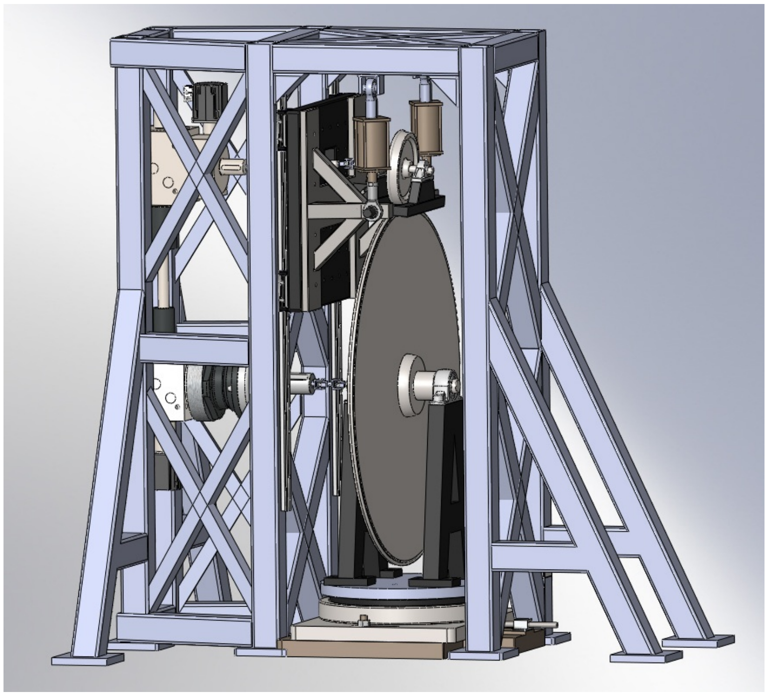
U.S. Department of
Transportation

**Federal Railroad
Administration**

Evaluation of Wheel-Rail Contact Mechanics

Roller Rig Concept Design Review

Office of Research
and Development
Washington, DC 20590



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Mehdi Ahmadian and Michael Craft

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Center for Vehicle Systems and Safety
Virginia Tech
3103 Commerce St
Blacksburg, VA 24061

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13. ABSTRACT (Maximum 200 words)

A need exists for a new test rig design with advanced sensing technologies that will allow the railroad industry and regulatory agencies to better understand the wheel-rail contact dynamics and mechanics, especially as it pertains to high-speed rail. Both scaled and full-scale designs are being investigated. The use of scaled designs will make testing possible at much lower investment and complexity than is required for full-scale testing. However, a scaled rig eliminates the ability to directly test with fielded and standard (off-the-shelf) components. Irrespective of the scaling, the controlled laboratory environment will assist with obtaining data on the mechanics and dynamics of the creepage and creep forces within the contact ellipse under various conditions; this evaluation process is essential for better understanding the fundamentals of wheel-rail contact dynamics and more effective rail dynamics modeling. Therefore, we recommend developing a streamlined test rig of 1/4 to 1/5 full-scale with precise test control and sensory system that allows for accurate measurement of the wheel forces and moments that occur in conditions representative of actual field occurrences. The scaled test rig may serve as a steppingstone for future development of a full-size rig.

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1 yard (yd)	=	0.9 meter (m)	1 meter (m)	=	3.3 feet (ft)
1 mile (mi)	=	1.6 kilometers (km)	1 meter (m)	=	1.1 yards (yd)
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				=	1.1 short tons
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1 tablespoon (tbsp)	=	15 milliliters (ml)	1 liter (l)	=	2.1 pints (pt)
1 fluid ounce (fl oz)	=	30 milliliters (ml)	1 liter (l)	=	1.06 quarts (qt)
1 cup (c)	=	0.24 liter (l)	1 liter (l)	=	0.26 gallon (gal)
1 pint (pt)	=	0.47 liter (l)			
1 quart (qt)	=	0.96 liter (l)			
1 gallon (gal)	=	3.8 liters (l)			
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)	1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)	1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)
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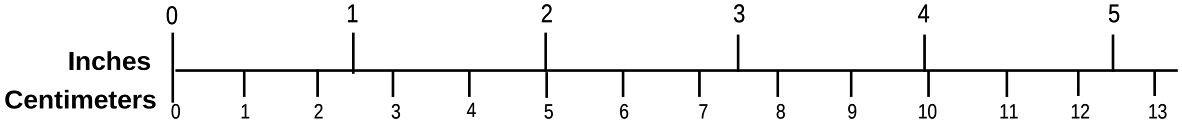

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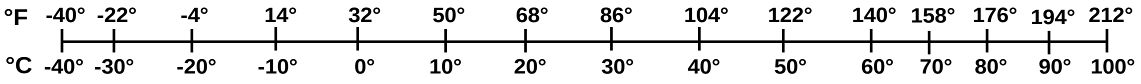

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Executive Summary

This report covers the conceptual design phase of a Wheel-Rail Contact Test Rig originally outlined in the proposal entitled *Evaluation of Wheel-Rail Contact Mechanics* submitted to FRA in July of 2010. A wide variety of test systems are covered here, along with the critical aspects of each design. Although roller testing rigs and fatigue test rigs have been built prior to this research, there is a need for a new rig design with beyond-state-of-the-art sensing technologies that would allow the railroad industry and regulatory agencies to thoroughly test and research the wheel-rail dynamics, especially as it pertains to validating rail vehicle models and gaining a better understanding of the fundamentals of the wheel-rail contact mechanics and dynamics.

Both scaled and full-scale designs are being investigated for this purpose. While these two systems vary significantly in size and cost, their goals are the same. Scaled designs require much lower investments and simpler logistics than is required for full-scale testing facilities because of simpler facility requirements, safety systems, load actuators, and constraint systems. The sensors required, however, will be similar—sometimes identical—to those used on a full-scale rig, offering little savings over a full-scale rig testing facility. The major drawback of a scaled system is that it eliminates the ability to directly test with fielded and standard components such as off-the-shelf wheels, wheelsets, and rail segments.

The controlled laboratory environment will assist with obtaining data on the mechanics and dynamics of the creepage and creep forces within the wheel-rail contact patch under various conditions, irrespective of whether a scaled or full-size system is being used or not. Such data will be essential for better understanding the fundamentals of wheel-rail contact dynamics and more effective rail dynamics modeling. We believe that the key to the success of this project—as measured by collecting useful data—lies in maintaining extremely precise control over the test set up and data collection process, such that one can carry out effective design of experiments.

It is our recommendation that a *scaled*, single wheel roller rig design be pursued in the next phase of this study. Although a perpendicular roller rig has not previously been used for this purpose, it has the most potential of maintaining the contract patch formation. The proposed roller rig would be arranged so that the roller rail would rotate in a horizontal plane perpendicular to the wheel plane, reducing the rail curvature effect and the associated contact patch distortion that is common with a dynamometer-style roller rig in which the roller rail rotates in the same plane as the wheel. Although the scaled rig would be used primarily for precise creep force data collection and creepage model validation, it could also serve as a steppingstone for a full-scale rig that allows for standard and fielded component testing. Because of its vast logistical and cost requirements, the full-scale rig is not anticipated to become a reality for another decade, whereas the scaled-model (⅓ to ½ of full size) can be realized in 1 or 2 years. Our discussions with a major U.S. dynamic test rig manufacturer indicate that the risks associated with fabricating and operating the scaled system is reasonably small.

1. Introduction

This report covers the concept generation and evaluation phase of the work outlined in the proposal entitled *Evaluation of Wheel-Rail Contact Mechanics* submitted to the FRA in July of 2010. A variety of wheel-rail contact mechanics testing rigs are presented along with supporting information for each design. In addition to the research being conducted on specific design types, mathematical modeling of a truck system on rails is also being investigated to assist with determining design issues when going from the laboratory environment to the real world. The intended purpose of this document is to provide a comprehensive summary of the created concepts and the recommendations for further study based on information from FRA, and Virginia Tech's (VT's) industrial partner. The following section of the report discusses the preliminary design phase and details the concepts designed to meet the stated wheel-rail test rig specifications.

1.1 Background

A roller rig is a type of railway vehicle testing facility. It is a system capable of testing a single wheel, wheelset, or truck in a running condition without field tests. It provides an effective means of studying the interaction between a railway wheel and the rail.

The application of roller rigs to the study of vehicle system dynamics and the development of high-speed trains and other railway vehicles has become more widespread in recent decades. Roller rigs are used by researchers and railway organizations around the world to assist in better understanding the behavior of railway vehicles and developing faster, safer, and more efficient trains. Roller rigs have contributed to many current designs of railway vehicles [3].

Existing research on wheel-rail contact mechanics is quite extensive, especially in foreign countries and regions of the world with extensive government rail research programs. But there remains a need for U.S. railroads and governing bodies to move beyond past analytical and experimental studies of wheel-rail contact mechanics [3, 4]. Rolling rig and vibration test facilities have been used by various agencies in different regions of the world at various times, but all test rigs suffer from design limitations and are built for only specific studies. Some test facilities, such as the one at TTCI, are no longer in service because of inadequate test flexibility, safety concerns, data gathering limitations, cost, or reaching the end of their useful life. The test rig under consideration for this program will help advance the study of wheel-rail contact. With guidance from FRA, industrial partners, and sensor manufacturers, program objectives are likely to be met.

1.1.1 Industrial Partners

Norfolk Southern (NS) has provided guidance on the concepts formulated for this report and has reviewed our concept scoring for the different designs. This guidance has been and will continue to be an invaluable part of the design process.

1.1.2 Wheel-Rail Contact Mechanics Test Rig Specifications

This chapter briefly reviews some of the performance specifications of the proposed wheel-rail test facility. Table 1 provides a summary of the test rig specifications for a full-scale rig. Figure

1 illustrates the loading and AoA versus the simulated test speed. Table 2 presents the sensor requirements for a full-scale, single wheelset test rig.

Table 1. Summary Table of Test Rig Specifications

Specification	Required	Desired	Adjusting Resolution
Wheel Size	32–40 in	25 in (min)–50 in (max)	N/A
Wheelset Spacing	70 in (min)–138 in (max)	-	1 in
Maximum Axle Load	62 kip (passenger) 100 kip (freight)	-	100 lb
Maximum Speed	220 mph (passenger) 110 mph (freight)	-	1 mph
Track Width	55.5–59 in	-	0.1 in
Angle of Attack (AoA)	+/- 2° high speed +/- 5° low speed	+/- 20° turnout testing	0.1°
Lateral Position	+/- 2 in	-	0.1 in
Rail Superelevation	Up to 7 in height difference	-	0.1 in

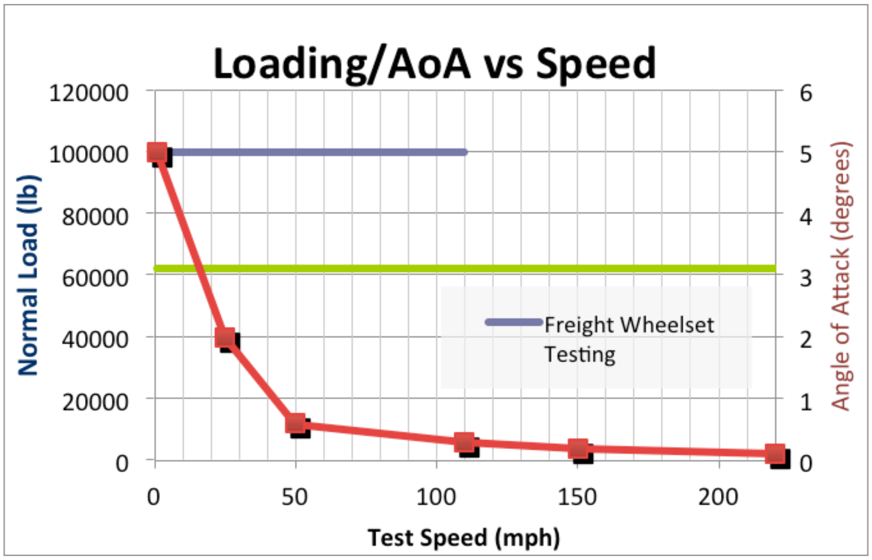


Figure 1. Graphical representation of AoA specification and loading specification versus the test speed

Table 2. Anticipated Sensor Requirements for Testing a Single Wheelset

Displacement sensors			**Velocity sensors**			**Acceleration sensors**			**Strain-based sensors**			**Other sensors**		
LIDAR			LIDAR			Accelerometer			Strain gauge or similar					
Name	Range	Sensitivity	Name	Range	Sensitivity	Name	Range	Sensitivity	Name	Range	Sensitivity	Name	Range	Sensitivity
Max wheel vertical displ	±2 in	0.05 in	Rail tangential velocity, left and right	2200 in/s	2 in/s	Max wheel vertical accel, left and right	200 g	10 mV/g	Vertical force, left and right wheels	50000 lb	10 lb	Video 1		1000 fps
Max wheel lateral displ	±2 in	0.05 in	Wheel tangential velocity, left and right	2200 in/s	2 in/s	Max wheel lateral accel, left and right	200 g	10 mV/g	Lateral force, left and right wheels	30000 lb	10 lb	Video 2		1000 fps
Max side frame vertical displ	±2 in	0.05 in				Max side frame vertical accel, left and right	20 g	100 mV/g	Longitudinal force, left and right wheels	30000 lb	10 lb	Ambient temperature	40-120 °F	0.1 °F
Max side frame lateral displ	±2 in	0.05 in				Max sideframe lateral accel, left and right	20 g	100 mV/g	Moment_X, left and right wheels	30000 ft-lb	5 ft-lb	Angle of Attack	±5°	±0.1°
Max rail vertical displ	±1 in	0.05 in				Vertical acceleration of truck	20 g	100 mV/g	Moment_Y, left and right wheels	30000 ft-lb	5 ft-lb			
Max rail lateral displ	±1 in	0.05 in							Moment_Z, left and right wheels	30000 ft-lb	5 ft-lb			

The truck, wheelsets, or wheels will be tested in steady-state loading conditions. Should full truck testing be pursued, provisions will be made to load the truck at the car body center plate. This interface will also allow for application of load to the bolster. Should wheelset testing be performed without use of the full truck, the wheelset would be constrained through the roller bearing interface. Such an interface should allow for the testing of various wheelsets and axle bearing mounts. Should a single wheel be the test specimen, a specially constructed rig would be used to load and constrain the motion of the wheel.

