

Recent Experimental and Simulation Efforts to Mitigate Wobble and Shimmy in Commercial Line Haul Vehicles

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ABSTRACT

Wobble and shimmy vibrations are commonly observed in commercial highway vehicles with solid-beam front axles. These vibrations are typically self-excited and manifest themselves as sustained oscillations about the kingpin and axle tramp.

A study was initiated to investigate and quantify wobble and shimmy behaviors, with a primary focus on wobble. A cross functional team including test and simulation engineers evaluated a vehicle exhibiting these behaviors. The team developed an ADAMS model to reproduce the behaviors and developed a DOE to quantify the impact of variables and combinations of variables.

The evaluation demonstrated that dynamic imbalance in the rotating masses is a primary source of excitation. Wheel run-out, caster angle, tire brand, tire wear and tire inflation are also significant sources. Future studies will use these findings to mitigate the concern.

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INTRODUCTION

A front wheel vibration concern was sporadically observed on a Navistar® line haul tractor during specific conditions. For example, reports from Field Service Engineering noted that "the steering system may vibrate at specific speeds sometimes after hitting a bump or during a curve." In some cases, the driver of the vehicle suddenly and unexpectedly experienced vibration in the cab and rotational oscillations in the steering wheel at vehicle speeds typically exceeding 55 mph.

The concern is particularly challenging to resolve for a number of reasons:

- The behavior is a natural characteristic of vehicles that can only be suppressed or mitigated.
- It is difficult to pin the vibration to any particular root cause due to the many factors with influence.
- Based on benchmarking the behavior is present to a measurable degree on vehicles throughout the line-haul market.
- Many of the factors impacting the vibration are beyond the engineer's control.

- Considerations for commercial vehicle architecture, cost and weight constrain the engineer.
- The behavior can mysteriously come and go with no obvious trigger.

Famed Vehicle Dynamicist Maurice Olley summed it up this way- "The most dangerous form of unsprung oscillation was an old-fashioned classic shimmy, occurring with a front axle. A real detonation of front wheel shimmy is seldom seen nowadays except on truck front axles. Yet, the shimmy cycle is not completely cured. There was often considerable doubt about what had detonated a shimmy. A driver might go for a year without a recognizable shimmy, and then have the cycle occur suddenly for no apparent cause." [1]

Figure 1 shows the front suspension and steering architecture of a typical commercial vehicle in which a solid beam axle and tie rod connects the two knuckles together. Steering input by the driver is transferred from the input shaft to the steering gear which results in the sector gear rotating the pitman arm. This motion is then passed on by the draglink to the steering arm; finally rotating the knuckle.

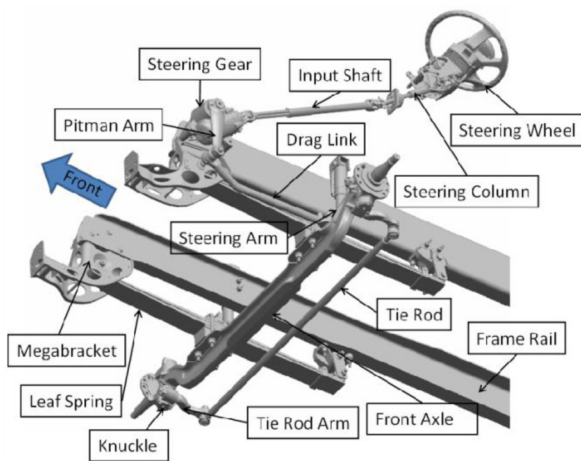


Figure 1. A view of the Front Suspension of a Typical Class 8 Line Haul Vehicle from the underside of the vehicle

Commercial vehicles may develop oscillations at the knuckle about the kingpin during driving that are self-excited and self-sustaining. Moreover, the oscillations can be coupled with axle tramp because of the close modal proximity of the resonances [2].

In line-haul tractors, wobble and shimmy are two distinct forms of vibration, but as commonly observed in the field of vibration, they can overlap. Wobble is characterized by wheel rotation about the kingpin, but can contain other lesser motions including axle tramp. The classical definition of shimmy is wobble plus tramp. These two degrees of freedom (kingpin rotation and vertical axle travel) are coupled through at least two mechanisms: gyroscopic precession (a dynamic mechanism) and caster (a kinematic mechanism).

