Preliminary Investigation

Caltrans Division of Research, Innovation and System Information

Natural Frequencies of Pickups and Medium and Heavy Trucks for Use in Component Design

Requested by

Angela Wheeler, Division of Equipment, Caltrans

Developed by the
Advanced Highway Maintenance and Construction Technology (AHMCT)
Research Center

July 19, 2018

The Caltrans Division of Research, Innovation and System Information (DRISI) receives and evaluates numerous research problem statements for funding every year. DRISI conducts Preliminary Investigations on these problem statements to better scope and prioritize the proposed research in light of existing credible work on the topics nationally and internationally. Online and print sources for Preliminary Investigations include the National Cooperative Highway Research Program (NCHRP) and other Transportation Research Board (TRB) programs, the American Association of State Highway and Transportation Officials (AASHTO), the research and practices of other transportation agencies, and related academic and industry research. The views and conclusions in cited works, while generally peer reviewed or published by authoritative sources, may not be accepted without qualification by all experts in the field. The contents of this document reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the California Department of Transportation (Caltrans), the State of California, or the Federal Highway Administration. This document does not constitute a standard, specification, or regulation. No part of this publication should be construed as an endorsement for a commercial product, manufacturer, contractor, or consultant. Any trade names or photos of commercial products appearing in this publication are for clarity only.

Table of Contents

Executive Summary

Background

The Caltrans Division of Equipment (DOE) Engineering Design staff develops complete truck designs to meet the requirements of various Caltrans programs. These trucks are subject to vibrations when they are traveling the city streets, backroads, highways, and freeways of California. These vibrations can result in components' fatigue failures and at a minimum, vehicle downtime and work to repair the failures.

There is a need to accurately define the natural frequency values of Caltrans two- and three-axle trucks. This information is being requested in order to improve the analysis of the components and reduce fatigue failures.

The purpose of this preliminary investigation (PI) is to find and summarize natural frequency values that can be used in the design and analysis of components installed on Caltrans equipment. There are several truck sizes and locations on trucks that are of particular interest.

The PI includes a survey or interview of industry and select research institutions to identify practices or information they have that may be helpful to Caltrans along with any best practices, products, remediations, and recommendations of which they are aware. The specifics are:

A. Vehicle Natural Frequencies

- Perform a literature search to determine what studies have already been conducted on natural frequencies of pickups and medium and heavy trucks for use in component design.
- Condense the literature search study results into a table indicating the natural frequencies determined and the applicable conditions associated with the frequencies such as truck size, location on the vehicle, vehicle speed, and road type.
- Throughout the literature search, watch for any information particularly regarding natural frequencies for the vehicles listed below and specific locations. Any actual testing or other determination of natural frequencies for these or other vehicles is left for future research.
    - Pickup truck: Behind cab at the following locations: bed surface, top of bed sides, on top of light rack
    - 9' cargo or cone truck: Behind cab on top of truck frame and on top of sign frame
    - 12' cargo truck: Behind cab on top of truck frame and on top of sign frame
    - 4-yard dump truck: Behind cab on top of truck frame and on top of sign frame
    - 10-yard dump truck: Behind cab on top of truck frame and on top of sign frame

B. Component Design

- Perform a literature search to determine if there are studies on designing components to avoid or minimize impacts from pickup and medium and heavy truck natural frequencies.

C. Other

- Conduct a survey or interview of industry and select research institutions to identify practices or information they have that may be helpful to Caltrans. Provide a summary.

- Perform an internet search to identify any commercial services or software that deal with natural frequencies of pickups and medium and heavy vehicles and summarize the findings.
- Contact John Jewell of Caltrans DRISI to receive information from studies he may have performed previously and include in this PI.

Summary of Findings

Caltrans has an immediate need to understand what appears to be vibration-induced failure of frames supporting signboards and warning lights on trucks ranging in size and type from 1-ton pickups and stake-sides to 10-yard dump trucks with and without plows.

This investigation has determined that detailed vibration profiles of the specific trucks are not available and design guidance is available only through researching and applying the subject of vehicle dynamics. Although vibration is predictable in low frequencies based on theory, it requires extensive information on the dynamic properties of individual truck components, which is generally not available from manufacturers. Truck manufacturers may have access to this information, but they cannot know the as-built configuration of a truck assembled by a third party such as Caltrans. A successful detailed analysis requires extensive resources and engineering effort.

Good resources for understanding the basics of vehicle vibrations are papers and textbooks on vehicle dynamics. This investigation has determined that the best resource specific to trucks is the 1985 Society of Automotive Engineers (SAE) technical paper by T. Gillespie: 'Heavy Truck Ride.' Based on the review of the literature, a summary of the vibrations in the range 1 to 25 Hz was developed and is shown in Table 1. Results of testing and analysis found in the literature generally confirmed the values listed. The Department of Defense test specification (Table 3, reference [15]) is a useful resource to establish minimum vibration amplitude design requirements.

Table 1: Important truck resonant frequency values

Type of Vibration	Frequency
Rigid Body Resonance (Bounce and pitch of body on springs)	2 to 5 Hz
Frame Bending Vertical Bending Resonance (Also known as 'beaming')	6 to 9 Hz
Axle Hop Resonance	10 to 13 Hz
Miscellaneous dual axle bogie and other vibrations	13 to 20 Hz

Common truck tires for this class of vehicles have a diameter of 32 in (size R19.5) or 42 in (size R22.5). At 65 mph, the excitation frequency, due to the first mode of tire vibration, is 11.4 Hz for the smaller tire and 8.6 Hz for the larger tire. Based on the investigation, tire/wheel assemblies should be considered a major source of excitation especially at highway speeds, and a plot of the resonances and tire excitation is provided. It is likely that the smaller truck tire/wheel assemblies will excite the axle hop resonances under some conditions.

Caltrans asked for vibrations at specific locations behind the cab where the sign frames are typically located. This cannot be determined without additional data and further investigation. A qualitative description of the expected vibration is described.