It should be noted that there is a great desire by both the rail industry and FRA to test worn or fielded components on the test rig. Such a capability would give researchers, industry, and regulators the ability to study the conditions and effects of various components in a laboratory setting, under a controlled environment that provides a high degree of test repeatability. The full-scale test rig will be designed so that it can be used to test fielded trucks and perhaps fielded rails.

The testing of the specimen(s) outlined in this chapter may be completed any number of ways. The intention of this document is not to favor any particular technique, but to outline the testing goals. It is, however, important to remember that some testing may involve the use of hydraulic or electromechanical positioning systems to constrain the bogey, wheelsets, and/or wheel(s) during the testing. Such constrained testing does not allow the movement that commonly occurs during primary and secondary hunting. Nevertheless, the force and vibration data that will be gathered is expected to be useful for indirectly assessing the propensity for hunting. The use of positioning systems will allow the simulation of a wide range of dynamics including multiple contact tests, flange climbing events, and AoA or lateral position sweeps.

1.2 Objectives

The primary purpose of this Concept Design Review (CDR) is to consider the implementation of the rig requirements with respect to a specific design. Each design has been reviewed with the stakeholders to ensure concurrence on its feasibility while keeping in mind the overall objectives of the research, which are as follows:

- Provide the means for thorough understanding of the mechanics and dynamics associated with the wheel-rail interaction, commonly occurring during railway operation, under realistic field conditions or conditions that can be scientifically related to the field conditions
- Design a wheel-rail contact mechanics evaluation test rig that can be used for the needs of both freight and high-speed intercity trains.
- Allow testing in conditions that can simulate both tangent track and curved track operation.
- Provide the means for measuring necessary parameters for modeling studies that are of interest to FRA and the U.S. rail industry.

The realization of the preceding objectives may be achieved through the completion of the following research goals:

1. Study of the traction ellipse

The traction ellipse has been studied in detail for many years, resulting in improved understanding of the mechanism and its overall effect on rail vehicle dynamics [1, 2]. The use of new, beyond-state-of-the-art sensing technologies combined with an advanced testing facility will further the understanding of the traction ellipse to a point necessary for high-speed passenger and freight rail research and regulatory studies.

2. Measure all possible parameters of the dynamics

   Researchers hope that the proposed test facility will be able to measure the dynamics of the wheel/rail interface at a level more comprehensive and precise than ever previously performed in a field or laboratory environment. A vast array of sensors and test conditions should allow for a complete picture of the dynamics of the wheel-rail interface over most common rail conditions.

3. Test fielded and standard wheels and rails

   In addition to testing the theoretical behavior of the wheel-rail interface, both the FRA and industry partners have expressed interest in the testing of fielded and production rail equipment. Through this testing, researchers, regulators, and operators can gain clear insight into the specific mechanisms resulting from rail or wheel wear occurring in the field, the machining practices used to true wheels and other components, and the interaction of an entire truck (bogie) on the car body dynamics.

Although meeting these three goals would be ideal, parameter estimate requirements for traction ellipse studies may prove to be too extreme if fielded wheels, wheelsets, and bogey assemblies are to be considered as testing specimens. Concept design discussions have indicated that study of the traction ellipse should be carried out in a precisely controlled environment, most likely scaled and fielded wheels and rails should be tested in a separate fashion under the extreme loading conditions required for the full-scale tests. These issues will be discussed further in the Summary of Findings and the Conclusions and Recommendations sections.

1.3 Overall approach

A team of researchers generated design concepts based on past or existing research, council with industry and industrial suppliers, similar test rigs used in other industries, or original ideas. Each test rig was refined through a collaborative process and basic drawings were produced for each design.

A summary of the concept design process is as follows:

- Met with FRA in February 2011 to discuss the Specifications recommendations
- Based on Specifications Review, the Specification Design Report was revised to adequately cover the needs of FRA (March 2011)
- VT developed new design concepts intended to further the study of the traction ellipse in ways not previously achieved
- VT investigated all concepts (old and new) to quantify their relative ability to meet or exceed the requirements of the test rig (March–May 2011)

- VT developed a simple mathematical modeling program to study the behavior of a truck on a track under specified operating conditions. This program was used to assist with the design and review process (March 2011–Present)
- VT scored the concepts by concurrence of all researchers regarding all aspects of each design
- VT met with NS (May 2011) to review the design concepts and scoring
- CDR was held at FRA (June 2011)
- Teleconferenced with FRA to further discuss the critical design aspects of a wheel-rail contact rig; received input from Dr. Pascal, rail dynamics researcher who used a ¼-scale rig for years to conduct rail studies (July 2011)
- Parameter sensitivity studies were performed by Volpe. The results were passed along to VT researchers to be used to help specify certain components of the rig (July 2011)
- Discussions with TTCI have been instrumental in reviewing the work of past studies (August 2011)

1.4 Scope

The following design concepts represent current configurations that have been considered for a test rig. Each design can be constructed as a one-quarter or similarly scaled version, but the feasibility evaluations shown below are based on the full-scale versions. Many of the design aspects are very similar between the scaled and full-scale versions, and any notable differences will be covered in the appropriate sections.

1.5 Organization of the report

All design concepts are grouped in terms of the test article and article constraint. First, single-wheel test rigs are considered, followed by single wheelset rigs. Finally, complete truck testing facilities are investigated. Each design is rated relative to those of the same group, not across groups.

1.5.1 Critical Design Considerations

The proposed test rigs offer common design aspects that should be noted when considering each design type. These design aspects range from the speed control and inputs into the test articles, to the practical limitations of the constraint systems and power requirements. The following sections break down these design considerations and offer guidelines to designers on how to ensure the success of the chosen design path.

Sensor Systems

The most critical aspect of these rigs is the sensor suite that will be used to gather all critical test-article performance. To achieve an ideal test setup and improve upon the current models of the wheel-rail mechanical interface, the sensors must be more comprehensive and exact than any used previously. Precise physical readings of component strain, loading, displacements, vibrations, etc. must be taken to ensure a comprehensive study of the wheel-rail performance.

Test Article Setup (Constraint)

Although the accurate readings of the physical system are of utmost importance to any dynamic study, the test setup must still be designed such that the system is accurately replicating the physical system that the test is set up to represent. In the case of the wheel-rail interface, the test rig designers must consider the following aspects of the design and how they may stray from the actual dynamic system of interest:

- Compliance of the wheel constraint setup (including but not limited to the bearing play, rail stiffness due to one and two point loads, wheel fixture stiffness, and any compliance of systems that control AoA, rail cant, or lateral displacement of the loads)
- Application of power systems to allow various rolling speeds and slip conditions (including but not limited to motor drive systems for the rail (roller), power systems for controlling longitudinal slip, speed/torque control systems, and drive system gearing backlash)
- Wheel constraint setup (including, but not limited to, the integration of wheel force transducers, axle bearing arrangement, and static or dynamic wheel locating mechanisms)

Considering these and other aspects of the test setup during the concept design stage will ensure a successful design path.

Concept Scoring

Once the concept design creation and refinement process was complete, each design was reviewed and scored based on the importance of the following design aspects to the overall design:

- Standard Components Usage
    - Fielded Rail
    - Fielded Wheels
    - Fielded Bogey
- Loads at Speed (Freight)
    - Less than 40 miles per hour (mph)
    - 40–80 mph
    - More than 80 mph
- Loads at Speed (Passenger)
    - Less than 70 mph
    - 70–140 mph
    - More than 140 mph
- Test Article Constraint
    - Angle of Attack (forced-steer)
    - Minimally Constrained Article (hunting)
    - Lateral Position Hold
- Special Conditions
    - Cornering (self-steer)

    - Rail Cant
    - Superelevation
    - Two-Point Contact
    - Switch Simulation
- Data Collection
    - Steady-State Test
    - Strain (Force) Measurement
    - Displacement/Velocity Measurement
- Implementation
    - Current or Past Studies of the Concept
    - Similarity to Typical Rail
    - Actuators
    - System Complexity (Number of System Components)

The scores were initially based on consensus among members of the Virginia Tech design team, but FRA project members later scored the designs separately. With few exceptions, both sets of scores were very similar; they are presented below. As previously stated, each design is rated relative to those of the same group, not across the group sets (single wheel, wheelset, or full truck). The highest-scoring concept will be the basis of future design work.

2. Single-Wheel Test Rig Concepts

Single wheel test rigs are designed to test a single wheel on a rail setup. The single wheel setup is the simplest overall system but does not allow for study of the behavioral interactions associated with a complete suspension setup or the slip and stick of a single axle during cornering operations. Primarily, the testing constraints of the single wheel testing rigs will be used to verify computer simulations at various AoAs, speeds, and slip conditions.

2.1 Potential Advantage of Single-Wheel Test Rigs

As far as control systems, sensor systems, and constraint systems are concerned, a single-wheel test rig offers several potential advantages. The biggest potential advantages are listed below:

- Single wheel design may make integration with wheel load transducers feasible
- Single rail system reduces cost
- Optical sensors get the best vantage point to test specimen, as compared with wheelset and truck test rigs
- Advanced constraint system may allow the most precise control and data collection for AoA testing

2.2 Potential Limitations of Single-Wheel Test Rigs

Just as these system designs have a large number of potential advantages, they also have some potential disadvantages. The potential disadvantages are as follows:

- Wheel constraint and loading systems will likely vary significantly from fielded components to the point where the study of those components (side frames, bearings, suspensions, etc.) will be limited or not possible.
- Hunting studies that minimally constrain the test article are not possible.
- Wheels may require modification for fitment onto a wheel force transducer.

2.3 Single-Wheel Roller Rig Concepts

A roller rig is the most common piece of laboratory test equipment needed to study rail vehicle dynamics because it allows the study of the interaction between a railway wheel and the rail in a controlled environment. The application of roller rigs for studying vehicle system dynamics, development of higher speed trains, study of power or braking ability, and other studies, has continued for many decades.

2.3.1 Vertical Plane Roller (Typical Roller Rig)

This type of roller rig has been used for testing railway vehicles as far back as the turn of the twentieth century. There are various configurations of roller rigs, although the simplest and most common of these is the single-wheel roller (Figure 2). In this configuration, the wheel is placed on one roller that has a profile similar to that of a rail. Typically, this setup allows for adjustment of the simulated weight of the train on the test wheel, the AoA, the rail cant, and other parameters. The rolling rail is usually powered to rotate the wheel up to a specified speed where steady-state testing is performed. Some rigs have the ability to perform dynamic vibration actuation while taking measurements using various sensors.

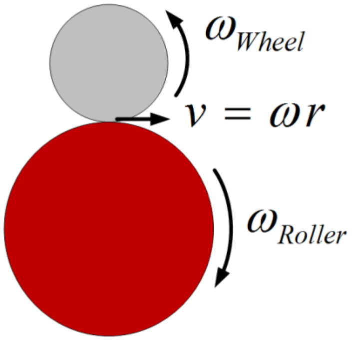


Figure 2. Diagram of a Vertical Plane Roller Rig (conventional orientation)

Relevant Design Information

There is a rich body of literature on various aspects of a roller rig design, both from mathematical modeling and experimental testing viewpoints [5–7] (see Figure 3). The focus of this research project varies significantly from hunting studies to power requirements.