Hans Pacejka provides an in-depth theoretical treatment of wheel wobble (referred to as shimmy) in which he describes it as a self-excited oscillatory motion of the wheel about (an almost) vertical steering axis. Pacejka credits Fromm, cf. Becker, Fromm and Maruhn (1931) as one of the first investigators to developed a theory establishing the gyroscopic coupling between angular motion about the longitudinal axis and about the steering axis as the main factor [3].

In our vehicles, wobble is driven or excited by 1st order tire rotation and peaks around 8.5 Hz. Prior experience with shimmy has shown that it is triggered by a single wheel event or staggered bump and occurs around 12 Hz.

The wobble vibration should not be confused with brake judder as brake judder is the vibration induced by braking torque fluctuation during a brake maneuver Wobble and shimmy do not require the application of brakes to excite [4].

Although wobble and steering nibble are sometimes used synonymously this paper will differentiate the two in the following way. Wobble is a self-excited or spontaneous oscillation of the front wheels at a set vehicle speed or speed range. This contrasts with Steering nibble which is a forced vibration of the steering system, and of (generally) low amplitude. [5].

HISTORICAL PERSPECTIVE

Wobble had been experienced in the automotive industry for many years but it was manageable until the advent of “balloon” tires and front-wheel brakes. The first published technical papers on the subject appeared in 1922 citing the new tires and brakes as troublesome relative to less flexible and lower mass designs that preceded them.

The auto industry found a proven cure for wobble in the form of the independent front suspension (IFS). The vibration tendency is suppressed by linking the two front wheels via the vehicle sprung mass rather than via an unsprung solid axle. Furthermore caster angle changes are eliminated even under heavy braking, an important feature as caster provides an aligning force. Finally IFS wheels move predominantly up and down in a vertical plane eliminating gyroscopic effects. In summary with IFS the left and right wheels are not directly connected, caster changes are eliminated and camber changes are minimal.

By the mid-thirties the problem was reduced in magnitude to the point that any remaining vibration could be readily handled by the addition of a shimmy damper. In fact the combination of an IFS and damper are commonly used today.

There are a variety of reasons why IFS has not been adopted on heavy commercial vehicles. The primary factor may be the difficulty in packaging suspension linkages into the ladder-frame chassis that dominates the heavy vehicle architecture. It is then necessary for us to find other means for suppressing the vibration.

VEHICLE TESTING

Testing Methodology

A comprehensive analysis primarily focusing on wobble was performed through a series of on-vehicle measurements. An International® ProStar® tractor equipped with a 12,000 lb. capacity solid beam front axle and parabolic taper leaf front suspension was selected. The test vehicle is shown in Figure 2.



Figure 2. 2007 International ProStar Test Vehicle.

A section of highway was identified which consisted of a smooth asphalt surface for the measurement cycle. The vehicle was driven over the route at constant vehicle speeds of 55, 60 and 65 mph, respectively, for each test.

Vibration at the tire can be classified into two types. One is forced-vibration excited by road irregularities. The other is self-vibration induced by non-uniformity of tire. Tire non-uniformity includes geometry, mass, and stiffness variation in the tire. If these variations are increased to some extent, a driver may feel vibration during driving [6].

Throughout the investigation, three main types of steer tires were used; standard, high scrub and low rolling resistance tires with varying tread depths. All tire and wheel sets were both statically and dynamically balanced, match mounted and fully characterized in order to minimize the radial run-out and loaded force variation of the assembly. The results of the characterization can be found in Table of the Appendix. New steer tire brands/models were tested at different points in the program.

Field Service Engineering generated reports focused on a small population of vehicles. The foundation for the initial investigation into wobble came from these reports and the team set about duplicating the wobble condition described by the reports. It was found that wobble can be consistently replicated by strategically replacing the steer tires with a worn set. Consequently, an initial test plan was developed which focused on quantifying the effect of worn steer tires.

In order to consistently replicate the wobble behavior, shaved steer tires were used. The shaved tires had a tread depth of 6/32" because 4/32" is the minimum legally allowable steer tire tread depth. As such 6/32" steer tires were considered to be well worn but were not worn out. Data acquired with the "worn" steer tires was compared to data with new, fully treaded steer tires for each different vehicle configuration.

In contrast, the rear drive tires were held constant throughout the testing with one exception. The drive tires were updated early in the program to reflect the latest high volume low rolling resistance tire offering for the test vehicle. The drive tire swap from a standard offering to a low rolling resistance did not impact the results when compared to the results from a

common set of steer tires. It should be noted that a wide assortment of wheel and tire combinations are available to the customer when specifying the vehicle as well as in the aftermarket. Based on the results presented here, certain combinations can have a significant impact on the wobble performance of the vehicle.

