to that of 2030 fuel cell trucks.
    - In 2030 it will cost more to purchase alternative fuel trucks than diesel trucks, especially fuel cell and battery electric trucks (up to 45 percent more for battery electric trucks). By 2050, it is expected that the costs of fuel cell and battery electric trucks will be closer to those of diesel trucks, except for long-haul battery electric trucks, which are expected to remain expensive. The study did not consider the costs of fuel and maintenance.
    - Converting the state truck fleet to alternative fuel trucks by 2030 is expected to lower the annual propulsion life cycle, or well-to-wheel, greenhouse gas emissions from truck vehicle miles travelled between 3 and 7 percent compared to business as usual (the current level of implementation), depending on the market

  penetration scenario. By 2050, the conversion is expected to reduce annual emissions between 16 and 87 percent compared to business as usual, again depending on the scenario.

  - In converting the state truck fleet to alternative fuel trucks, the net annual propulsion life cycle, or well-to-wheel, CO_2-e reduction estimated for the most aggressive market penetration scenario is approximately 2,700 kT of CO_2-e by 2030 and 34,000 kT by 2050. The net annual reduction estimated for the least aggressive scenario is approximately 1,200 kT by 2030 and 6,300 kT by 2050. For comparison, the entire transportation sector's emissions in 2016 were about 175,000 kT, or 41 percent of the total for the entire California economy. While these numbers are not directly comparable because the numbers of vehicle miles travelled by trucks is expected to increase in 2030 and 2050, it provides an indication of the order of magnitude of the reduction that the conversion can achieve.
  - These estimates do not include reductions of CO_2-e from a portion of the medium-duty trucks operating in the state, and they do not include any of the light-duty trucks.

- From Chapter 3, Estimating Freight Flows in California 2020 – 2040:
  - Using estimates based on the *California Statewide Travel Demand Model* (CSTDM), the total estimated VMT for the 2015 base year on all the state and local roads in California is approximately 50 million miles per day for heavy-duty trucks, and about 32 and 25 million miles per day for medium- and light-duty trucks, respectively. It should be noted that the CSTDM and the ITS Davis alternative fuel truck implementation model define long-haul trucks similarly, but the CSTDM considers all medium-duty and light-duty trucks, while the ITS Davis model only considers some medium-duty trucks and no light-duty trucks. It should also be noted that the CSTDM also only extends to 2040 and this study included estimates to 2050.
  - The *California Statewide Travel Demand Model* (CSTDM) indicates that light- and medium- trucks dominate local and arterial roads in terms of VMT, but it also indicates that on highways and freeways the VMT of heavy-duty trucks exceeds the combined VMT of the lighter trucks by more than 20 percent. The faster growth of light-duty truck VMT compared with medium-duty truck VMT is due in part to the expected growth in residential last-mile–type deliveries compared with current use of medium-duty trucks for last-mile hauling to retail stores. The effects of using light-duty trucks on residential streets were not modeled in the pavement damage portion of this study because the axle loads are too light to have much impact, if any.
  - Eleven out 58 of the counties in California are expected to receive about 75 percent of the state's truck VMT, with these percentages remaining unchanged in the years considered. It is expected that the market penetration of the AFTs in the state will follow a similar distribution.

- From Chapter 4, Effects of Increased Axle Loads on Bridges:
  - Extrapolation of the national CTSWL study on the effects of increased truck weights on bridge condition indicates that a first-order estimate of one-time costs to strengthen and replace bridges in California would be about $9 million in 2011 dollars. Since costs have increased approximately 35 percent nationally from 2011 to late 2018 *(32)*, this cost is approximately $12 million in 2018 dollars. Although this number seems unreasonably low, no better information could be found within the scope of this project. The national study identified the need for better models and cost estimate methods to address this problem. Because the ability to model the effects of heavier alternative fuel trucks on bridges is very limited, the US Department of Transportation recommends not raising weight limits on bridges until impacts can be better understood.