A conservative assessment is that any vertical vibrations at the rear axle, whether from tire/wheel assembly imbalances or the road, are fully reflected as a fore/aft excitation to the top of the sign frame. The fore/aft vibration at the top of the truck frame is very low.

Gaps in Findings

In order to understand the failure modes of the sign frames, the following gaps in information must be filled. The gaps are listed as questions to be answered beginning with the most important:

a) What are the resonant vibration frequencies of the sign frames that have failed?

b) What truck vibration frequencies in Table 1 match the sign frame resonant frequencies?

c) What is the likelihood that the truck vibrations are causing the failure? Are there other possible explanations for the failures, such as wind loading, hard braking, road vibrations, or fabrication quality control problems?

Given the wide variety of trucks used by Caltrans and different sign frame designs, it is important to consider the possibility that more than one mechanism of failure is involved. Caltrans has begun measuring the vibrations with a Slam Stick.[1] The results from this effort will be useful in establishing the potential scope of the failure diagnosis process.

Next Steps

The following steps are recommended:

1. Determine the best available answers to the gaps in information listed above.
2. Collect Slam Stick measurements to determine resonant and excitation frequencies.
3. Document the different failures in detail and determine the likely cause for each case.
4. Verify the expected lifetime of the parts with particular attention to the effects of stress concentrations and welds.

If confidence in the failure diagnosis is satisfactory, the design solutions should be obvious and the failure diagnosis can be completed. A more detailed characterization of the truck vibrations will most likely be unnecessary.

If further investigation is required, it is likely that detailed characterization of the truck vibrations will be necessary. This would potentially require significant resources in time and equipment. The information collected would likely have future value to Caltrans and others. A detailed review of the problem and definition of the scope would be required.

[1] https://www.mide.com/collections/shock-vibration-data-loggers

Detailed Findings

Caltrans Example of Vibration Failure

Caltrans DOE engineering was queried to understand the history of vibration-induced failures that led to the request for this PI.

Fatigue stress failures have been observed in cantilevered structures (sign frames) mounted on Caltrans trucks. The sign frames are typically used to support items, such as signboards and warning lights, and are usually located behind the truck cab. Figure 1 shows an example of such a structure. Examples of sign frames that have failed are shown in Figures 2, 3, and 4.

Figure 1: Apparent direction of forces causing potential failure of cantilevered structure attached behind cab.

The trucks on which this type of failure occurs range in size and type from 1-ton pickups and stake-sides to 10-yard dump trucks with and without plows. Examples of these trucks are shown in Table 2. The sign frame designs vary depending on the configuration of the truck on which it is installed, and the failure has occurred with different designs on different trucks. For example, sign frames attached to the top rim of the pickup bed have caused sheet metal failures within the bed.

Based on initial investigations at Caltrans, the failures do appear to be caused by vibration forces acting in the fore/aft or pitching directions. Based on this problem, Caltrans is interested in identifying the vibration on the listed trucks at the top of the truck frame behind the cab and at the top of the sign frame. In the case of the pickup, the corresponding points are at the bed and on the top of the pickup bed walls.

Questions were developed in conjunction with Caltrans to query others who would be contacted as part of this investigation. The specific responses received are included in the last section titled ‘Contacts’.

The questions were the following:

1. What information is available to truck body builders, component manufacturers, and fleet owners to describe and quantify the common vibrations under 25 Hz in these trucks?

2. What design guidance can be provided to avoid vibration-induced failures of components mounted on these trucks?

3. What are the characteristics of the vibrations that are induced on components attached to the frame or pickup bed immediately behind the cab?

4. Are there examples of similar fatigue stress-induced failures in other fleets?

5. What experimental measurements of vibration have been made on these trucks with typical bodies and loads? How can the results of these experiments be obtained?

6. What data, specific to these trucks, is available to perform vibration modeling and analysis? Data needed includes mass properties of the major sub-components and suspension spring and damping constants.

7. What vibration analysis software is recommended for the analysis of the vibrations?
8. What vibration data logging tools are recommended for the analysis of the vibrations?
9. Where is the pitch center of the vehicle? What is the natural frequency about this point?
10. What are the natural frequencies of the axle assemblies?
11. What are the predominant vibrations that are transmitted by wheels and tires?
12. Do truck and fleet owners balance wheels and tires and check for out-of-roundness?
13. What remedies can be implemented to avoid the potential failures of cantilevered structures (sign frames) such as the structure shown in Figure 1?

Table 2: Examples of Class 3 to Class 7 trucks in Caltrans fleet Literature Search

Pickup (1 ton) 14,000 lb GVWR Crew cab / extended cab Class 3 (10,001-14,000 lb) 	**9-ft Cargo Truck** 15,000 lb GVWR or more Crew cab / extended cab Class 4 (14,001-16,000 lb) 
Cargo Truck 26,000 lb GVWR or less Crew cab Class 6 (19,501–26,000 lb) 	**4-yd Dump Truck** 33,000 lb GVWR Class 7 (26,001–33,000 lb) 
10-yd Dump Truck 64,000 GVWR Class 8 (Above 33,001 lb) 	

Details of Failures

At this time, the specific design shown in Figure 1 has not failed. Caltrans provided the following three examples of failures that have occurred in the past (see Figures 2 through 4.)