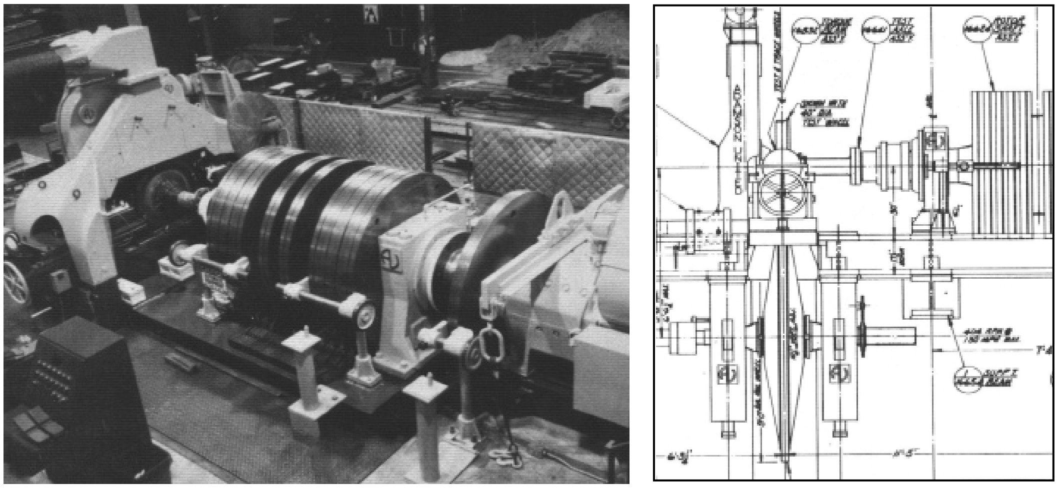


Figure 3. AAR/TTCi Brake Dynamometer (used for brake and fatigue testing, wheel "drives" the rail roller)

Concept Benefits

- Most common design of rail testing rig
- Fielded wheels and other components may be used as test specimens
- Can be coupled with inertial elements to simulate various loading conditions
- Flexibility for accommodating various configurations
- Capable of high speeds
- Wheel may be mounted to a wheel force transducer
- Roller strain gauges may be used for wheel force calculations

Concept Drawbacks

- Fielded rails cannot be tested
- Rail profile not easily altered
- Test data obtained from roller rig experiments have to be correlated with straight rail via mathematical models; they are not precise replications of conventional track

Concept Score

This concept rated the highest of all the single-wheel concepts reviewed. This score was bolstered by the fact that this test rig arrangement is by far the most common, with a rich body of literature to support data obtained from the rigs. The breakdown of the scoring is as follows:

Table 3. Single-Wheel, Vertical Plane Roller Rig Scoring

Test Conditions	Specific Testing Aspect	Vertical Plane Roller (conventional orientation)	
Standard Components Usage	**Fielded Rail**	2	Rail must be modified
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	0	NA
Loads at Speed (Freight)	**<40 mph**	5	Proven design
	40-80 mph	5	
	> 80 mph	5	
Loads at Speed (Passenger)	**<70 mph**	5	Proven design
	70-140 mph	5	
	> 140 mph	5	
Test Article Constraints	**Angle of Attack**	5	Proven design
	Laterally Unconstrained Bolster	0	NA
	Lateral Position Hold	5	Proven design
Special Conditions	**Cornering**	0	NA (AoA tests indirectly)
	Rail Cant	4	Proven design
	Superelevation	0	NA
	Two-point Contact	3	Geometry of rollers dissimilar to straight rail
	Switch Simulation	1	Can be done with special roller
Data Collection	**Steady State Tests**	5	Proven design
	Strain (Force) Measurement	4	Proven design, but expensive if using instrumented wheels, instrumented roller also possible
	Displacement / Velocity Measurement	5	Measurement technologies available
Implementation	**Current or past studies of the concept**	5	Proven design
	Similarity to Typical Rail	3	Geometry of rollers dissimilar to straight rail
	Actuators	5	Proven design
	System Complexity (number of system components)	4	Moderate
Totals (Importance x Implementation Rating)		332	VT score
		378	FRA score

2.3.2 Perpendicular Roller

Another version of the roller rig design has the rollers in the horizontal plane, as shown in Figure 4. In this configuration, the wheel is placed on one roller that has a profile similar to that of a rail but travels in a circular path perpendicular to a typical roller rig. Similar to other roller rigs, this setup can allow adjustment of the simulated weight of the train on the test wheel, the AoA, the rail cant, and other parameters. The rolling rail is usually powered to rotate the wheel up to a specified speed where steady-state testing is performed. While this design concept is untested, it may offer some key advantages over a typical rolling rig.

Relevant Design Information

Unlike other roller rig designs, there is no literature available on this particular design concept from either a mathematical modeling or experimental viewpoint. For this reason, more design work will be required to ensure success. Several key distinctions make this an attractive design concept, even though it scores lower than a typical roller design.

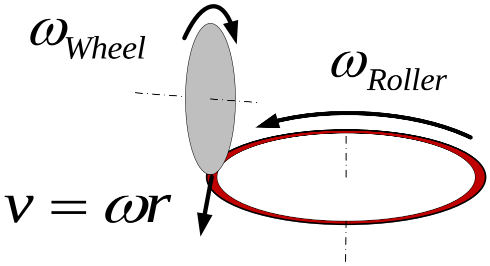


Figure 4. A roller rig design with horizontal roller configuration

Concept Benefits

- An actual rail crown may be used in this configuration, but that decision will ultimately depend on desired top speeds, power availability, operating costs, and other aspects.
- “Flat” rail profile is expected to reduce the result differences from conventional rail. Typical roller rigs suffer from having longitudinal creep behavior that varies from flat track due to the curvature of the rolling rail.
- Underside of rail roller below the contact patch could be supported by bearings that allow real-time adjustments of the vertical stiffness of the simulated track.

Concept Drawbacks

- Large moments are created because of the large radius of the roller. This implies that auxiliary bearings will be required to counteract those forces.
- Concept has never been implemented and no known literature exists concerning this design.

Concept Score

This concept rated in the top three of all the single-wheel concepts reviewed, even though, in some categories, it did not score as high as some of the previous concepts because of lack of past data. This design, however, offers the intriguing possibility of eliminating the contact patch distortion that is often cited as a negative element conventional roller rigs.

The scoring breakdown is as follows:

Table 4. Single-Wheel, Horizontal Roller Rig Scoring

Test Conditions	Specific Testing Aspect	Horizontal Roller (perp. orientation)	
Standard Components Usage	**Fielded Rail**	2	Rail must be modified
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	0	NA
Loads at Speed (Freight)	**<40 mph**	4	Bearing surface needed for offset load
	40-80 mph	4	
	> 80 mph	4	
Loads at Speed (Passenger)	**<70 mph**	4	Bearing surface needed for offset load
	70-140 mph	4	
	> 140 mph	4	
Test Article Constraints	**Angle of Attack**	5	Similar to vert plane roller
	Laterally Unconstrained Bolster	0	NA
	Lateral Position Hold	5	similar to vert plane roller
Special Conditions	**Cornering**	0	NA (AoA tests indirectly)
	Rail Cant	4	Similar to vert plane roller
	Superelevation	0	NA
	Two-point Contact	3	Geometry of rollers dissimilar to straight rail
	Switch Simulation	1	Can be done with special roller
Data Collection	**Steady State Tests**	5	Similar to vert plane roller
	Strain (Force) Measurement	4	Conventional force measurement systems may be integrated into this setup
	Displacement / Velocity Measurement	5	Similar to vert plane roller
Implementation	**Current or past studies of the concept**	0	No literature available
	Similarity to Typical Rail	3	Geometry of rollers dissimilar to straight rail
	Actuators	5	Similar to vert plane roller
	System Complexity (number of system components)	4	Moderate
Totals (Importance x Implementation Rating)		293	VT score
		333	FRA score

2.3.3 *Tangent Roller, Internal*

In this variation of the roller rig design, the wheel is internally contacting the roller, as shown in Figure 5. Examples of this concept can be found in roller rigs that are used for transit rail and automotive tire studies.

Relevant Design Information

As previously stated, this concept has been implemented for city transit rail vehicles with a rig being built by Fraunhofer LBF. Although similar to a typical roller rig, it is important to note that this rig is naturally stabilizing due to the geometric effects of the rail radius.

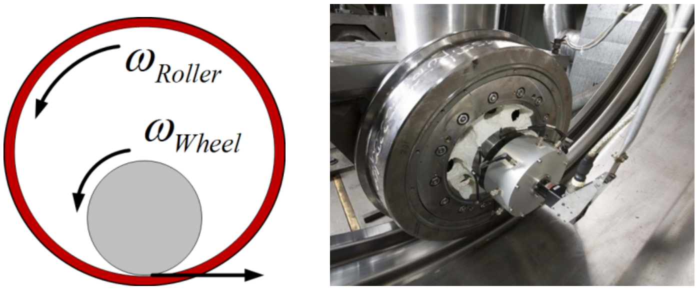


Figure 5. A roller rig diagram with internal tangent roller and a produced example (Fraunhofer LBF)

<u>Concept Benefits</u>

- More stable than the external roller configuration
- Previously implemented
- Used in automotive industry

<u>Concept Drawbacks</u>

- Large roller (cylinder) will have very large mass
- Not common design
- Bearing placement not ideal for taking high normal loads

Concept Score

The score of this concept was the second highest of the single wheel designs, just besting the perpendicular roller idea by a small percentage. It is important to note, however, that obtaining the desired high speeds for this concept would probably be significantly more costly than doing so for a conventional roller rig because of the likelihood of a much larger rotating mass.

Table 5. Single-Wheel, Internal Vertical Plane Roller Rig Scoring

Test Conditions	Specific Testing Aspect	Internal Vertical Plane Roller	
Standard Components Usage	**Fielded Rail**	2	Rail must be modified
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	0	NA
Loads at Speed (Freight)	**<40 mph**	4	Offset loading requires bigger bearing
	40-80 mph	4	
	> 80 mph	4	
Loads at Speed (Passenger)	**<70 mph**	4	Offset loading requires bigger bearing
	70-140 mph	4	
	> 140 mph	4	
Test Article Constraints	**Angle of Attack**	5	Proven design
	Laterally Unconstrained Bolster	0	NA
	Lateral Position Hold	5	Proven design
Special Conditions	**Cornering**	0	NA (AoA tests indirectly)
	Rail Cant	4	Similar to vert plane roller
	Superelevation	0	NA
	Two-point Contact	3	Geometry of rollers dissimilar to straight rail
	Switch Simulation	1	Can be done with special roller
Data Collection	**Steady State Tests**	5	Proven design
	Strain (Force) Measurement	4	Similar to both roller designs
	Displacement / Velocity Measurement	5	Similar to both roller designs
Implementation	**Current or past studies of the concept**	2	Some studies performed, similar to automotive test rigs
	Similarity to Typical Rail	3	Geometry of rollers dissimilar to straight rail
	Actuators	5	Similar to both roller designs
	System Complexity (number of system components)	4	Moderate
Totals (Importance x Implementation Rating)		299	VT score
		340	FRA score

2.4 Stationary Wheel, Track in Motion

To avoid some of the problems associated with conventional roller rigs (such as the longitudinal creep dissimilarity to conventional rail), researchers considered the design of a test rig that utilizes a section of conventional rail for the repeatable laboratory testing.

2.4.1 Short Stroke Oscillating Rail

The most feasible of flat rail testing rigs utilizes a short length of rail, which is passed underneath a rail wheel. This length of rail is moved forward and backward under the wheel to simulate track conditions. Oscillating test machines such as these have been built and are in use; however, they have primarily been used for testing rail strength or joint bar fatigue.

Relevant Design Information

The oscillating rail concept included the use of a short length of rail on a bearing platform that allows the rail to move back and forth relative to the wheel, in a reciprocating motion. While antiquated versions of this concept rely on mechanical actuators to oscillate the rail, at least one modern version of this concept has been created that uses hydraulic actuators to apply normal loading on the wheel and positioning the rail (Figure 6).

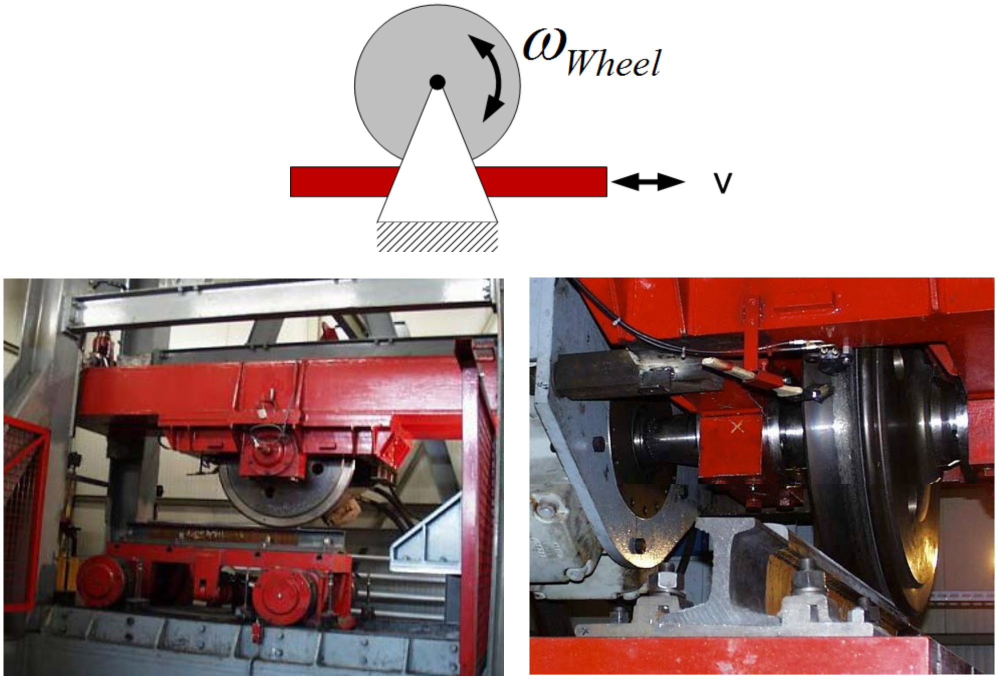


Figure 6. Oscillating Rail Rig Diagram and Produced Design

Concept Benefits

- Equivalent behavior to conventional rail
- Previously implemented
- Simple to implement

<u>Concept Drawbacks</u>

- Low speeds only
- Steady-state testing not possible

Concept Score

The poor concept scores for this design reflect the anticipated performance in terms of high speed testing.