- From Chapter 5, Estimation of Changes in Axle Load Distributions:

  - The portion of alternative fuel trucks in the 2030 truck fleet is projected to be low, with these vehicles making up approximately 5 to 15 percent of the fleet depending on the implementation scenario; their percentage is expected to be much higher in 2050, when they are expected to make up 40 to 95 percent of the truck fleet.
  - Between 2030 and 2050 few long-haul trucks are expected to be converted to battery electric because of range issues; instead, they will be converted to fuel cells as their primary alternative fuel technology; a relatively high percentage of them will retain their diesel propulsion systems compared to short-haul and medium-duty trucks.
  - Short-haul and medium-duty trucks are expected to have small percentages of alternative fuel technologies by 2030, but approximately 40 to 95 percent are expected to be converted to battery electric and fuel cell technologies by 2050, depending on the implementation scenario; in 2050 an approximately equal split is expected between the two alternative technologies.
  - Natural gas conversion is expected to be concentrated in medium-duty trucks and to peak in 2030 (compared to 2020 and 2050). At that 2030 peak, natural gas conversions are expected to be approximately 4 to 11 percent of all medium-duty trucks. In both 2030 and 2050, natural gas conversions are expected to be less than 1 percent for the short-haul and medium-haul trucks.
  - The adjustments made to axle load spectra to consider (a) three market penetration scenarios in 2030 and 2050 and (b) the estimated changes in truck weights after the conversion to AFTs both resulted in only very small differences from the baseline spectra. They were small in both years because the trailer axles that make up a large portion of the single axles were unchanged by the fuel technology changes in both 2030 and 2050. They were also small because the proportion of trucks with alternative fuel technologies was very small in 2030—when axle loads are heavier for the battery electric (BE) and fuel cell (FC) trucks—and because in 2050, after the proportion of BE and FC trucks are expected to have grown, these technologies are assumed to have become lighter.
  - There were negative adjustment factors (weight reductions) in some spectra in 2050 because the combined proportions of battery electric vehicles (BEVs) and fuel cell vehicles (FCVs) had lightened the overall spectra for Class 9 (short-haul and long-haul tractor-trailers) single-axle trucks.

- From Chapter 6, Assessment of the Impact of Increased Truck Weights on Pavement Damage, Costs, and Environmental Impacts:
  - The pavement damage analyses of the example state highway pavements and the county roads and urban arterials indicated that the projected changes for implementation of AFTs in 2030 and 2050 would cause a zero to approximately one percent increase in life reduction across all cases.
  - The damage analysis for residential streets only modeled for 500- to 2,000-lb. increases in the weights of waste-hauling trucks indicated that these pavements would continue to fail by exposure to the environment rather than by the waste truck loading, despite the increased axle loads.
  - The damage analysis for an example waste facility access road modeled only for 500- to 2,000-lb. increases in the weights of waste-hauling trucks from conversion to natural gas indicated (a) that for fully loaded inbound trucks, the 500-lb. vehicle weight increase reduced the life of pavement overlays by approximately 5 percent and (b) that there was an approximately 13 percent reduction in life with the 2,000-lb. vehicle weight increase. On the outbound lane that emptied trucks use to leave the facility—a lane typically built to the same thickness as the inbound lane—the change in axle loads did not change the pavement's failure

    mechanism—that is, it did not change the failure mechanism from environmental exposure (its usual failure mechanism) to truck loading.