Figure 2: Detail of failure example 1

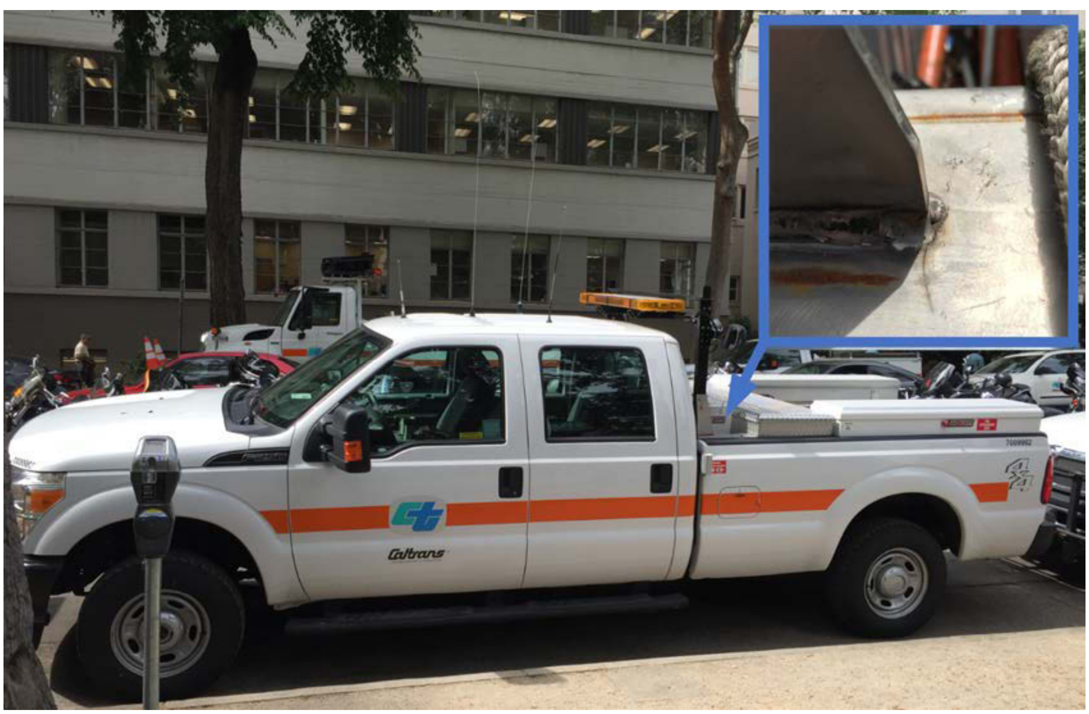

Figure 3: Detail of failure example 2

Figure 4: Detail of failure example 3

Literature Search

The more significant reports found in this literature search are presented in Table 3. Any reference numbers in this report, e.g. [1], are cited with respect to Table 3. The literature search did not find reports that explicitly answered the questions posed in this investigation.

Many thousands of papers and reports have been written on the subject of vehicle dynamics and vibrations. This subject matter is highly researched due to its value within the automobile industry, which is driven to optimize vehicle handling and comfort for passengers. Designers and manufacturers of trucks are focused on the vehicle load carrying capability while adequately protecting the operator and vehicle from annoying and damaging vibrations. Road handling safety is integral to the design process in both categories. The majority of reports described efforts to apply the engineering fundamentals of dynamics to mathematical models that could be used successfully in the design process. The SAE is the primary repository for publicly available information.

Searches for vibration in trucks, tires, and axles were performed in an effort to find specific information to the vibration problem defined in this investigation. Common report subjects are:

- Multi-axle truck tire damage to roads
- Vibration of goods transported in trucks on various international roadways
- Effect of vibration affecting operators in the cab

- Development of models to describe highly non-linear leaf springs
- Development of mathematical and computer models to predict vibration responses

Table 3: Sample of reports found in literature search

Textbooks and Papers on Theory and Fundamentals	
1. Gillespie, T. D., “Heavy truck ride,” SAE Technical Paper, 1985	Summary of truck ride phenomena and the design variables that affect ride. Compilation of studies. Expands the subject of vehicle dynamics in his textbook [2] to trucks.
2. Gillespie, T. D., "Fundamentals of Vehicle Dynamics,” Society of Automotive Engineers, 1992	Textbook on the subject of vehicle dynamics.
3. Wong, J. Y., “Theory of Ground Vehicles,” 2001	Textbook on the subject of vehicle dynamics.
Modeling and Simulation of Vehicles	
4. Cebon, D., “Heavy vehicle vibration - a case study,” 1986	Digital simulation of a 3-axle rigid heavy commercial vehicle. Development of vibration model comparing experiment to simulation.
5. Campbell, C., “Vibration Analysis of Heavy Duty Diesel Vehicles,” 2009	Analysis of vibrations for 22 different trucks. Five trucks analyzed with a computer-based model using Adams software. Investigated vibration in cab. Verified potential use of Adams model. Data from manufacturers was not available.
6. Kudritzki, D K., “Optimization of chassis vibrations at single irregularities,” SAE Technical Paper, 2005	Investigation of single irregularities such as concrete road joints on comfort of car.
7. Tufano, A. et al., “Medium frequency phenomena on heavy vehicles: experimental analysis and numerical applications,” 2015	Experimental modal analysis of whole truck. Summary of resonant frequencies and pictures of mode shapes.
8. Winkler, C. B., “Inertial properties of commercial vehicles-descriptive parameters used in analyzing the braking and handling of heavy trucks. Volume 2. Final report,” 1983	Example of measured data of various trucks, cars, and trailers. Originally published in 1981. Includes pitch moment of inertia.
Tire Vibrations Affecting Truck Ride	
9. Gillespie, T. D., “Influence of tire/wheel nonuniformities on heavy truck ride quality,” 1982	Investigation of tire nonuniformities on ride ratings. The Highway Safety Research Institute at the University of Michigan. Spectral maps of tractor on a smooth road are similar to those in [1].
Heavy Vehicle and Road Interaction	
10. Cebon, D., “Interaction between heavy vehicles and roads,” SAE Technical Paper, 1993	Investigates road damage caused by heavy vehicles. Calculates road damage based on static and dynamic models. Confirms tire frequencies in ranges of 1.5-4 Hz and also 8-15 Hz.