Table 6. Single-Wheel, Oscillating Flat Rail Rig Scoring

Test Conditions	Specific Testing Aspect	Oscillating Flat Rail, short stroke (~1-2m)	
Standard Components Usage	**Fielded Rail**	5	Easily used
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	0	NA
Loads at Speed (Freight)	**<40 mph**	1	Cannot achieve high speeds
	40-80 mph	0	
	> 80 mph	0	
Loads at Speed (Passenger)	**<70 mph**	1	Cannot achieve high speeds
	70-140 mph	0	
	> 140 mph	0	
Test Article Constraints	**Angle of Attack**	5	Proven design
	Laterally Unconstrained Bolster	0	NA
	Lateral Position Hold	5	Proven design
Special Conditions	**Cornering**	0	NA (AoA tests indirectly)
	Rail Cant	5	Proven design
	Superelevation	0	NA
	Two-point Contact	5	Equivalent rail geometry
	Switch Simulation	5	Piece of switch track may be used
Data Collection	**Steady State Tests**	1	Not possible due to small length of rail
	Strain (Force) Measurement	4	Proven design
	Displacement / Velocity Measurement	5	Proven design
Implementation	**Current or past studies of the concept**	5	Proven design
	Similarity to Typical Rail	5	Equivalent rail geometry
	Actuators	5	Proven design
	System Complexity (number of system components)	5	Simple
Totals (Importance x Implementation Rating)		241	VT score
		285	FRA score

2.4.2 High Speed Shooting Rail

As an alternative to the oscillating rail idea, a high-speed shooting rail concept was envisioned. Using a rail panel of 30 – 40 feet long, this design propels the rail at high speeds along adjustable guides that constrain the rail under the wheel assembly, as depicted in Figure 7.

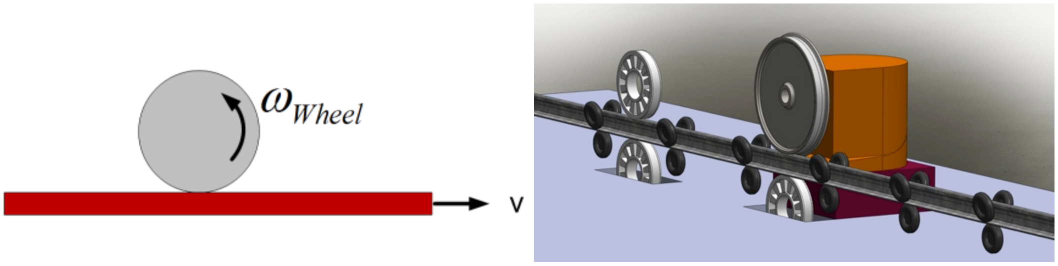


Figure 7. Stationary bogey, track in motion

Relevant Design Information

The greatest limiting factor of this type of design, as with the previous design, is the difficulty associated with the acceleration of the rail to elevated test speeds. For example, consider the acceleration of 115 pound/yard rail (very light rail) to a speed of 220 mph. Neglecting the weight of guide bearings or other necessary components for such a device, and assuming a constant acceleration of the rail, it is found that regardless of the length of rail, the force required is 60 kip. If a 50-foot section of rail were chosen, the acceleration of the rail needed (just to *reach* 220 mph) would be 31 times the acceleration of gravity. For this reason, high speed testing on such a rig is improbable.

<u>Concept Benefits</u>

- Contact mechanics equivalent to typical

<u>Concept Drawbacks</u>

- Huge loads required to accelerate the track to high speeds
- Constraining the rail could be difficult depending on the speeds and conditions required

Concept Score

The scores of this design reflect the drawbacks previously discussed: huge loads are required to reach high speeds for this concept and the rail guide system will likely be very complex and will add significantly to the friction forces that need to be overcome.

Table 7. Single-Wheel, Shooting Rail Rig Scoring

Test Conditions	Specific Testing Aspect	Shooting Flat Rail, long stroke	
Standard Components Usage	**Fielded Rail**	3	Fielded rail too heavy
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	0	NA
Loads at Speed (Freight)	**<40 mph**	3	Refer to calcs
	40-80 mph	2	
	> 80 mph	1	
Loads at Speed (Passenger)	**<70 mph**	2	Refer to calcs
	70-140 mph	1	
	> 140 mph	0	
Test Article Constraints	**Angle of Attack**	5	Similar to oscillating flat rail design
	Laterally Unconstrained Bolster	0	NA
	Lateral Position Hold	5	Similar to oscillating flat rail design
Special Conditions	**Cornering**	0	NA (AoA tests indirectly)
	Rail Cant	5	Similar to oscillating flat rail design
	Superelevation	0	NA
	Two-point Contact	5	Equivalent rail geometry
	Switch Simulation	2	Piece of switch track may be used
Data Collection	**Steady State Tests**	2	Longer rails allow better steady state conditions
	Strain (Force) Measurement	4	Similar to oscillating flat rail design
	Displacement / Velocity Measurement	4	Contactless measurement technologies must be utilized
Implementation	**Current or past studies of the concept**	0	No literature available
	Similarity to Typical Rail	5	Equivalent rail geometry
	Actuators	1	Massive forces needed over a great distance
	System Complexity (number of system components)	1	Very complex facility req'd
Totals (Importance x Implementation Rating)		211	VT score
		253	FRA score

2.5 Modified Rail (Crown and Gauge Face)

Another concept was developed to combine the contact mechanics similarities of the flat-rail design, but allow the capability of obtaining higher test speeds. In this configuration, a modified rail crown will be used as the rail and it will be passed under the rail wheel in the same way an automotive rolling road tester performs.

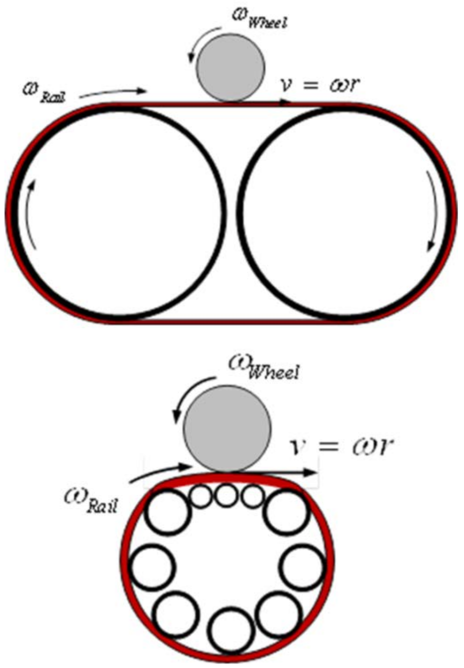


Figure 8. Roller rigs diagrams with modified rail crown

Relevant Design Information

Although this configuration uses a modified rail crown, the roller diameters should be large enough to allow deflection of the rail in the elastic region.

Concept Benefits

- Continuous testing of wheels
- Uses a field rail crown for testing. This will allow for investigation of wheel-rail interaction under real operating conditions.

Concept Drawbacks

- Possible plastic deformation of the rail crown will greatly reduce the time between belt replacements.
- Stress on rail may exceed the limits of the material at higher loads and speeds.
- Rail band placement and control may be difficult.

Concept Score

Although this test design is unlike anything in the rail industry, automotive rolling dynamometers provide significant similarities, although at much lighter loads and, typically, speeds less than 180 mph.

Table 8. Single-Wheel, Continuous Rail Band Roller Rig Scoring

Test Conditions	Specific Testing Aspect	Continuous Deformable Rail Band Roller	
Standard Components Usage	**Fielded Rail**	2	Must be modified
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	0	NA
Loads at Speed (Freight)	**<40 mph**	4	Automotive rolling roads exist, but high loads and high speeds are uncertain
	40-80 mph	3	
	> 80 mph	2	
Loads at Speed (Passenger)	**<70 mph**	4	Automotive rolling roads exist, but high loads and high speeds are uncertain
	70-140 mph	3	
	> 140 mph	2	
Test Article Constraints	**Angle of Attack**	5	Proven design for automotive applications
	Laterally Unconstrained Bolster	0	NA
	Lateral Position Hold	5	Proven design for automotive applications
Special Conditions	**Cornering**	0	NA (AoA tests indirectly)
	Rail Cant	5	Deformable rail band may be tilted
	Superelevation	0	NA
	Two-point Contact	4	Second band required but allows for same linear speed at both contact points
	Switch Simulation	0	Implausible condition
Data Collection	**Steady State Tests**	5	Similar to automotive testing
	Strain (Force) Measurement	4	Proven technologies exist
	Displacement / Velocity Measurement	5	Similar to automotive testing
Implementation	**Current or past studies of the concept**	3	Similar to automotive testing
	Similarity to Typical Rail	4	Similar geometry but not real rail
	Actuators	4	Similar to automotive testing
	System Complexity (number of system components)	3	Similar to automotive testing
Totals (Importance x Implementation Rating)		275	VT score
		321	FRA score

3. Wheelset Concepts

Wheelset test rigs are designed to test a single wheelset on a rail setup. The single wheelset setup significantly increases system complexity over the single-wheel design, but offers advantages such as the ability to study the interaction associated with a complete suspension setup or the stick-slip dynamics of a single axle during cornering. A single-wheel rig, however, cannot be used for hunting studies. Primarily, the testing constraints of a single wheelset test rig will allow verification of computer simulations at various AoAs, speeds, and slip conditions, yet may also allow testing of the axle in stock bearings, sideframe, and truck assemblies to quantify their behavior.

3.1 Potential Advantages of Wheelset Test Rigs

There are several potential advantages of a wheelset test rig related to control systems, sensor systems, and constraint systems. The biggest potential advantages are listed below:

- Wheelset rail systems may allow for curvature studies
- Wheelset rig may be used to test complete suspension compliance (if bogey is still one unit)
- Wheel constraint and loading systems may be designed to closely replicate that of fielded components, giving the rig ability to accurately study those components (side frames, bearings, suspensions, etc.)

3.2 Potential Limitations of Single-Wheel Test Rigs

Just as these system designs have a large number of potential advantages, they also have some potential disadvantages. The potential disadvantages are listed below:

- Wheelset test rig requires additional rolling rail, significantly increasing the cost and control system complexity.
- Single wheelset design will greatly increase complexity of wheel force transducer integration.
- Optical sensors may prove to be less effective for monitoring wheel-rail contact patch as compared with a single wheel rig because of a more limited line of sight.
- Constraint system must have increased complexity to allow precise control and data collection of AoA testing.
- Hunting studies that minimally constrain the test article may not be possible.
- Wheels may require modification for fitment onto a wheel force transducer.

3.3 Single-Wheelset Roller Rig Concepts

3.3.1 Vertical Plane Roller, (Typical Roller Rig)

As stated in Section 2.3, this is the most common type of rig for testing railway vehicle dynamics in the laboratory. However, there is little information regarding this type of rig as this design is relatively recent. An example of this rig has been produced by Renk of Germany (see Figure 9.

Renk wheelset test rig for high-speed rail). In this configuration, a wheelset is placed on two independently controlled rollers that have a profile similar to that of a rail. Among other changes possible, this setup would enable simulating loading, angle of attack, and rail cant.

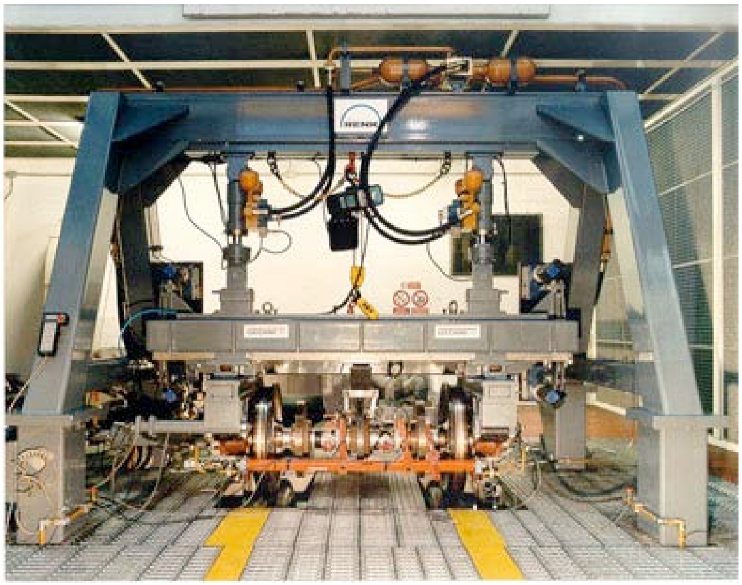


Figure 9. Renk wheelset test rig for high-speed rail

Relevant Design Information

A wide range of literature is available for single-wheel and full truck or car roller rigs which may be applied to a wheelset test rig. This design of rig could reproduce curving dynamics, although the differential speeds of the rollers would require extremely precise control for accurate slip measurements. Also, wheelset hunting tests may be possible but the constraint system must be designed to allow such a test. This system design still suffers from having contact mechanics that are different from conventional rail, just like the single wheel design concept.