  - Summarizing the results from the entire study, based on a one percent reduction in pavement life, a first-order estimate is that the annual increase in cost for pavement will be between $0 and $21 million for the state highway network, and $0 and $33 million for the local roads network, in constant 2018 dollars.
  - Any cost increases for the local road networks are expected to be focused in the counties with the current highest truck miles traveled: Los Angeles, San Bernardino, Riverside, San Diego, Orange, Alameda, Kern, Fresno, Santa Clara, Sacramento, and Contra Costa.
  - For the state and local networks, improved pavement construction quality, design, management, and materials over the next 10 to 30 years are expected to easily compensate for the expected maximum one percent increase in cost from the alternative fuel trucks and the projected increased costs on both the state and local networks.
  - A decrease in a waste facility access road's pavement life will result in, at most, an approximate 18 percent increase (1/0.85) in overlay life cycle costs, in constant dollars, if the same treatments as before are applied. If these pavements are given increased capacity with their next overlay, this increase in damage can be compensated for with small increases in overlay thickness that will likely result in less than an 18 percent cost increase because of returns to scale for pavement construction costs.
  - A first-order estimate of an expected increase in annual greenhouse gas emissions resulting from a one percent reduction in life of the state and local pavement networks is approximately 38 kT per year.
  - A comparison of the expected maximum increase in pavement rehabilitation-related GHG emissions from materials and construction with the most aggressive implementation scenario for 2030 and 2050 indicates that the reductions in truck emissions from implementing alternative fuel technologies are approximately 70 times greater in 2030 and 900 times greater in 2050 than the increases in pavement rehabilitation emissions. Reductions in years between 2030 and 2050 are expected to fall within that range.
  - These estimates do not include reductions of CO_2-e from a portion of the medium-duty trucks operating in the state, and do not include any of the light-duty trucks. Consideration of the additional medium-duty trucks and the light-duty trucks would result in even greater reductions in truck emissions relative to pavement rehabilitation emissions because light-duty trucks cause very little damage to pavement.

Based on these conclusions, which have been drawn from currently available information, the following are the study's conceptual-level, first-order findings addressing the objectives of the project:

- Provide estimates of the effects on freight logistics of an increased number of NGV, FC, and BEV trucks.
  - Answer: The increased numbers of NGV, EV, and FC trucks are expected to occur mainly in the short-haul and medium-duty types because of the range issues that exist for EV and FC long-haul trucks. However, depending on the implementation scenario, by 2050 an estimated 25 to 70 percent of long-haul trucks are predicted to be powered by alternative fuels. Further, depending on the scenario, it is expected that by 2050 between 40 and 95 percent of the short-haul and medium-duty trucks will be powered by alternative fuel technologies. Implementation of alternative fuel trucks is expected to be focused in the eleven counties that already have the greatest freight traffic; these counties are primarily urban and along major freight corridors.

- Provide an estimate of the additional damage to local- and state-government pavements caused by all trucks operating with an additional gross weight of 500 to 2,000 lbs.
    - Answer: Based on results from the implementation scenarios analyzed, introducing the heavier alternative fuel trucks is expected to result in minimal additional damage to local- and state-government-owned pavements. The extent of the additional damage will vary according to the pavement structure and to the AFT implementation scenario. Two trends contribute to this conclusion. First, the technologies for EV and FC trucks are expected to remain heavier than current trucks between now and around 2030, but from 2030 to 2050 their weights are expected to decrease as the technologies are improved. Second, the extent of implementation of these technologies is small to 2030 but is expected to increase rapidly after that, moving towards large market shares by 2050, but at the same time the propulsion technologies are getting lighter. Together, these two trends, low market share while heavier to 2030 and becoming lighter as market share grows towards 2050, result in limited damage. Pavement damage is also limited because it is especially driven by the heaviest axle loads. Axle weight limits are not being changed and very few axles are currently at or above the current axle load limits where increases due to new propulsion technologies will be most damaging. In addition, only the tractor axles on short-haul and long-haul tractor-trailer combination vehicles will have axle load changes, and almost none of the loads on the many trailer axles are expected to change, diluting the effects of the few axle load changes on overall pavement damage. The NG technology cannot become lighter, but it is not expected to have significant market penetration. The study showed that using specific technologies at very high levels before their expected weight reductions can result in increased damage levels, as was shown in the examination of a waste facility access road. The somewhat increased damage levels that are expected on waste facility roads if diesel trucks are replaced with NG trucks can likely be compensated for by increasing those specific roads' structural capacity at costs that are less than about 20 percent, even for the cases where damage is greatest.
- Provide an estimate of the weight restriction problems for local- and state-government bridges caused by all trucks operating with additional gross vehicle weight of 500 to 2,000 lbs.
    - Answer: This objective was difficult to complete well, even at the first-order conceptual level, because of a lack of bridge damage models, the same issue identified in the most recent national study. Although allowing weight increases of up to 2,000 lbs. is unlikely to cause major issues for trucks on more modern bridges, the effects of concentrations of trucks at those new legal limits on bridges that are already inadequate, and which are mostly owned by local governments, should be evaluated more carefully on a case-by-case basis.
- Provide an estimate of the change in GHG emissions resulting from implementing vehicle fleet changes that consider well-to-wheel vehicle emissions and pavement maintenance and rehabilitation.
    - Answer: The study's most aggressive market penetration scenario yielded a net reduction in annual well-to-wheel truck propulsion emissions of approximately 2,700 kT of CO_2-e per year by 2030 and 34,000 kT by 2050 compared to keeping the current truck technologies. Its least aggressive scenario yielded a net reduction of approximately 1,200 kT per year by 2030 and 6,300 kT by 2050 compared to keeping the current truck technologies. These estimates consider expected growth in the truck fleet. For an order of magnitude comparison, in 2016 the annual emissions from the entire transportation sector were about 175,000 kT per year, which is 41 percent of the statewide total for the entire economy. None of the scenarios considered changes in GHG emissions from vehicle manufacture. Pavement-related emissions increases were estimated to be 70 to 900 times less than reductions from changes to truck operations.