Suspension Dynamics	
11. Hoyle, J., “Modelling the static stiffness and dynamic frequency response characteristics of a leaf spring truck suspension,” 2004	A state variable linear 5 degree-of-freedom spring-mass-damper model of the vehicle was created within MATLAB in an attempt to predict the frequency response characteristics of the vehicle.
12. Davis, L, “Heavy Vehicle Suspensions-Testing and Analysis,” Ph.D. thesis, 2010	Queensland University of Technology, investigation of modifications to air suspension. Bus body bounce 1.0 Hz, bus drive axle hop 10.0 Hz, triaxle trailer body bounce 1.7 Hz, axle hop 10 and 12 Hz.
Truck Transport Vibrations	
13. Soleimani, B. and Ahmadi E., “Measurement and analysis of truck vibration levels as a function of package location in truck bed and suspension,” 2014	Measurement and analysis of vibrations on packaged fruit transported in trucks.
Industry Technical Information	
14. “Vibrations, wheelbase and chassis strength,” primemovermag.com.au, March 2014	Australian Road Transport Supplies Association, ARTSA Chairman’s Technical column. Summarizes heavy truck vibrations and body attachment recommendations. Pitching 3-5 Hz, axle hop 10Hz, beaming 6-9 Hz.
Testing Standards	
15. Department of Defense Test Method Standard MIL-STD-810G w/ Change 1 15 April 2014, Environmental Engineering Considerations and Laboratory Tests	Method 514.7 Annex C - Transportation Tailoring Guidance for Vibration Exposure Definition. Provides testing requirements for components carried on medium to heavy trucks. Shows peaks at 7-8 Hz and 14-16 Hz. This is a useful resource to establish minimum design requirements.
Publication Listing	
16. Grimm, A. et al., “Bibliography on Heavy Vehicle Dynamics,” 1999	Research Information and Publications Center, University of Michigan Transportation Research Institute.

Discussion

Vibrations in Trucks

Based on the literature review, the best resource that defines vibrations specific to trucks is the 1985 SAE technical paper by Gillespie titled 'Heavy Truck Ride' [1]. It is a very complete overview of theory, analysis, and experimental results describing the low-frequency vibrations up to 25 Hz that can be expected in trucks. It includes information pertaining to the effect on the operator in the cab but begins by defining the principles of vehicle dynamics describing the dynamic interaction of body, axle, tires, and suspensions as rigid bodies. It then describes, in significant detail, the vibrations found on a tractor-trailer.

The excitation sources of the truck dynamic system are road roughness, tire/wheel, driveline, and engine.

Road roughness can be represented as power spectral densities of elevation profiles and equations of average roughness are developed from measurements of typical roads. Portland cement concrete (PCC) roads are shown to have a greater average excitation at higher frequency than bituminous roads. At lower frequencies, a bituminous road will have a higher excitation. The crossover point is at a profile wavelength of approximately 25 ft, equivalent to 3.3 Hz at 55 mph. Marked periodicity in elevation profile due to PCC slab length is shown and significant variations between different sites can be seen. Based on general discussions with various drivers and personal experience, deteriorating PCC can excite noticeable resonant vibrations in a vehicle, but the effect appears to be insignificant when averaged over longer distances.

Excitation from the tires and wheels result from dimensional variation, mass imbalance, and stiffness variations which create a very complicated dynamic system. These forces will result in forces at the axle in all three directions: longitudinal, lateral, and vertical. For purposes of understanding the vibrations of interest, the vertical forces are the most significant and are represented as two modes. The first-order vibration can be viewed as a circular disk rotating on an offset axis which creates one force cycle per wheel revolution. The second-order vibration can be viewed as an oval disc which creates two force cycles per wheel revolution. The first-order vibration can be simplified as an out-of-roundness and/or out-of-balance condition. First-order vibrations will occur at the frequencies shown in Table 4.

Table 4: Truck tire rotation frequency at freeway speeds

Truck Tire, Diameter (in), Circumference (ft)	55 mph	60 mph	65 mph
225/70Rx19.5 G, 31.9 in, 8.4 ft	9.7 Hz	10.5 Hz	11.4 Hz
11R22.56, 42.1 in, 11.0 ft	7.3 Hz	8.0 Hz	8.6 Hz

Driveline and engine vibrations are significant causes of vibrations at higher frequencies. The typical low operating speed of truck engines is about 1000 rpm (16.7 Hz). Drive shafts will rotate at the axle ratio multiplied by wheel rotation speed. The amplitudes of vibrations from these components are minimized by the truck designers and would not likely excite the sign frame.

At certain speeds, the excitations discussed above will excite the truck vibration modes and any installed components such as a sign frame. There are dozens of low-frequency vibration modes on a truck. A sample of the vibration modes of a 3-axle tractor is shown in Table 5 [1]. These values were measured on a tractor-trailer combination and do not include vibration modes of the trailer. The excitation and resonances will also affect components such as the sign frames and similar components. Excitation forcing frequencies will change as the vehicle speed changes and the magnitude of the forcing excitations can also change with speed. The force from an out-of-balance wheel, for example, will increase as a function of speed squared.

Table 5: Sample of reported vibration modes of tractor-trailer [1]

Rigid body lateral translation (1.45 Hz)	Radiator pitch (10.1 Hz)
Rigid body fore/aft translation (1.4-1.5 Hz)	Tandem bounce (axles out of phase) (11.7-12.7 Hz)
Vehicle yaw (2.1-2.3 Hz)	Battery box/fuel tanks/exhaust stack (12.6 -12.8 Hz)
Vehicle vertical translation (3.2-3.6 Hz)	Engine/transmission bounce at rear (14.7 Hz)
Front end torsion (3.8-4.1 Hz)	Shift tower/ battery box (14.9 Hz)
Tractor pitch (4.0-4.9)	Cab bounce at rear/fuel tank vertical (15.2 Hz)
Tractor roll/cab motion at mounts (6.1-6.2 Hz)	Front axle roll mode (15.3 Hz)
Exhaust stack fore/aft (6.9 and 10 Hz)	Tandem bounce (axles in phase) (16.5-17.1 Hz)
Tractor vertical bending (6.5-7.0 Hz	Radiator lateral mode (17.3 Hz)
Battery box and fuel tank lateral (7.3 Hz)	Cab and engine/transmission pitch (18.4 Hz)
Lateral bending of tractor (7.9 Hz)	Trailer tandem bounce (out of phase) (18.6 Hz)
Tractor tandem yaw mode (8.9 Hz)	Tractor tandem roll (axles in phase) (18.7 Hz)
Tractor torsional mode (9.7 and 11.6-13.1Hz)	Front axle bounce (20.4 Hz)
Tractor tandem lateral (9.8-10.3 Hz)	