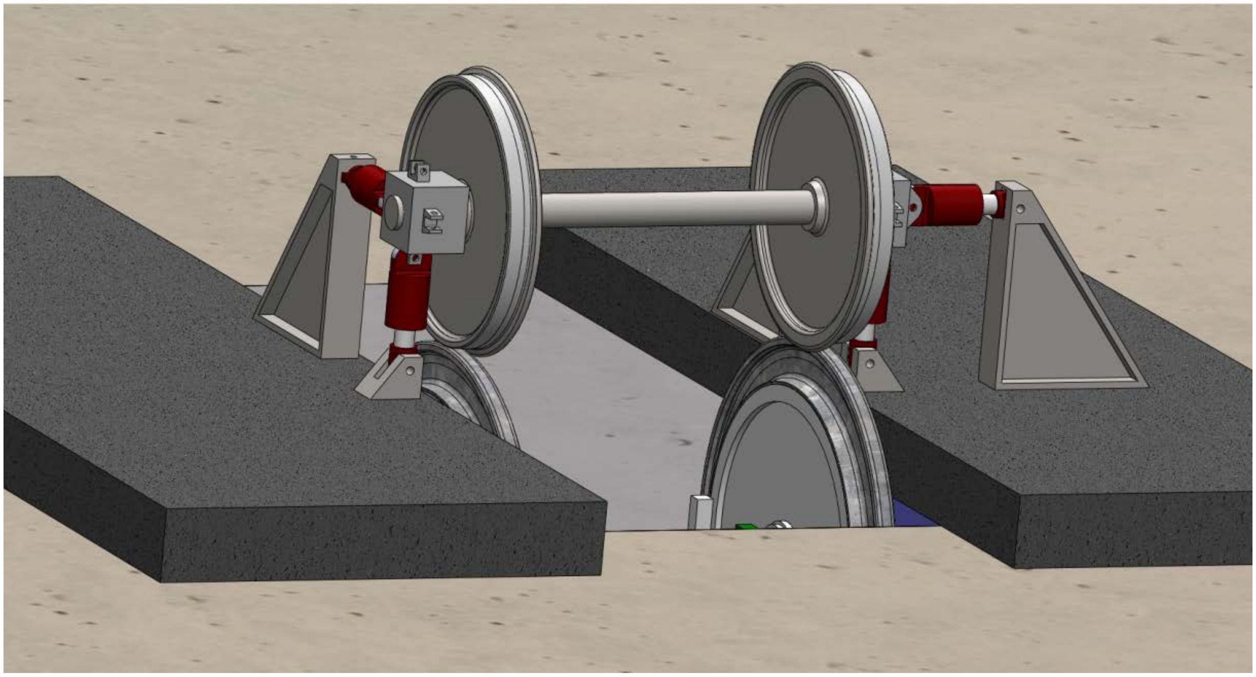


Figure 10. Concept of a wheelset roller test rig

<u>Concept Benefits</u>

- Most common design of rail testing rig
- Fielded wheels and other components may be used as test specimens
- Flexibility for accommodating various configurations
- Capable of high speeds
- Roller strain gauges may be used for wheel force measurements
- Curvature testing is possible, although AoA tests introduce more instability due to geometric effects of the rail roller radius

<u>Concept Drawbacks</u>

- Fielded rails cannot be tested
- Rail profile is not easily altered
- Cannot be easily coupled with inertial elements to simulate various loading conditions
- Test data obtained from roller rig experiments have to be correlated with straight rail via mathematical models, in order to replicate field data.

Concept Score

Like the single wheel design, the vertical plane roller scored the highest of all the wheelset concepts.

Table 9. Wheelset Vertical Plane Roller Rig Scoring

Test Conditions	Specific Testing Aspect	Individual Vertical Plane Rollers (conventional orientation)	
Standard Components Usage	**Fielded Rail**	2	Rail must be modified
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	0	NA
Loads at Speed (Freight)	**<40 mph**	5	Similar to proven single wheel
	40-80 mph	5	
	> 80 mph	5	
Loads at Speed (Passenger)	**<70 mph**	5	Similar to proven single wheel
	70-140 mph	5	
	> 140 mph	5	
Test Article Constraints	**Angle of Attack**	5	Similar to proven single wheel
	Laterally Unconstrained Bolster	0	NA
	Lateral Position Hold	5	Similar to proven single wheel
Special Conditions	**Cornering**	5	Differential speeds possible
	Rail Cant	4	Proven design
	Superelevation	5	Proven for full bogies
	Two-point Contact	3	Geometry of rollers dissimilar to straight rail
	Switch Simulation	1	Can be done with special roller
Data Collection	**Steady State Tests**	5	Proven design
	Strain (Force) Measurement	4	Proven design, but expensive if using instrumented wheels, instrumented roller also possible
	Displacement / Velocity Measurement	5	Measurement technologies available
Implementation	**Current or past studies of the concept**	3	Similar to single wheel and bogie designs
	Similarity to Typical Rail	3	Geometry of rollers dissimilar to straight rail
	Actuators	5	Proven actuation technologies
	System Complexity (number of system components)	3	Moderate
Totals (Importance x Implementation Rating)		357	VT score
		410	FRA score

3.3.2 Perpendicular Roller

Again, in this configuration, each wheel is placed on a roller that has a profile similar to that of a rail but travels in a circular path perpendicular to a typical roller rig. Similar to the single wheel setup, this setup allows adjustment of the simulated weight of the train on the test wheel, the AoA, the rail cant, in addition to differential rail speeds, rail cant, or superelevation, if so equipped. The rolling rail is intended to power to rotate the wheel up to a specified speed where steady-state testing is performed. While this concept is untested, it may offer some key advantages over a typical rolling rig.

Relevant Design Information

Unlike previous roller rig designs, there is no literature available directly pertaining to this particular design concept from either a mathematical modeling or experimental viewpoints. For this reason, more design work will be required to ensure a successful design. However, several key distinctions make this an attractive design concept, even though it scores lower than a typical roller design.

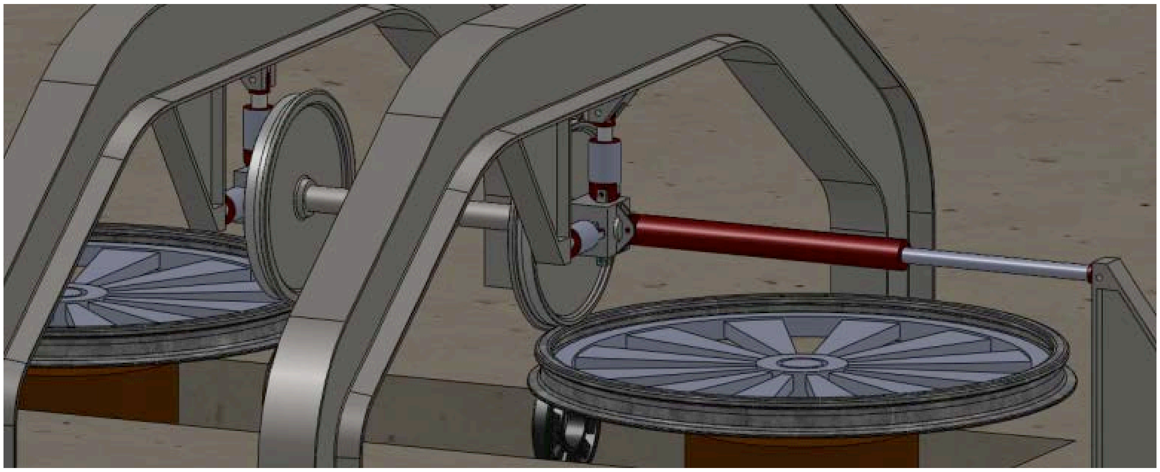


Figure 11. A roller rig design with horizontal roller configuration

<u>Concept Benefits</u>

- An actual rail crown may be used in this configuration, but that decision will ultimately depend on desired top speeds, power availability, operating costs, and other aspects.
- “Flat” rail profile is expected to reduce the result differences from conventional rail. Typical roller rigs suffer from having longitudinal creep behavior that varies from flat track due to the curvature of the rolling rail.
- Underside of rail roller below the contact patch could be supported by bearings that allow real-time adjustments of the vertical stiffness of the simulated track.
- Differential speeds needed for curving studies will be possible.

Concept Drawbacks

- Large moments are created because of the large radius of the roller. This implies that auxiliary bearings will be required to counteract these forces.
- Concept has never been implemented and no known literature existed concerning this design.
- Differential speed systems will likely require two separate drive systems (rather than the use of a quill drive).
- Drive system control must be extremely precise for accurate slip condition testing.

Concept Score

This concept rated second of all the wheelset concepts reviewed. This score was hampered by the fact that there is no available literature on this design concept. Although having two separate drive systems will raise the cost, this concept does offer the intriguing possibility of avoiding the limitation that a conventional roller rig suffers where longitudinal creep behavior is concerned. The breakdown of the scoring is as follows:

Table 10. Wheelset Horizontal Plane Roller Rig Scoring

Test Conditions	Specific Testing Aspect	Individual Horizontal Rollers (perp. orientation)	
Standard Components Usage	**Fielded Rail**	2	Rail must be modified
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	0	NA
Loads at Speed (Freight)	**<40 mph**	4	Bearing surface needed for offset load
	40-80 mph	4	
	> 80 mph	4	
Loads at Speed (Passenger)	**<70 mph**	4	Bearing surface needed for offset load
	70-140 mph	4	
	> 140 mph	4	
Test Article Constraints	**Angle of Attack**	5	Similar to vert plane roller
	Laterally Unconstrained Bolster	0	NA
	Lateral Position Hold	5	Similar to vert plane roller
Special Conditions	**Cornering**	5	Differential speeds possible
	Rail Cant	4	Similar to vert plane roller
	Superelevation	5	Similar to vert plane roller
	Two-point Contact	3	Geometry of rollers dissimilar to straight rail
	Switch Simulation	1	Can be done with special roller
Data Collection	**Steady State Tests**	5	Similar to vert plane roller
	Strain (Force) Measurement	4	Conventional force measurement systems may be integrated into this setup
	Displacement / Velocity Measurement	5	Similar to vert plane roller
Implementation	**Current or past studies of the concept**	0	No literature available
	Similarity to Typical Rail	3	Geometry of rollers dissimilar to straight rail
	Actuators	5	Similar to vert plane roller
	System Complexity (number of system components)	3	Moderate
Totals (Importance x Implementation Rating)		324	VT score
		372	FRA score

3.3.3 *Tangent Roller, Internal*

In this variation of the roller rig design, the wheels are internally contacting two separate rollers. While one single-wheel example of this design and many others examples of tire testing rigs in automotive laboratories have been found for rail transit use, no designs have been implemented for wheelset use, most likely because of the practical limitations of constraining such a design.

Relevant Design Information

As previously stated, this concept has been implemented for city transit rail vehicles as a single-wheel test rig (see section 2.3.3). Although similar to a typical roller rig, it is important to note that, unlike a conventional roller, this rig is naturally stabilizing due to the geometric effects of the rail radius.

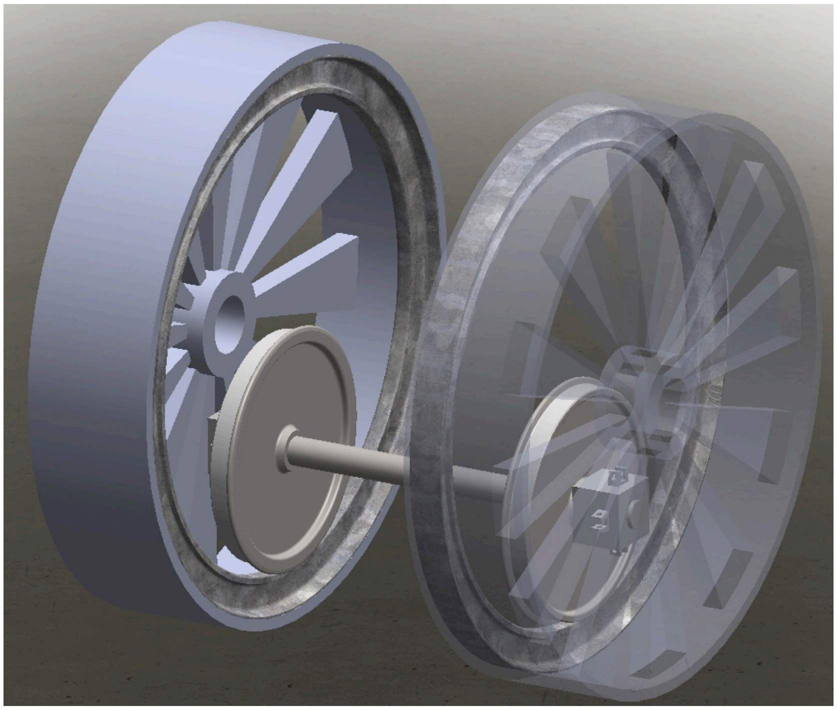


Figure 12. A roller rig with internal tangent roller shows the difficulty with axle constraints

Concept Benefits

- More stable than the external roller configuration
- Single-wheel designs have been used in automotive and rail transit studies and industry

Concept Drawbacks

- Axle constraint system not feasible for most truck designs
- Large rollers (cylinder) will have very large mass
- Rolling rail bearing placement not ideal for taking high normal loads

Concept Score

Unlike the single wheel design, the score of this concept was the second lowest of the wheelset designs. This low score is a result of the impracticality of implementing this design considering the wheelset bearing placement inside the roller drum, which would require unusual constraint systems that most likely do not meet stiffness and loading requirements. It is also important to note that obtaining the desired high speeds for this concept would possibly be significantly more costly than doing so for a conventional roller rig because of the likelihood of a much larger rotating mass.