Vehicle CAN data and ambient temperature were measured. The vibration associated with the wobble that was felt throughout the cab and in the steering wheel was subjectively assessed. During the vehicle tests, attempts were made to counteract the rotational vibration of the steering wheel by gripping the steering wheel tightly and holding it steady. Finally three metrics, a) maximum measured angular velocity, b) wobble frequency and c) maximum RMS magnitude at the wobble frequency, were used to quantify the difference in wobble performance between each vehicle configuration. The data was post-processed in both the time and frequency domains. Figure 3 demonstrates the self-excited nature of wobble in the time domain. The test vehicle was driven at a constant speed of 55 mph and the angular velocity increases to approximately 20 deg/s. The example in Figure 4 shows the frequency domain FFT where the wobble frequency peak is 7.63 Hz with an amplitude of 1.32 deg/s RMS.

An effort was made to correlate the objective data with the subjective experience in the vehicle. Therefore, particular components, their combinations and vehicle specifications which were suspected to excite wobble were evaluated.

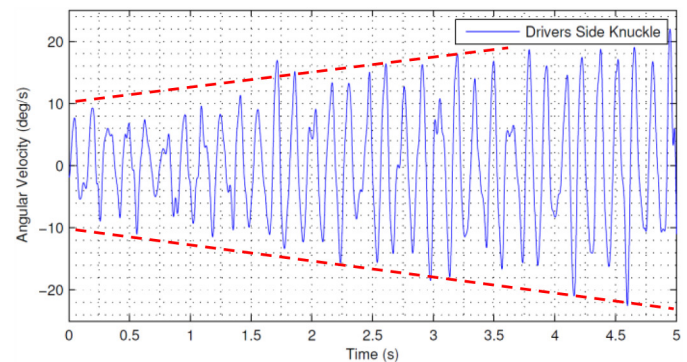


Figure 3. Kingpin rotational velocity collected at 55 mph on the test vehicle.

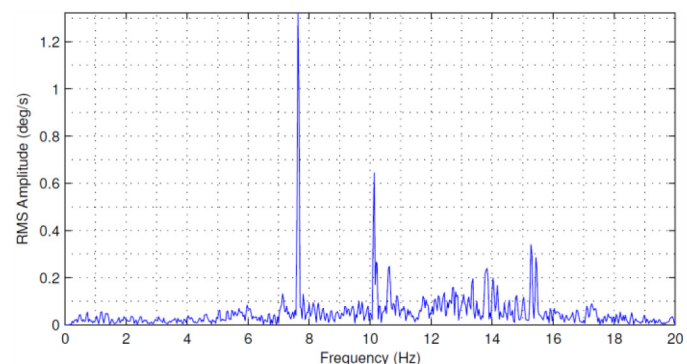


Figure 4. FFT of a typical wobble vehicle.



Consideration was given to front axle thrust bearings, king pin bushings and steering dampers as those components were being added or replaced in the field. Based on the field reports, 55 mph was chosen as the main speed of interest which correlated to a wobble frequency of approximately 7.75 Hz. As the testing progressed and sensitivities were discovered, the test plan was modified to focus on front axle caster, steer tire brand/model and steer tire pressure. Finally, an RMS magnitude of 0.30 deg/s was established as an acceptance limit based on the subjective perception of wobble.

For the sake of completeness, a number of competitive vehicles were obtained and tested to ascertain if wobble was present. It was determined that all the competitive vehicles tested presented a measurable level of wobble. A comprehensive list of the configurations tested can be found in [Table 2](#) of the Appendix.

Testing Results

In the baseline OEM configuration, tests 1A and 1B, the standard steer tires were replaced with high scrub worn steer tires. This first test was used as validation. The large disparity found at 55 mph and approximately 7.75 Hz between the standard tires RMS magnitude of 0.153 deg/s and the high scrub worn tires at 2.430 deg/s RMS confirmed that wobble could be reproduced on the selected vehicle. Furthermore, the increase or decrease in RMS magnitude for a given vehicle configuration was applicable at increased vehicle speeds of 60 and 65 mph. The frequency also increased accordingly up to approximately 9.0 Hz at 65 mph. In all the tests a higher frequency rotational component was identified that lined up with the shimmy frequency range of 10-12 Hz. The shimmy component was independent of the wobble component and had an RMS magnitude in the range of 0.20 - 0.40 deg/s. In regards to the subjective experience, the worn tires produced a very prominent wobble in the vehicle with a maximum angular velocity of 30 deg/s. This could be felt throughout the vehicle but most notably in the steering wheel, which rotated in concert with the steer tires. Two additional locations that provided considerable amounts of feedback were the driver's foot well and the driver's seat. Due to the proximity of the cab mounting points with the driver's foot well, low levels of oscillatory vibration could be easily detected in the driver's foot well.