Truck Dynamic Response

In order to model the dynamic behavior of vehicles, engineers begin with a model known as the quarter vehicle, which represents the body of the vehicle suspended on its suspension and tires as shown in Figure 5. For comfort reasons, springs are selected such that passenger vehicles are designed to have a basic resonant frequency of 1 Hz. Trucks are designed with relatively stiffer springs to optimize load-carrying capabilities and have a basic resonance of about 3 Hz.

Since tires function as stiff springs, the axles themselves will have a resonance which can result in axle hop if not adequately damped with shocks. This occurs in both cars and trucks in the range of 10-13 Hz.

The ratio of excitation from the vibration source (road roughness) to the resulting deflections of the rigid body (truck) is known as gain. This is always highest at the point of resonance and is typically 1.5 to 3.0 in cars at 1 Hz. The gain is as high as 5 or 6 at the 3 Hz rigid body resonance of trucks. Higher resonance and higher gain results in a rougher ride in trucks.

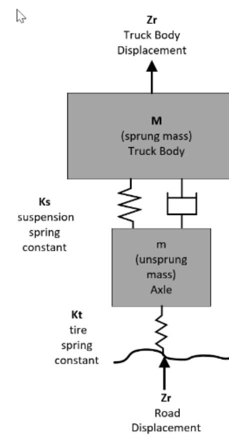

Figure 5: A quarter vehicle model

In order to understand the fore/aft vibrations that the sign frame exhibits, the concept of pitching must be considered. Figure 6 provides a brief representation of model development that shows how the vibration response will change at different points on the truck [1]. Pitching vibrations results in fore/aft vibration above the pitching center, which is likely near the center of gravity. The location of the sign frame is close to the pitch center, but the signboard is typically far above the pitch center, which amplifies the effect of pitch. Generally, a longer wheelbase should reduce this effect.

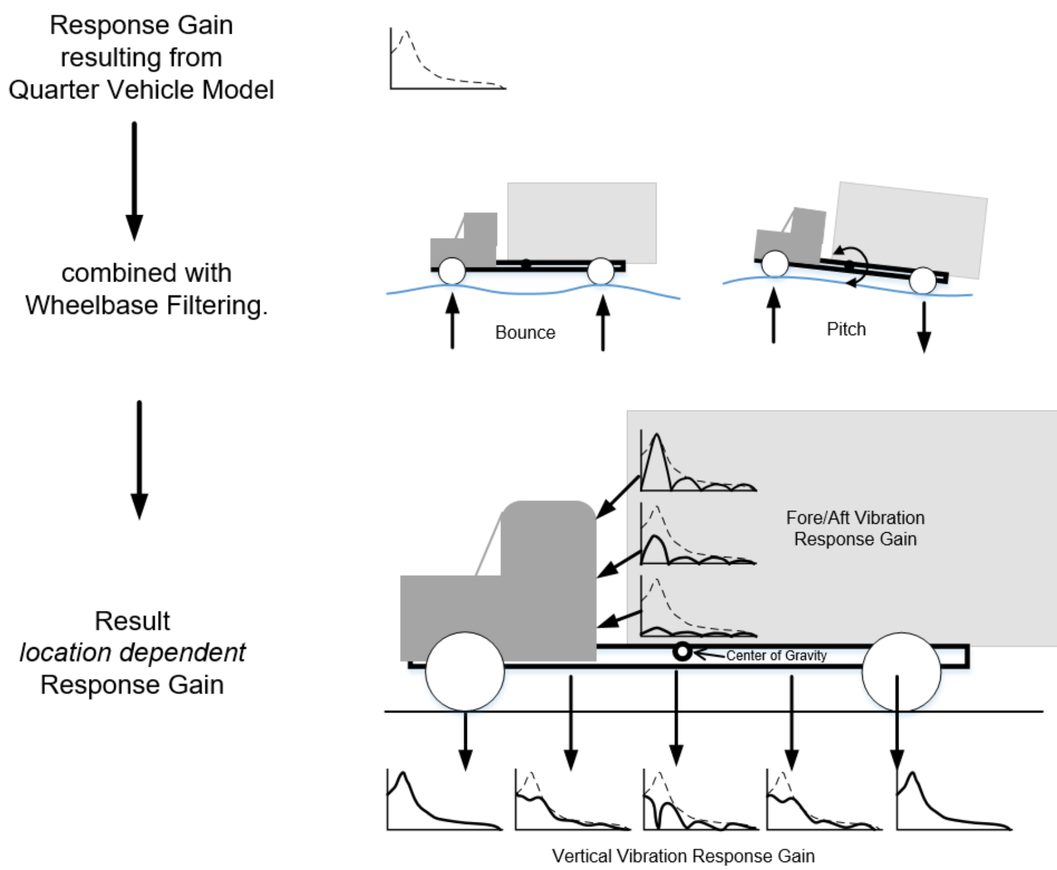

Figure 6: Description of the interaction of pitching and bouncing [1]

On sign frames located near a truck's center of gravity, a conservative assessment is that any vertical vibrations at either axle are fully reflected as a fore/aft excitation to the top of the sign frame. The fore/aft vibration at the top of the truck frame is very low.