7.3 Recommendations

The following recommendations are made based on the results of this study:

- Overall recommendation: To achieve large reductions in GHG emissions while still considering changes in costs, move ahead with the implementation of alternative fuel trucks but also monitor changes in pavement and bridge damage, particularly older bridges not built to modern standards.
- Because the key assumptions controlling the calculations in this report are that there will be small market penetration for AFTs by 2030 when their propulsion systems are still heavy, and that their propulsion systems will have become considerably lighter by the time there is large market penetration, it is important to continue to periodically improve data and models for AFT implementation and GHG emissions related to truck use, and measurement of AFT weight change trends and projections and pavement axle load spectra changes.
- Improve the modeling capability for bridge structural damage as a function of vehicle and axle weights.
- Develop models for the effects of road roughness on AFT energy use and propulsion system life.
- Develop improved models for GHG emissions from truck manufacture, including changes in vehicle propulsion systems and other changes to the overall truck and trailer intended to reduce weight.
- In future modeling scenarios, include the potential effects on GHG emissions of implementing semi-autonomous and autonomous truck operations.
- Develop improved models for bridge deterioration as a function of truck axle loads.

8. References

1. Personal communication from meeting with Thomas Lawson, California Natural Gas Vehicle Coalition, Sacramento, May 3, 2017.

2. Mareev, I., J. Becker, and D.U. Sauer. Battery Dimensioning and Life Cycle Costs Analysis for a Heavy-Duty Truck Considering the Requirements of Long-Haul Transportation. *Energies,* 2018. 11: 55. www.mdpi.com/1996-1073/11/1/55/htm. Accessed October 15, 2019.

3. Cummins 2019. Cummins spec sheet, found on the Internet. www.heavyequipmentguide.ca/product/3619/cummins-x15. Accessed December 2019.

4. Ford 2019. Ford specification sheet, found on the Internet. www.dieselhub.com/specs/ford-6.8-triton-v10.html. Accessed December 2019.

5. Results from simulations run on the Advisor Vehicle Simulation Model in the Institute of Transportation Studies, at the University of California, Davis, 2019. (Burke, A., G. Collantes, M. Miller, and H. Zhao. 2013. Analytic Tool to Support the Implementation of Electric Vehicle Programs. Research Report – UCD-ITS-RR-13-53, Institute of Transportation Studies, University of California, Davis. itspubs.ucdavis.edu/wp-content/themes/ucdavis/pubs/download_pdf.php?id=2455. Accessed July 24, 2020.