In tests 2 and 3, the original roller type thrust bearings were replaced with composite versions that had a higher coefficient of friction. The driver side thrust bearing was replaced and tested followed by the combination of both driver and passenger side thrust bearings. When compared with the OEM configuration, wobble increased for both configurations with the standard and high scrub worn tires. Only when test 3C was run with a set of low rolling resistance "A" tires did the vehicle perform adequately with an RMS magnitude of 0.324 deg/s. Subjectively, the composite thrust bearings performed worse than the roller type bearing. The composite thrust bearings increased the amount of high frequency vibration in the steering wheel, increased steering efforts and reduced

returnability. In addition, the dual composite thrust bearing configuration performed worse than the single composite thrust bearing configuration in all of the subjective categories. Before performing any subsequent tests, the roller type thrust bearings were reinstalled in the vehicle.

For test 4 and all subsequent tests, the original Garlock king pin bushings were replaced with bronze variants honed to 0.002" over the measured king pin diameter. The bronze bushings were selected because they have a higher coefficient of friction and were used with varying degrees of success in the field on complaint vehicles. The 0.002" over specification was chosen because it is in the middle of the range of the reaming specification. For this particular test, the front axle alignment was out of specification with over 6.0 degrees of caster on the driver side along with 1.5 degrees of cross caster. Cross caster is defined as the difference between the driver and passenger side caster. Therefore it should not be used for comparison. Of note, the worn high scrub tires produced the highest RMS magnitude of the testing at 4.485 deg/s.

In tests 5 and 6, the vehicle was realigned and the steer axle caster was set to each end of the range of the 12K front axle alignment specification. For test 5, the axle caster was set at 5.75 degrees on the driver side and 6.5 degrees on the passenger side. For test 6, the axle caster was set at 4.75 degrees on the driver side and 5.5 degrees on the passenger side. At this point, a second brand X low rolling resistance tire "B" was added to the testing. Both the standard and the low rolling resistance "B" tires had essentially the same wobble performance with only a slight decrease in RMS magnitude with increasing caster. Unexpectedly, the high scrub tire did not follow the trend of the other two tires and it showed a notable increase in wobble RMS magnitude from 0.895 to 1.470 deg/s with increasing caster. This result was particularly interesting because it indicated that both the caster and the tire construction can have a large impact on wobble performance.

These tests were used to define an acceptable wobble limit of 0.30 deg/s RMS. This limit is dependent on the architecture of the vehicle and most likely cannot be applied to all vehicles. Angular velocity at or below this acceptance limit can only be detected in either the steering wheel or the foot well. In the steering wheel it manifests itself as a slight rotational vibration at times, and in the foot well a slight vibration can be detected in the driver's calves.

In tests 7 and 8, a steering damper was added to the vehicle and its effect was quantified. Again, a brand "X" worn variant of the low rolling resistance tire "B" was added to the testing. As the results for test 7 were being post-processed, an issue with the vehicle was identified. The RMS magnitude was amplified from 0.321 to 1.160 deg/s with the same vehicle configuration from test 6C. The cause of the change in wobble performance was due to an out of balance wheel located at the outside position of the passenger side RR axle. This interruption which halted test 7, demonstrated the vehicle's sensitivity to out of balance wheels when equipped with balanced wheel sets. This was interesting.

because the sentiment received from numerous commercial tire resellers in our area was one in which commercial wheel and tire combinations are not balanced regularly. It also demonstrated that the steering damper can be quite effective. The RMS magnitude was reduced from 1.160 to 0.851 deg/s. This result was mimicked in test 8 where the low rolling resistance tire "B" variants were tested with and without the damper. A reduction in wobble RMS magnitude to below the acceptable limit in some instances was achieved.