Conclusions

This investigation has determined that detailed vibration profiles of the specific trucks are not available and design guidance is available only through researching and applying the subject of vehicle dynamics. Although vibration is predictable in low frequencies based on theory, it requires extensive information on the dynamic properties of individual truck components, which is generally not available from manufacturers. Truck manufacturers may have access to this information, but they cannot know the as-built configuration of a truck assembled by a third party such as Caltrans. Development of a complete vibration analysis requires extensive resources and engineering efforts.

Good resources for understanding the basics of vehicle vibrations are papers and textbooks on vehicle dynamics. This investigation has determined that the best resource specific to trucks is the 1985 Society of Automotive Engineers (SAE) technical paper by T. Gillespie: 'Heavy Truck Ride.' Based on the review of the literature, a summary of the vibrations in the range 1 to 25 Hz was developed and is shown in Figure 7 and Table 1. Results of testing and analysis found in the literature generally confirmed the values listed. The Department of Defense test specification (Table 2, reference [15]) is a useful resource to establish minimum vibration amplitude design requirements.

Caltrans asked for vibrations at specific locations behind the cab where the sign frames are typically located. The location of the sign frames is close to the pitch center of the vehicle and the forward aft vibrations may be the result of a pitching action. A conservative assessment is that any vertical vibrations at the rear axle, whether from tire/wheel assembly imbalances or the road, are fully reflected as a fore/aft excitation to the top of the sign frame. The fore/aft vibration at the top of the truck frame is very low.

Common truck tires for this class of vehicles have a diameter of 32 in (size R19.5) or 42 in (size R22.5). Based on the investigation, tire/wheel assemblies should be considered a major source of excitation especially at highway speeds. Tire/wheel assembly excitation is overlaid on the plot of the truck vibration resonances in Figure 7. It is likely that the smaller truck tire/wheel assemblies will excite the axle hop resonances under some conditions at freeway speeds. The larger truck tires do not overlap the axle hop frequencies which might explain why they are not usually balanced.

No commercial services that deal specifically with natural frequencies of pickups and medium and heavy vehicles were found with the exception of drive train analyzers and associated professionals. There are listings of professional engineers that are identified as vibration experts. A highly developed aspect of the field is the analysis of rotating machinery. A wide range of vibration logging equipment is available. John Jewell has identified a very complete system that would be used for a detailed analysis if necessary.

Two simulation software products were recommended, TruckSim by MathWorks and Adams by MSC Software. The use of this type of software is likely beyond the scope of what is required solve sign frame problem. Analysis is severely limited by the lack of manufacturer data.

Caltrans has initiated vibration testing with a Slam Stick to find the resonant vibration frequencies of the sign frames that have failed and the truck vibration frequencies that might be causing the excitation of the resonant frequencies. Analyzing Caltrans testing results and comparing them to the expected vibrations described in this PI will be necessary before investigating and ruling out the other possible explanations for the failures, such as wind loading, hard braking, road vibrations, or fabrication quality control problems. Given the wide variety of trucks used by Caltrans and different sign frame designs, it is important to consider the possibility that more than one mechanism of failure is involved.