6. Burke, A., and M. Miller. Zero-Emission Medium and Heavy-duty Truck Technology, Marketing, and Policy Assessments for California, 2020. escholarship.org/uc/item/7n68r0q8. Accessed June 30, 2020.

7. Fulton, L., M. Miller, A. Burke, Q. Wang, and C. Yang. *Technology and Fuel Transition Scenarios to Low Greenhouse Gas Futures for Cars and Trucks in California.* Research Report UCD-ITS-RR-19-35. Institute of Transportation Studies, University of California, Davis, 2019. escholarship.org/uc/item/8wn8920p. Accessed July 10, 2020.

8. California Air Resources Board. Proposed Advanced Clean Trucks Regulation. December 12, 2019. ww3.arb.ca.gov/board/books/2019/121219/pres19-12-4.pdf. Accessed June 29, 2020.

9. California Air Resources Board. 2014. EMFAC2014 Web Database. arb.ca.gov/emfac/2014/. Accessed July 24, 2020.

10. Khan, M., A. Komanduri, K. Pacheco, C. Ayvalik, K. Proussaloglou, J. Brogan, M. McCourt, and R. Mak. 2019. Findings from the California Vehicle Inventory and Use Survey. Transportation Research Record 2019, Vol. 2673(11) 349–360.

11. Martin, C. Quick Take: Better Batteries. *BloombergNEF.* October 11, 2019. www.bloomberg.com/quicktake/batteries. Accessed June 30, 2020.

12. Moultak, M., N. Lutsey, and D. Hall. *Transitioning to Zero-Emission Heavy-Duty Freight Vehicles.* The International Council on Clean Transportation. White paper. September 2017. theicct.org/sites/default/files/publications/Zero-emission-freight-trucks_ICCT-white-paper_26092017_vF.pdf. Accessed December 6, 2019.

13. James, B. D., J.M. Huya-Kouadio, C. Houchins, and D.A. DeSantis. Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2016 Update. Strategic Analysis, September 2016. www.energy.gov/sites/prod/files/2019/12/f70/fcto-sa-2018-transportation-fuel-cell-cost-analysis.pdf. Accessed November 15, 2019.

14. California Department of Transportation (2020). California Statewide Travel Demand Model (CSTDM). dot.ca.gov/programs/transportation-planning/multi-modal-system-planning/statewide-modeling

15. Federal Highway Administration. Bridge Structure Comparative Analysis Technical Report. Comprehensive Truck Size and Weight Limits Study. June 2015. ops.fhwa.dot.gov/freight/sw/map21tswstudy/technical_rpts/bscanalysis.pdf. Accessed November 12, 2019.

16. Federal Highway Administration. Bridge Formula Weights. August 2019. ops.fhwa.dot.gov/freight/publications/brdg_frm_wghts/fhwahop19028.pdf. Accessed October 15, 2019.

17. Federal Highway Administration. Final Report to Congress. Comprehensive Truck Size and Weight Limits Study. April 2016. ops.fhwa.dot.gov/freight/sw/map21tswstudy/ctsw/CTSLWS%20Report%20to%20Congress%20FINAL.pdf. Accessed June 2, 2020.

18. California Department of Transportation, Traffic Operations Program, Weigh-in-Motion, 2019. dot.ca.gov/programs/traffic-operations/wim. Accessed December 10, 2019.

19. Kim, C. J.D. Lea, J.T. Harvey, and V. Kannekanti. A Decision Tree Analysis for Developing Weigh-in-Motion (WIM) Spectra in California Pavement Management System (PaveM). *Transportation Research Record: Journal of the Transportation Research Board,* 2019. In press.

20. California Air Resources Board. Summary of Alternative Fuel Trucks Proposed Regulation, August 21, 2019. ww2.arb.ca.gov/sites/default/files/2019-08/190821actpres_0.pdf. Accessed December 10, 2019.