Table 11. Wheelset Internal Vertical Plane Roller Rig Scoring

Test Conditions	Specific Testing Aspect	Individual Internal Vertical Plane Rollers	
Standard Components Usage	**Fielded Rail**	2	Rail must be modified
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	0	NA
Loads at Speed (Freight)	**<40 mph**	1	Not feasible due to space constraints
	40-80 mph	1	
	> 80 mph	1	
Loads at Speed (Passenger)	**<70 mph**	1	Not feasible due to space constraints
	70-140 mph	1	
	> 140 mph	1	
Test Article Constraints	**Angle of Attack**	3	Difficult due to space constraints
	Laterally Unconstrained Bolster	2	Roller geometry induces some stability
	Lateral Position Hold	3	Difficult due to space constraints
Special Conditions	**Cornering**	5	Differential speeds possible
	Rail Cant	4	Similar to vert plane roller
	Superelevation	5	Similar to vert plane roller
	Two-point Contact	3	Geometry of rollers dissimilar to straight rail
	Switch Simulation	1	Can be done with special roller
Data Collection	**Steady State Tests**	5	Proven design
	Strain (Force) Measurement	4	Similar to both roller designs
	Displacement / Velocity Measurement	5	Similar to both roller designs
Implementation	**Current or past studies of the concept**	1	Single wheel studies performed
	Similarity to Typical Rail	3	Geometry of rollers dissimilar to straight rail
	Actuators	5	Similar to both roller designs
	System Complexity (number of system components)	3	Moderate
Totals (Importance x Implementation Rating)		241	VT score
		282	FRA score

3.3.4 Drum Roller

A variation of the Vertical Plane Roller (section 5.3.1) is where the rail rollers rotate at the same angular velocity (no differential speeds). These types of rigs have been used for bogey or full car test rigs, usually for hunting or braking test rigs, but not to study curving or contact mechanics. The primary advantage of this type of rig is reduced cost and complexity compared with the individual vertical plane roller. Although this setup allows simulating loading and the AoA, it does not enable making adjustments for superelevation and rail cant.

Relevant Design Information

Literature is available on full truck or complete car drum roller rigs and may be applied to a wheelset test rig. This rig design could not reproduce curving dynamics. Wheelset hunting tests may be possible but the constraint system must be designed to allow for such a test. This system design still suffers from having contact mechanics that vary from conventional rail.

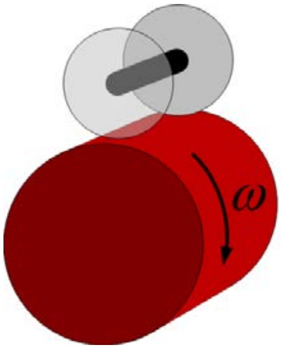


Figure 13. Simple diagram of wheelset on a drum roller

<u>Concept Benefits</u>

- Simple variation of the most common design of rail testing rig
- Fielded wheels and other components may be used as test specimens
- Can be coupled with inertial elements to simulate various loading conditions
- Flexibility for accommodating various configurations
- Capable of high speeds
- Wheel may be mounted to a wheel force transducer
- Roller strain gauges may be used for wheel force calculations

<u>Concept Drawbacks</u>

- Fielded rails cannot be tested
- Rail profile not easily altered
- Test data obtained from roller rig experiments have to be correlated to straight rail via mathematical models; they are not precise replications of conventional track
- Differential speed testing (curving) is not possible
- AoA tests introduce instability due to geometric effects of the rail roller radius compared with the normal force

Concept Score

The drum roller design scored reasonably well due to its use in past and ongoing studies.

Table 12. Wheelset Drum Roller Rig Scoring

Test Conditions	Specific Testing Aspect	Drum Roller	
Standard Components Usage	**Fielded Rail**	2	Rail must be modified
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	0	NA
Loads at Speed (Freight)	**<40 mph**	5	Proven for full bogies
	40-80 mph	5	
	> 80 mph	5	
Loads at Speed (Passenger)	**<70 mph**	5	Proven for full bogies
	70-140 mph	5	
	> 140 mph	5	
Test Article Constraints	**Angle of Attack**	5	Similar to proven single wheel
	Laterally Unconstrained Bolster	0	NA
	Lateral Position Hold	5	Similar to proven single wheel
Special Conditions	**Cornering**	0	NA
	Rail Cant	2	Shim rails
	Superelevation	0	NA
	Two-point Contact	3	Geometry of rollers dissimilar to straight rail
	Switch Simulation	1	Can be done with special roller
Data Collection	**Steady State Tests**	5	Proven design
	Strain (Force) Measurement	4	Proven design, but expensive if using instrumented wheels, instrumented roller also possible
	Displacement / Velocity Measurement	5	Measurement technologies available
Implementation	**Current or past studies of the concept**	3	Similar to single wheel and bogie designs
	Similarity to Typical Rail	3	Geometry of rollers dissimilar to straight rail
	Actuators	5	Similar to vert plane roller
	System Complexity (number of system components)	5	Simple
Totals (Importance x Implementation Rating)		326	VT score
		367	FRA score

3.4 Stationary Wheel, Track in Motion

Wheelset concepts were investigated to avoid some of the problems associated with conventional roller rigs (such as the longitudinal creep dissimilarity to conventional rail). For this reason, researchers considered test rig designs that utilize a section of conventional rail for repeatable laboratory testing.

3.4.1 Short Stroke Oscillating Rail

The most feasible of flat rail testing rigs utilizes a short length of rail, which is passed underneath a rail wheel. This length of rail is moved forward and backward under the wheel to simulate track conditions. Single wheel versions of oscillating test machines have been built and are in use; however, they have primarily been used for testing rail strength or joint bar fatigue.

Relevant Design Information

The oscillating rail concept considers the use of a short length of rail on the bearing platform, longitudinally displaced beneath a rail wheel. While antiquated versions of this concept rely on mechanical actuators to oscillate the rail, at least one modern version of this concept has been created that uses hydraulic actuators to apply normal loading on the wheel and position the rail (Figure 14). However, no known wheelset testing machines of this type have been designed or produced.

Figure 14. Single wheel test rig shown as an example of layout

<u>Concept Benefits</u>

- Equivalent behavior to conventional rail
- Single wheel versions have been previously implemented
- Simple to implement
- Depending on design, differential speeds possible
- Superelevation and rail cant are possible

<u>Concept Drawbacks</u>

- Low speeds only
- Steady-state testing not possible

Concept Score

The poor concept scores for this design reflect the anticipated performance with regard to high speed testing.

Table 13. Wheelset Oscillating Rail Rig Scoring

Test Conditions	Specific Testing Aspect	Oscillating Flat Rail, short stroke (~1-2m)	
Standard Components Usage	**Fielded Rail**	5	Easily used
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	0	NA
Loads at Speed (Freight)	**<40 mph**	1	Cannot achieve high speeds
	40-80 mph	0	
	> 80 mph	0	
Loads at Speed (Passenger)	**<70 mph**	1	Cannot achieve high speeds
	70-140 mph	0	
	> 140 mph	0	
Test Article Constraints	**Angle of Attack**	5	Similar to single wheel design
	Laterally Unconstrained Bolster	0	NA
	Lateral Position Hold	5	Similar to single wheel design
Special Conditions	**Cornering**	5	Differential speeds possible
	Rail Cant	5	Proven design
	Superelevation	5	Possible
	Two-point Contact	5	Equivalent rail geometry
	Switch Simulation	5	Piece of switch track may be used
Data Collection	**Steady State Tests**	1	Not possible due to small length of rail
	Strain (Force) Measurement	4	Proven design
	Displacement / Velocity Measurement	5	Proven design
Implementation	**Current or past studies of the concept**	3	Similar to single wheel designs
	Similarity to Typical Rail	5	Equivalent rail geometry
	Actuators	5	Equivalent to single rail
	System Complexity (number of system components)	4	Somewhat moderate
Totals (Importance x Implementation Rating)		266	VT score
		317	FRA score

3.4.2 High Speed Shooting Rail

Unlike the oscillating rail design that can only be run at lower speeds, the shooting rail concept can simulate far higher speeds, while keeping the contact patch undistorted. This design would utilize two rails that pass through adjustable guides that constrain the rail under the wheelset assembly (Figure 15).

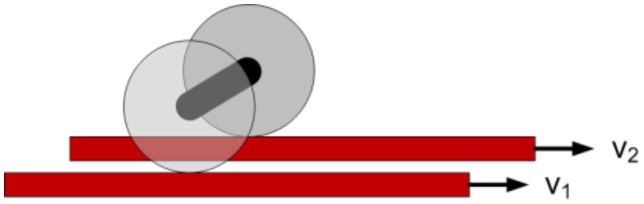


Figure 15. Stationary wheelset, track in motion

Relevant Design Information

The greatest limiting factor of this type of design, as with the previous design, is the difficulty associated with the acceleration of the rail to elevated test speeds. For example, consider the acceleration of a single, 115 pound/yard rail (very light rail) to a speed of 220 mph. Neglecting the weight of guide bearings or other necessary components for such a device, and assuming a constant acceleration of the rail, it is found that regardless of the length of rail, the force required is 60 kip (the time it takes to accelerate to speed varies depending on the length). If a 50-foot section of rail were chosen, the acceleration of the rail needed (just to *reach* 220 mph) would be 31 times the acceleration of gravity. For this reason, high speed testing on such a rig is highly improbable.

<u>Concept Benefits</u>

- Contact mechanics equivalent to typical
- Differential speeds theoretically possible

<u>Concept Drawbacks</u>

- Huge loads required to accelerate the track to high speeds
- Constraining the rail would be difficult depending on the speeds and conditions required

Concept Score

The scores of this design (provided in Table 14) reflect the drawbacks previously discussed: huge loads are required to reach high speeds for this concept and the rail guide system will likely be very complex and will add significantly to the friction forces that need to be overcome.

Table 14. Wheelset Shooting Rail Rig Scoring

Test Conditions	Specific Testing Aspect	Shooting Flat Rail, long stroke	
Standard Components Usage	**Fielded Rail**	3	Fielded rail too heavy
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	0	NA
Loads at Speed (Freight)	**<40 mph**	2	Refer to calcs
	40-80 mph	1	
	> 80 mph	0	
Loads at Speed (Passenger)	**<70 mph**	1	Refer to calcs
	70-140 mph	0	
	> 140 mph	0	
Test Article Constraints	**Angle of Attack**	5	Similar to oscillating flat rail design
	Laterally Unconstrained Bolster	0	NA
	Lateral Position Hold	5	Similar to oscillating flat rail design
Special Conditions	**Cornering**	5	Differential speeds possible
	Rail Cant	5	Similar to oscillating flat rail design
	Superelevation	5	Possible
	Two-point Contact	5	Equivalent rail geometry
	Switch Simulation	2	Piece of switch track may be used
Data Collection	**Steady State Tests**	2	Longer rails allow better steady state conditions
	Strain (Force) Measurement	4	Similar to oscillating flat rail design
	Displacement / Velocity Measurement	4	Contactless measurement technologies must be utilized
Implementation	**Current or past studies of the concept**	0	No literature available
	Similarity to Typical Rail	5	Equivalent rail geometry
	Actuators	1	Massive forces needed over a great distance
	System Complexity (number of system components)	1	Very complex facility req'd
Totals (Importance x Implementation Rating)		227	VT score
		273	FRA score

3.5 Modified Rail (Crown and Gauge Face)

The final concept for testing a wheelset is the modified rail (continuous rail band). As previously outlined for the single-wheel design, this concept allows testing at higher speeds while maintaining the flat rail contact mechanics. In this configuration, two rail bands will be used as the rail surface and will be passed under the rail wheel in the same way an automotive rolling road tester performs (see Figure 16).

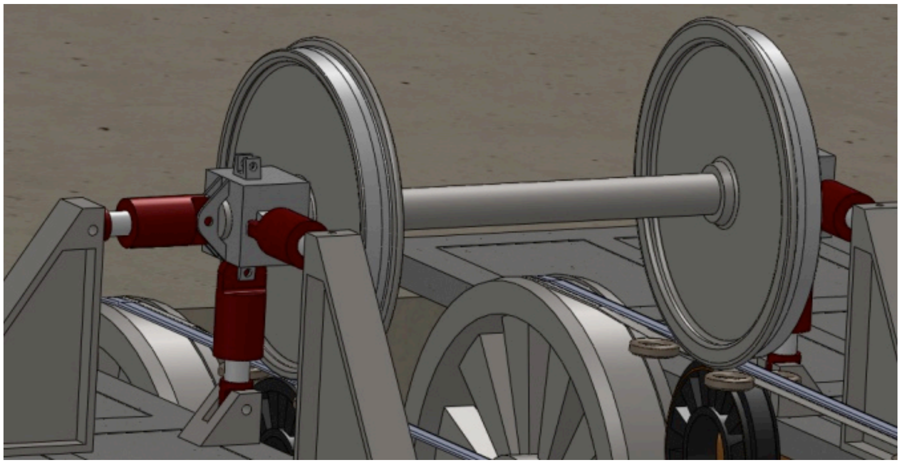


Figure 16. Continuous Roller Band concept for wheelset testing

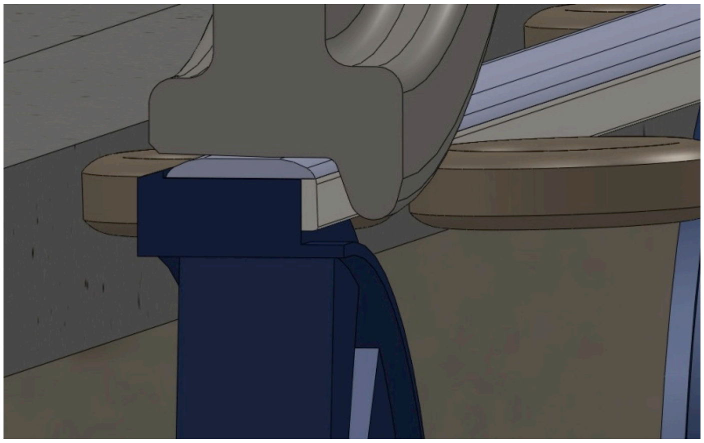


Figure 17. Close-up of simulated rail

Relevant Design Information

Although this configuration uses a modified rail crown, the roller diameters should be large enough to allow deflection of the rail elastic region (see Figure 17). Additionally, it can be seen in the previous figure that two bands are being used to recreate the rail profile. This band interface could possibly interfere with the predicted performance of the wheels on the rail and would require significant study.