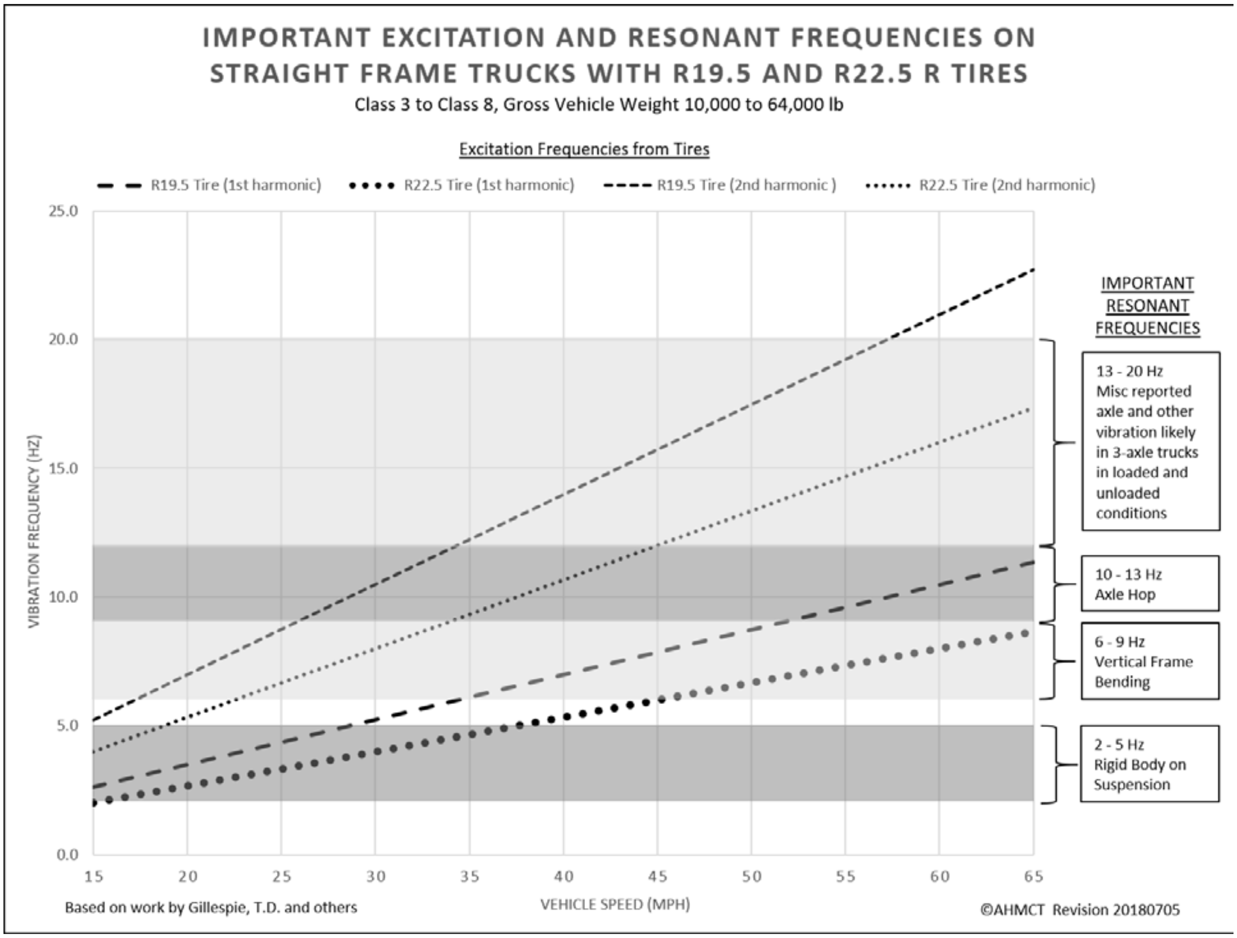

Figure 7: Proposed description of Caltrans truck vibration resonances overlaid by tire/wheel excitation frequencies.

Contacts

The following is the summary of information from contacts made during the course of the investigation. The background information shared with the contacts is described in the Caltrans Example of Vibration Failure and included Figure 1 and the list of 13 questions.

1. John Jewell

Senior Crash Testing Engineer
Roadside Safety Research Group
Office of Safety Innovation and Cooperative Research
Division of Research, Innovation and System Information
California DOT
Email: john.jewell at dot.ca.gov
Phone: 916-227-5824

(Contact with John Jewell was specifically listed in the scope since he performed the investigation of driver pain described below. Communicated via phone and email.)

a) John has not investigated natural frequencies in trucks, but he did perform modeling and instrumentation of the seat and floorboard in one particular truck to investigate reported pain to driver.

b) He spoke to Joe Holland[2] and Hector Romero[3] about Portland Cement Concrete (PCC) pavement issues. They both stated that the PCC pavement should have staggered joints. The spec has changed over the years, which means field installations of PCC have had various specs. Joe thought that, if anything, Asphalt Concrete (AC) paving is a worse problem than PCC paving.

c) Joe Holland and Hector Romero also believe that wind load is as likely a culprit as the pavement. Maybe wind buffeting from passing vehicles is causing the truck signboards to oscillate.

d) John described an example of buffeting. In the late 1990s, he was involved in an investigation of a failed large overhead sign that fell onto a freeway. It was cantilevered over the freeway on the 210 entering into the Valley. Passing trucks at certain spacing caused the sign to oscillate (rotate around its base) at some natural frequency. This, combined with the Santa Ana winds, likely caused the failure. Caltrans took that sign down and inspected others of similar design. They found some others with cracks.

e) Joe Holland and Hector Romero also agreed that instrumentation with both accelerometers and strain gages at key points would be the best way to start the investigation.

f) As for guidance on the instrumentation and software: They use DADiSP (https://www.dadisp.com) for some of our analysis because our datasets are very large. There are other packages that will work as well. For on-board data collection, they use a DtaBRICK3 from GMH engineering (http://www.gmheng.com/databrick3.php) for their crash testing. They are able to sync accelerometers, angular rate sensors, and strain gages while they collect data at 10,000 samples/second. He suspects that the sample rate would be less

[2] Joe Holland, Chief, Maintenance Applications Branch, Office of Materials Infrastructure, Caltrans Division of Research, Innovation & System Information

[3] Hector Augusto Romero, P.E., Senior Transportation Engineer, Chief of Preservation Design Branch, Pavement Management Program, Office of Concrete Pavements and Foundations, Caltrans Division of Maintenance

for investigating the signboard vibration. He recommends synchronizing data collection with on-board, front-facing video so that you could get an idea of where the loads are coming from.

2. Professor Steven A. Velinsky

Department of Mechanical and Aerospace Engineering
2132 Bainer Hall
University of California Davis
Davis, CA 95616
Email: savelinsky at ucdavis.edu
Phone: 530-752-4166

(Interviewed in person)

a) Recommended and provided textbooks on vehicle dynamics by Gillespie [2] and Wong [3].

b) Historically truck manufacturers do not provide vehicle dynamic properties for their vehicles.

c) Wind buffeting should be considered.

d) Recommends an analysis to confirm that the natural frequency is not near the axle hop frequency, then test and define the vibrations of the structure with strain gages and accelerometers.

3. Steven Karamihas

Senior Research Associate
University of Michigan
Transportation Research Institute
2901 Baxter Rd.
Ann Arbor, MI 48109-2150
Email: stevemk at umich.edu
Phone: 734-936-1068

(Contacted Steven Karamihas and Chris Winkler (below) via a single email to both.)
From Steven Karamihas email –
There are many resources out there for learning about vibration modes that are common to heavy trucks. Two places to start (beyond “Heavy Truck Ride” by Gillespie) are: (1) “Handbook of Vehicle Road Interaction” by David Cebon, (2) NCHRP Report 353. Follow the reference chain from those documents and you’ll do pretty well. A quick look at David Cebon’s web pages at the University of Cambridge might also give you a few more recent leads. I’d also suggest that if you plan to use simulation eventually, you might become familiar with TruckSim. If you have questions about pitch-plane simulations (circa NCHRP 353) or TruckSim, please let me know.

Only a few of the lectures pertain to the questions you’ve posed, but I’d feel remiss if I didn’t let you know about a course on heavy truck dynamics that Tom Gillespie, Chris Winkler, other true experts, and I teach every year in May:

http://isd.engin.umich.edu/professional-programs/dynamics-of-heavy-trucks/index.htm

There is much more emphasis on safety (handling, rollover, braking, etc.) than on vibration, but I thought you might want to know about it. (Tom teaches some of the materials from the Heavy Truck Ride publication in the course.)

You may also be interested to know that I have spent a considerable chunk of my professional life on the measurement and interpretation of road profiles. For background on that, start with the names Sayers and Gillespie.