21. Q. Lu, J. Harvey, T. Le, J. Lea, R. Quinley, D. Redo, J. Avis. *Truck Traffic Analysis using Weigh-In-Motion (WIM) Data in California.* Research report UCPRC-RR-2002-01. University of California Pavement Research Center, 2002. http://www.ucprc.ucdavis.edu/pdf/RevisedWIM%20Report.pdf. Accessed January 17, 2020.

22. Harvey, J., J. Meijer, A. Kendall. *Life Cycle Assessment of Pavements. Technical Brief.* Publication FHWA-HIF-15-001. FHWA, US Department of Transportation, October 2014. www.fhwa.dot.gov/pavement/sustainability/hif15001.pdf. Accessed February 10, 2020.

23. Van Dam, T.J., J.T. Harvey, S.T. Muench, K.D. Smith, M.B. Snyder, I.L. Al-Qadi, H. Ozer, J. Meijer, P.V. Ram, J.R. Roesler, and A. Kendall. *Towards Sustainable Pavement Systems: A Reference Document.* Publication FHWA-HIF-15-002. FHWA, US Department of Transportation, 2015. www.fhwa.dot.gov/pavement/sustainability/ref_doc.cfm. Accessed March 25, 2020.

24. Harvey, J. T., J. Meijer, H. Ozer, I. L. Al-Qadi, A. Saboori, and A. Kendall. *Pavement Life-Cycle Assessment Framework*. Publication FHWA-HIF-16-014. FHWA, US Department of Transportation, 2016. www.fhwa.dot.gov/pavement/sustainability/hif16014.pdf. Accessed March 25, 2020.

25. Ullidtz, P., J. T. Harvey, I. Basheer, D. Jones, R. Wu, J. Lea, and Q. Lu. CalME, A Mechanistic-Empirical Program to Analyze and Design Flexible Pavement Rehabilitation. *Transportation Research Record: Journal of the Transportation Research Board,* 2010. 2153: 143-152. www.researchgate.net/publication/270568534_CalME_a_Mechanistic-Empirical_Program_to_Analyze_and_Design_Flexible_Pavement_Rehabilitation. Accessed January 21, 2020.

26. AASHTO. AASHTOWare Pavement ME Design. American Association of State Highways Officials, Washington, D.C. me-design.com/MEDesign/?AspxAutoDetectCookieSupport=1. Accessed February 2020.

27. Saboori, A., H. Li, T. Wang, and J. T. Harvey. *Documentation of the UCPRC Life Cycle Inventory (LCI) Used for the CARB/Caltrans LBNL Heat Island Project and Other Caltrans LCA Studies.* Publication UCPRC-2017-01. University of California Pavement Research Center, in press.

28. Caltrans. *2015 State of the Pavement Report.* California Department of Transportation, Division of Maintenance Pavement Program. December 2015 www.epavellc.com/wp-

content/uploads/documents/CALTRANS%20State%20of%20Pavement%20Report%202015.pdf. Accessed April 16, 2020.

29. NCE. California Statewide Local Streets and Roads Needs Assessment. League of California Cities, California State Association of Counties, County Engineers Association of California. October 2018. www.savecaliforniastreets.org/wp-content/uploads/2018/10/2018-Statewide-Final-Report-1.pdf. Accessed October 21, 2019.

30. Caltrans. 2018. California Transportation Asset Management Plan Fiscal Years 2017/18 –2026/27. California Department of Transportation, January 2018. dot.ca.gov/-/media/dot-media/programs/asset-management/documents/20190726-am-finalcaliforniatamp-a11y.pdf. Accessed April 17, 2020.

31. California Air Resources Board. 2019. California Greenhouse Gas Emissions for 2000 to 2017, Trends of Emissions and Other Indicators. ww3.arb.ca.gov/cc/inventory/pubs/reports/2000_2017/ghg_inventory_trends_00-17.pdf. Accessed June 21, 2019.

32. Federal Highway Administration. National Highway Construction Cost Index (NHCCI) 2.0. www.fhwa.dot.gov/policy/otps/nhcci/pt1.cfm. Accessed April 21, 2020.