Concept Benefits

- Continuous, steady-state testing of wheels
- Uses a rail crown for testing with the optional addition of a gauge face band. This will allow for investigation of wheel-rail interaction under real operating conditions including flanging events.

Concept Drawbacks

- Possible plastic deformation of the rail crown will greatly reduce the time between belt replacements.
- Stress on rail may exceed the limits of the material at higher loads and speeds.
- Rail band placement and control may be difficult.

Concept Score

Although this concept is different from those commonly used in rail industry, it represents a proven concept for automotive tire testing at speeds as high as 180 mph. The concept scores are shown in Table 15.

Table 15. Wheelset Continuous Band Rail Rig Scoring

Test Conditions	Specific Testing Aspect	Continuous Deformable Rail Band Roller	
Standard Components Usage	**Fielded Rail**	2	Rail must be modified
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	0	NA
Loads at Speed (Freight)	**<40 mph**	4	Automotive rolling roads exist, but high loads and high speeds are uncertain
	40-80 mph	3	
	> 80 mph	2	
Loads at Speed (Passenger)	**<70 mph**	4	Automotive rolling roads exist, but high loads and high speeds are uncertain
	70-140 mph	3	
	> 140 mph	2	
Test Article Constraints	**Angle of Attack**	5	Proven design for automotive applications
	Laterally Unconstrained Bolster	0	NA
	Lateral Position Hold	5	Proven design for automotive applications
Special Conditions	**Cornering**	5	Differential speeds possible
	Rail Cant	5	Deformable rail bands may be tilted
	Superelevation	5	Possible
	Two-point Contact	4	Second band required but allows for same linear speed at both contact points
	Switch Simulation	0	Implausible condition
Data Collection	**Steady State Tests**	5	Similar to automotive testing
	Strain (Force) Measurement	4	Proven technologies exist
	Displacement / Velocity Measurement	5	Similar to automotive testing
Implementation	**Current or past studies of the concept**	2	Similar to automotive testing
	Similarity to Typical Rail	4	Similar geometry but not real rail
	Actuators	4	Similar to automotive testing
	System Complexity (number of system components)	3	Similar to automotive testing
Totals (Importance x Implementation Rating)		307	VT score
		360	FRA score

4. Full Truck Concepts

Full truck test rigs are designed to test a fully assembled truck (or bogie) on a track setup. Testing an assembled truck significantly increases system complexity over both the single wheel and wheelset designs, but potentially offers added benefits. A truck rig allows studying the complete system interaction with regard to friction studies, slip/stick of a single axle during cornering, and hunting studies. Constraining the test article may allow for testing of the bearings, sideframes, springs, friction wedges, bolster, center plate, and the interaction of these assemblies at various AoAs, speeds, and slip conditions, but will increase the difficulty of performing precise studies of the wheel-rail interface and contact ellipse.

4.1 Potential Advantages of Full Truck Test Rigs

A full truck test rig has several potential advantages related to studying rail vehicle dynamics; some of these are listed below:

- Truck assembles allow for curvature studies.
- Truck testing rig may be used to test complete suspension compliance.
- Full-scale rigs may be used to test fielded trucks or any subassemblies.
- Bogey constraint and loading systems may be designed to closely replicate field conditions.
- Hunting studies that minimally constrain the test article may be possible.

4.2 Potential Limitations of Full Truck Test Rigs

Just as these system designs have a large number of potential advantages, they also have some potential disadvantages. The potential disadvantages are listed below.

- Full truck test rigs require multiple rolling rails (depending on the design), significantly increasing the cost and control system complexity.
- Facilities must be able to accommodate large test equipment and test specimens, adding to facility requirements.
- Large power is required for drivetrain systems.
- Truck assembly will greatly increase complexity of wheel force transducer integration.
- Compared with a single wheel rig, optical sensors may get less beneficial vantage point from which to monitor the test specimen.
- Constraint system must have increased complexity to allow precise control and data collection of AoA testing.
- Wheels may require modification for fitment onto a wheel force transducer.

4.3 Conventional Rail, Truck in Motion

Unlike the other concepts, a full truck can be tested on a conventional railway line. The most feasible design of this type would allow the testing of a test bogey sled that was propelled down a test track. The bogey could be unconstrained or aligned using a separate guide system for lateral position offset, AoA studies, or hunting studies.

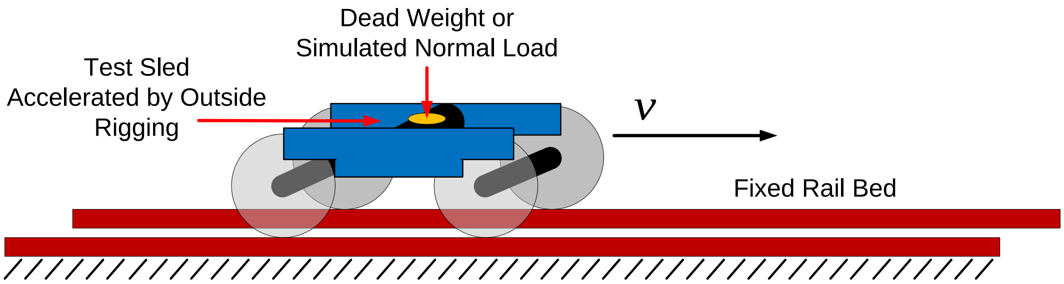


Figure 18. Fixed tangent rail, truck in motion

4.3.1 Relevant Design Information

Most relevant to this design are the requirements for the propulsion system. Assuming a max desired velocity and the known mass of the sled (with dead weight), simple calculations were performed to deduce the required force for a given length of test track or vice versa.

Considering a loaded bogey weight of 50,000 lb, and a maximum acceleration rate of 1 Gs (very difficult to produce for almost any type of vehicle testing, and in this case, a sustained load of 50,000 lb), a required track length just to reach the desired 220 mph test speed would be 1,600 ft. However, considering a more reasonable number force for the propulsion system, 0.25 Gs, the test track would need to be four times the length: 6,400 ft. This simple consideration does not take into account the massive undertaking of a high precision guide rail that would have to be added to this testing for precise lateral and AoA hold tests. In other words, using a long stretch on conventional line for a test bed is a possibility except that it would only allow for hunting and other unconstrained testing runs.

<u>Concept Benefits</u>

- Complete bogey assembly could be used for test sled.
- Contact mechanics equivalent to conventional rail

<u>Concept Drawbacks</u>

- Long track length required for high speeds
- Lateral positioning and AoA requires expensive guide system.

4.3.2 Concept Score

Even though this concept scored poorly overall, it is preferred design when compared with the other flat rail rigs (i.e., oscillating and shooting rail concepts). It is possible for this type of testing to be useful depending on the required goals of the testing.

Table 16. Full-Truck Test Sled on Traditional Track Scoring

Test Conditions	Specific Testing Aspect	Moving Truck on Stationary Track	
Standard Components Usage	**Fielded Rail**	5	Yes
	Fielded Wheels / Wheelsets	5	Yes
	Fielded Truck	5	Yes
Loads at Speed (Freight)	**<40 mph**	5	Yes, very long track lengths necessary
	40-80 mph	4	
	> 80 mph	3	
Loads at Speed (Passenger)	**<70 mph**	4	Yes, very long track lengths necessary
	70-140 mph	3	
	> 140 mph	2	
Test Article Constraints	**Angle of Attack**	0	Not feasibly controlled
	Laterally Unconstrained Bolster	5	yes
	Lateral Position Hold	0	Not feasibly controlled
Special Conditions	**Cornering**	2	Not in controllable lab environment
	Rail Cant	2	Not in controllable lab environment
	Superelevation	2	Not in controllable lab environment
	Two-point Contact	2	Not in controllable lab environment
	Switch Simulation	2	Not in controllable lab environment
Data Collection	**Steady State Tests**	2	Not in controllable lab environment
	Strain (Force) Measurement	4	Proven instrumented bogie and wheelsets
	Displacement / Velocity Measurement	5	Proven types exist
Implementation	**Current or past studies of the concept**	5	Extensive research
	Similarity to Typical Rail	5	Equivalent
	Actuators	2	Locomotive or propulsion engine needed
	System Complexity (number of system components)	3	Large track needed
Totals (Importance x Implementation Rating)		291	VT score
		333	FRA score

4.4 Single-Truck Roller Rig Concepts

4.4.1 Vertical Plane Roller, (Typical Roller Rig)

As stated in Section 2.3, this is the most common type of rig for testing railway vehicle dynamics in the laboratory. As with single wheel versions, use of the individual roller rigs for bogey and car testing has been widespread. In this configuration, a truck is placed on four independently controlled rollers that have a profile similar to that of a rail. This setup allows for adjustments of the simulated loading, the AoA, the rail cant, and other parameters.

Relevant Design Information

A wide range of studies is available for single-wheel and full truck or car roller rigs. The concept is often positively mentioned for its ability to reproduce curving dynamics, although the differential speeds of the rollers must be controlled precisely for accurate slip measurements. Additionally, wheelset hunting studies are possible. Because the wheels run on rollers, the contact patch would vary from flat rail.

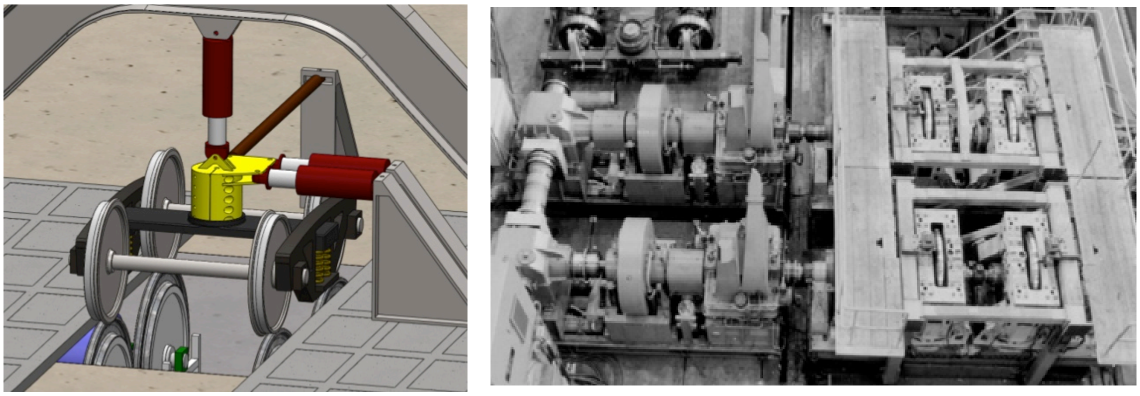


Figure 19. Full truck concept and photo of car test facility

<u>Concept Benefits</u>

- Most common design of rail dynamics testing rig
- Fielded wheels and other components may be used as test specimens.
- Flexibility for accommodating various configurations
- Capable of high speeds
- Roller strain gauges may be used for wheel force measurements.
- Curvature testing is possible, although AoA tests introduce more instability due to geometric effects of the rail roller radius from the normal force.
- Many options available for constraining the test article

<u>Concept Drawbacks</u>

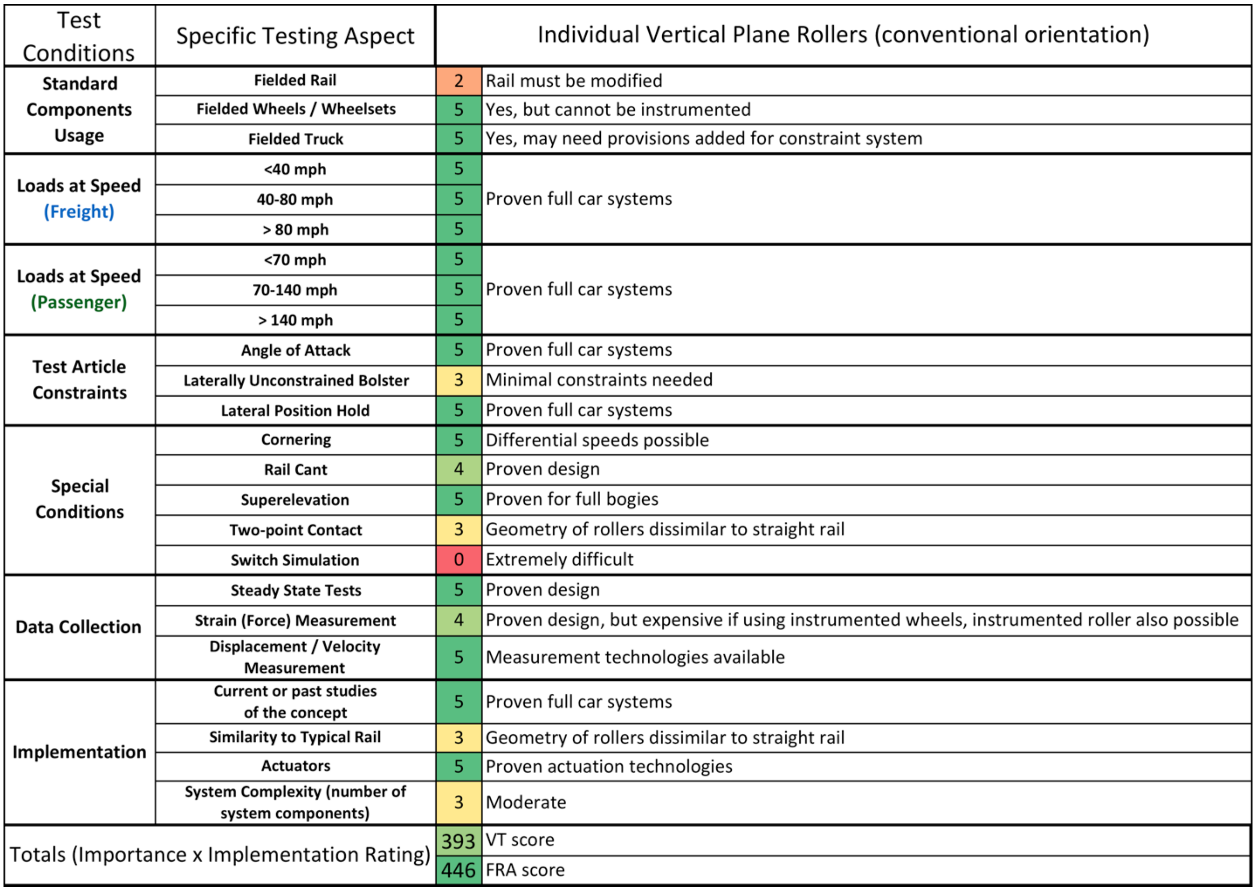
- Roller diameter limited in the case of a full truck. Wheelset spacing determines the spacing and allowable diameter of the rollers.