Finally, I think the problem may be less complicated than it appears. At the very least, your emphasis might eventually turn from the modes of vibration on common trucks to exclusive evaluation of the cantilevered structure itself. Judging from the photo (Figure 1), even if you greatly improve the isolation provided by the host vehicle, you will still see failures at the support of that cantilever. There's virtually no damping, and any transient input (sharp braking, passing over localized roughness, wind gusts) and many flavors of background input will cause that subsystem to vibrate at its resonance frequency.

4. Chris Winkler

Research Scientist Emeritus
University of Michigan
Transportation Research Institute
2901 Baxter Rd.
Ann Arbor, MI 48109-2150
Email: cbw at umich.edu
Phone: 734-936-1061

(Chris Winkler provided the following list of reference sources)
Cambridge Vehicle Dynamics Consortium https://www-cvdc.eng.cam.ac.uk/
Prof David Cebon https://www-cvdc.eng.cam.ac.uk/directory/dc@eng.cam.ac.uk

UM (UMTRI) Library Catalog http://mirlyn.lib.umich.edu/

University of Michigan DEEP BLUE http://deepblue.lib.umich.edu/
(Contains, in PDF form, all HSRI - Highway Safety Research Institute (HSRI) & University of Michigan Transportation Research Institute (UMTRI) reports and papers that are not copyrighted by other publishers.)

Bibliography on Heavy Vehicle Dynamics; Grimm, A, et al.; UMTRI; 1999-06.
http://deepblue.lib.umich.edu/handle/2027.42/108243

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, Virginia 22161
Phone: 703-487-4650
http://www.ntis.gov/

Society of Automotive Engineers
400 Commonwealth Drive
Warrendale, PA 15096-0001
Phone: 877-606-7323
http://www.sae.org
(Documents under "Standards" and "Publications")

International Standards Organization (ISO)
http://www.iso.org/iso/home.html
http://www.iso.org/iso/home/standards.htm
http://www.iso.org/iso/home/search.htm?qt=&sort=rel&type=simple&published=on

5. National Truck Equipment Association (NTEA), The Association for the Work Truck Industry

Suzie Clark York
Email: info at ntea.com
Address and phone: N/A

(NTEA was contacted through their website http://www.ntea.com/)
Response - Unfortunately, NTEA does not have the information you requested but recommends contacting the original equipment manufacturers (OEMs) directly. I hope this feedback helps with your research efforts.

6. Ford Truck Body Builder Advisory Service

Ford Truck Body Builder Advisory Service (TBBAS)
Contact Form Submission
Email: bbasqa at ford.com
Address and phone: N/A

(Ford Truck was contacted through their website https://fordbbas.com/)
Response - We cannot provide this type of information in support of your request. Our products are designed and tested to meet internal and external standards with respect to noise, vibration, and harshness. Our testing and results are not available for distribution outside of Ford Motor Company.

7. Melissa Gauger

Application Engineering, Navistar Inc., International Trucks
Email: melissa.gauger at navistar.com
Address and phone: N/A

(Phone call with Melissa Gauger arranged by Randy Jones randy.jones@navistar.com)
Summary of discussion is below)

a) Melissa planned to forward the query to the engineering design group. No follow-up communication was received.

b) All International trucks are delivered with balanced tires.

c) Frame beaming can be a vibration issue. Frame sizes are usually specified in the customer specification. Loads are assumed to be distributed on the frame, but a point load near the back of the cab may cause unexpected beaming vibrations.

d) The sign frame cross section in the photo provided appears small. May simply need to be stiffened.

8. William Steinauer

Freightliner Vocational Sales Manager – Southwest Region
Phoenix, Arizona
Email: William.steinauer at daimler.com
Phone: 704-223-9108

(Communicated via email summarized below)

a) Engineering at headquarters responded that they do extensive testing on vibration and its effects on the truck. They do not, however, test for aftermarket or secondary part installations. They said this didn't appear to be an issue with the chassis, and if it becomes one, engineering could get involved.

b) I would suggest contacting large body companies and part suppliers as they may do testing like this.

c) Balancing tires and checking for roundness is a suggested maintenance, but that doesn't mean that everyone complies. Usually only the steer tires, if any, get balanced.

d) There are vibration analysis tools available, but they are very expensive.

e) Off the record from my personal knowledge, if you are having failures it is typically due to abuse, or the part was under-engineered. Two theories are to use heavier gauge metal and the use of angle brackets inlo (sic) 90-degree parts, or to try and reduce vibration by adding something between the two parts.

f) Many truck body companies will use a rubber belting material between the chassis frame and the body to prevent vibration and several other issues such as corrosion. Aftermarket guards that protect the back of cab also come with a rubber piece.

g) The only place where we have experienced higher vibration and fail rates is in the off-road oil and mining industries. California roads are some of the roughest in the country (personal experience, not data) and may also lead to increased stress. As far as data analysis, we wouldn't perform that on anything other than the truck cab and chassis. You will most likely need to talk with some body manufacturing companies. I can't speak to whether people are balancing tires and checking for roundness. It is a suggested maintenance, but that doesn't mean that everyone complies.

9. Manuel Souza

Auto Tech
UC Davis Fleet Services
University of California, Davis
740 La Rue Rd
Davis, CA 95616
Email: N/A
Phone: 530-752-7171

(In person discussion at UC Davis Fleet Services. The discussion focused on tires only.)

a) The large truck tires (e.g. 11R22.56) are usually not balanced on rear truck axles because balancing does not appear to improve ride. Tires on the front axle are balanced to reduce steering wheel vibrations.

b) When large tires are installed on a bus, all tires must be balanced.

c) Smaller truck tires (e.g. 225/70Rx19.5) are usually balanced when installed on trucks. It is very important to balance this size tire when mounted on buses. Buses with these tires are very sensitive to tire vibrations.

d) Manuel showed examples of imbalance-induced tire damage (cupping, etc.).