Based on the results from tests 5 and 6, test 9 was purposely conducted with the front axle caster specification 1 degree above the passenger side limit and designed to determine if performance gains are achieved outside the envelope of the current specification range. The steer axle caster was set at 6.5 degrees on the driver side and 7.5 degrees on the passenger side. All of the tires tested up to this point were brand "X" variants but this test included steer tire sets from brands "Y" and "Z". Consistent with the results from test 6C as well as the trends discovered, test 9A with the same steer tires resulted in the expected reduction in wobble RMS magnitude. Similarly, test 9C also resulted in the expected increase in wobble RMS magnitude. Interestingly, the low rolling resistance "B" worn set of steer tires from test 8C, resulted in a decrease of wobble RMS magnitude below the acceptance limit. This would indicate that the low rolling resistance tire "B" does not have significant performance degradation over the life of the tire on the test vehicle. Of note, test 9D of the brand "Y" low rolling resistance tire yielded a rather high wobble RMS magnitude with the high degree of caster dialed into the vehicle.

As stated earlier but not quantified in Table 2, numerous competitive vehicles were tested after test 9 was concluded. These results indicated that all the vehicles tested exhibit wobble. Variation was found in their performance and in the subjective experience. The acceptance limit proposed earlier was not directly applicable to other vehicles.

VEHICLE SIMULATION

The primary objective of the simulation exercise was to evaluate the effectiveness of potential solutions through a *quantitative* assessment of influence factors. Particular emphasis was placed on identifying sources of excitation inherent to the operating conditions, and to distinguish these from amplification mechanisms attributed to vehicle configuration and other aspects of the design.

A *qualitative* understanding of the vehicle's behavior and the underlying physics was also desired. Modal analysis was used to explore the relation of wobble to shimmy and to help determine whether wobble is a natural mode of vibration inherent to highway tractors or an accidental consequence of particular designs - a design flaw - that can be completely eliminated.

The simulation effort progressed through the following stages

1. Model Development
2. Model Correlation
3. Subsystem Simulation
4. Modal Analysis
5. Vehicle Parameter Study

Model Development

An Adams model, shown in Figure 5, was configured identically to the ProStar test vehicle (E4135) in order to allow for model correlation. The main modeling features included (1) leaf springs modeled as discretized beams with interleaf contact and friction, (2) flexible frame, cab, hood, front axle, steering linkage, and rear suspension trailing arms, (3) rigid steering knuckle, brake drum, hub, and (4) wheel and tires based on Magic Formula tire (PAC 2002).

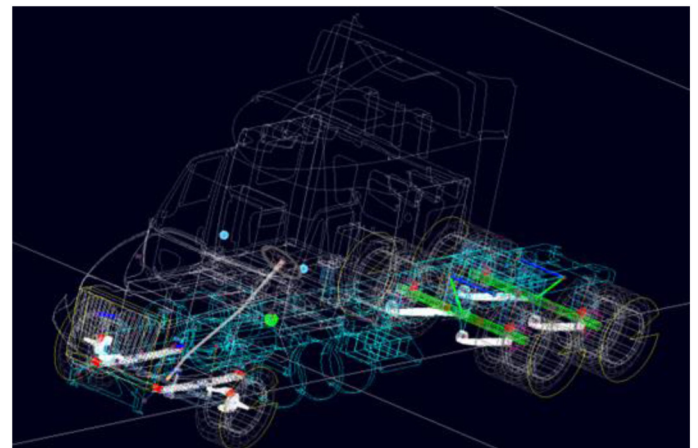


Figure 5. A 2007 ProStar Full vehicle Model was assembled in ADAMS to study the shimmy/wobble phenomenon. The vehicle was built to have the same characteristics as the test vehicle.

The approach to model development consisted of starting with our standard fidelity model used for ride quality and handling predictions and introducing additional refinements until the intensity and character of wobble were reproduced, thereby fulfilling one of the objectives - identification of excitation sources.

Guided by observations from the field and physical testing, special consideration was given to parts that could introduce a rotating imbalance, such as drums, hubs, wheels, and tires. In particular, drums were understood to exhibit significant asymmetry due to design features, manufacturing processes, and material density variation.

Although *static* imbalance, which induces excitation in the plane of the wheel, was understood to be a major source of excitation, new vehicles are typically shipped with statically balanced wheels and tires. In addition, testing had demonstrated wobble during braking to be associated with a couple or *dynamic* imbalance, which induces excitation about the kingpin. These types are illustrated in Figure 6.