- Fielded rails cannot be tested.
- Rail profile is not easily altered.
- Cannot be easily coupled with inertial elements to simulate various loading conditions
- Test data obtained from roller rig experiments have to be correlated to straight rail via mathematical models; they are not precise replications of conventional track.
- Constraining the bolster for test article placement will allow significant compliance of the assembly, possibly leading to poor test results.

Concept Score

Like the single wheel and wheelset designs, the vertical plane roller scored the highest of all the full truck concepts.

Table 17. Full-Truck Vertical Plane Roller Rig Scoring



Test Conditions	Specific Testing Aspect	Individual Vertical Plane Rollers (conventional orientation)	
Standard Components Usage	**Fielded Rail**	2	Rail must be modified
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	5	Yes, may need provisions added for constraint system
Loads at Speed (Freight)	**<40 mph**	5	Proven full car systems
	40-80 mph	5	
	> 80 mph	5	
Loads at Speed (Passenger)	**<70 mph**	5	Proven full car systems
	70-140 mph	5	
	> 140 mph	5	
Test Article Constraints	**Angle of Attack**	5	Proven full car systems
	Laterally Unconstrained Bolster	3	Minimal constraints needed
	Lateral Position Hold	5	Proven full car systems
Special Conditions	**Cornering**	5	Differential speeds possible
	Rail Cant	4	Proven design
	Superelevation	5	Proven for full bogies
	Two-point Contact	3	Geometry of rollers dissimilar to straight rail
	Switch Simulation	0	Extremely difficult
Data Collection	**Steady State Tests**	5	Proven design
	Strain (Force) Measurement	4	Proven design, but expensive if using instrumented wheels, instrumented roller also possible
	Displacement / Velocity Measurement	5	Measurement technologies available
Implementation	**Current or past studies of the concept**	5	Proven full car systems
	Similarity to Typical Rail	3	Geometry of rollers dissimilar to straight rail
	Actuators	5	Proven actuation technologies
	System Complexity (number of system components)	3	Moderate
Totals (Importance x Implementation Rating)		393	VT score
		446	FRA score

4.4.2 Perpendicular Roller

Again, in this configuration, each wheel is placed on a roller that has a profile similar to that of a rail, but travels in a circular path perpendicular to a typical roller rig. Similar to the single wheel setup, this setup can allow simulating the wheelset loads, AoA, rail cant. Curving studies are also possible with this concept. The rolling rail is intended to power to rotate the wheel up to a specified speed where steady-state testing is performed. While this concept is an untested design, it may offer some key advantages over a typical rolling rig.

Relevant Design Information

Unlike other past roller rig designs, there is no know literature available directly pertaining to this particular design concept from either a mathematical modeling or experimental viewpoint. For this reason, more design work will be required to ensure a successful design. However, several key distinctions make this an attractive design concept (Figure 20), even though it scores lower than a typical roller design.

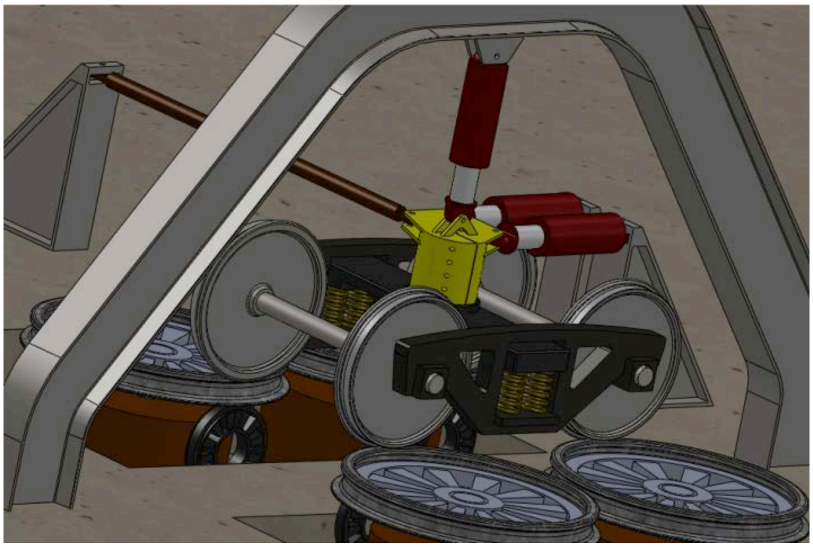


Figure 20. A roller rig design with horizontal roller configuration

<u>Concept Benefits</u>

- An actual rail crown may be used in this configuration, but that decision will ultimately depend on desired top speeds, power availability, operating costs, and other aspects.
- “Flat” rail profile is expected to reduce the result differences from conventional rail. Typical roller rigs suffer from having longitudinal creep behavior that varies from flat track due to the curvature of the rolling rail.
- Underside of rail roller below the contact patch could be supported by bearings that allow real-time adjustments of the vertical stiffness of the simulated track.
- Differential speeds needed for curving studies will be possible.

Concept Drawbacks

- Roller diameter limited in the case of a full truck. Wheelset spacing determines the spacing and allowable diameter of the rollers.
- Large moments are created because of the large radius of the roller. This implies that auxiliary bearings will be required to counteract these forces.
- Concept has never been implemented and no known literature exists concerning this design.
- Differential speed systems will likely require two separate drive systems (rather than the use of a quill drive).
- Drive system control must be extremely precise for accurate slip condition testing.

Concept Score

This concept rated second of all the full truck concepts reviewed. This score was hampered by the fact that no known literature is available on this design concept. Although the need for two separate drive systems will increase cost, this concept does offer the intriguing possibility of avoiding the limitation that a conventional roller rig suffers regarding the longitudinal creep behavior when compared with flat track. The breakdown of the scoring is as follows:

Table 18. Full-Truck Horizontal Plane Roller Rig Scoring

Test Conditions	Specific Testing Aspect	Individual Horizontal Rollers (perp. orientation)	
Standard Components Usage	**Fielded Rail**	2	Rail must be modified
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	5	Yes, may need provisions added for constraint system
Loads at Speed (Freight)	**<40 mph**	4	Bearing surface needed for offset load
	40-80 mph	4	
	> 80 mph	4	
Loads at Speed (Passenger)	**<70 mph**	4	Bearing surface needed for offset load
	70-140 mph	4	
	> 140 mph	4	
Test Article Constraints	**Angle of Attack**	5	Similar to vert plane roller
	Laterally Unconstrained Bolster	3	Minimal constraints needed
	Lateral Position Hold	5	Similar to vert plane roller
Special Conditions	**Cornering**	5	Differential speeds possible
	Rail Cant	4	Similar to vert plane roller
	Superelevation	5	Similar to vert plane roller
	Two-point Contact	3	Geometry of rollers dissimilar to straight rail
	Switch Simulation	0	Extremely difficult
Data Collection	**Steady State Tests**	5	Similar to vert plane roller
	Strain (Force) Measurement	4	Conventional force measurement systems may be integrated into this setup
	Displacement / Velocity Measurement	5	Similar to vert plane roller
Implementation	**Current or past studies of the concept**	0	No literature available
	Similarity to Typical Rail	3	Geometry of rollers dissimilar to straight rail
	Actuators	5	Similar to vert plane roller
	System Complexity (number of system components)	3	Moderate
Totals (Importance x Implementation Rating)		354	VT score
		401	FRA score

4.4.3 Tangent Roller, Internal

Omitted due to design incompatibility with the test needs.

4.4.4 Drum Roller

A variation of the Vertical Plane Roller (4.4.1) is where the rail rollers rotate at the same angular velocity (no differential speeds). These types of rigs have been used for bogey or full car test rigs, but are more commonly used for hunting or braking test rigs, not for curving or directly studying contact mechanics. The advantage of this type of rig is reduced cost and complexity compared with the individual vertical plane rollers. This setup may be designed to make adjustments to the simulated loading and the AoA, but will not be able to make adjustments for superelevation, and rail cant will be difficult to simulate.

Relevant Design Information

Similar to other roller rig concepts, the interface between the wheels and rollers may lead to contact patch distortion. Although the rig can be used for hunting studies, it cannot reproduce curving dynamics accurately.

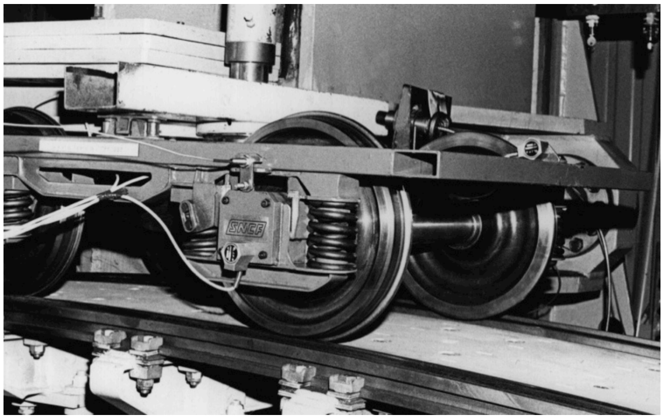


Figure 21. INRETS represents a unique design of the drum roller concept

Concept Benefits

- Simple variation of the most common design of rail testing rig
- Fielded wheels and other components may be used as test specimens.
- Can be coupled with inertial elements to simulate various loading conditions
- Flexibility for accommodating various configurations
- Capable of high speeds
- Wheel may be mounted to a wheel force transducer.
- Roller strain gauges may be used for wheel force calculations.
- AoA tests introduce instability due to geometric effects of the rail roller radius from the normal force.

Concept Drawbacks

- Fielded rails cannot be tested.
- Rail profile is not easily altered.
- Test data obtained from roller rig experiments have to be correlated to straight rail via mathematical models; they are not precise replications of conventional track.
- Differential speed testing (curving) is not possible.

Concept Score

The drum roller design scored reasonably well due to its use in past and ongoing studies.

Table 19. Full-Truck Vertical Plane Drum Roller Rig Scoring

Test Conditions	Specific Testing Aspect	Drum Roller	
Standard Components Usage	**Fielded Rail**	2	Rail must be modified
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	5	Yes, may need provisions added for constraint system
Loads at Speed (Freight)	**<40 mph**	5	Proven for full bogies
	40-80 mph	5	
	> 80 mph	5	
Loads at Speed (Passenger)	**<70 mph**	5	Proven for full bogies
	70-140 mph	5	
	> 140 mph	5	
Test Article Constraints	**Angle of Attack**	5	Proven for full bogies
	Laterally Unconstrained Bolster	3	Minimal constraints needed
	Lateral Position Hold	5	Proven for full bogies
Special Conditions	**Cornering**	0	NA
	Rail Cant	2	Shim rails
	Superelevation	0	NA
	Two-point Contact	3	Geometry of rollers dissimilar to straight rail
	Switch Simulation	0	Extremely difficult
Data Collection	**Steady State Tests**	5	Proven design
	Strain (Force) Measurement	4	Proven design, but expensive if using instrumented wheels, instrumented roller also possible
	Displacement / Velocity Measurement	5	Measurement technologies available
Implementation	**Current or past studies of the concept**	5	Proven full car systems
	Similarity to Typical Rail	3	Geometry of rollers dissimilar to straight rail
	Actuators	5	Similar to vert plane roller
	System Complexity (number of system components)	5	Simple
Totals (Importance x Implementation Rating)		362	VT score
		403	FRA score

4.5 Stationary Wheel, Track in Motion

Full truck testing concepts were investigated to avoid some of the problems associated with conventional roller rigs (such as the longitudinal creep dissimilarity to conventional rail). For this reason, researchers considered the design of test rigs that utilize short sections of conventional rail for repeatable laboratory testing.

4.5.1 Short Stroke Oscillating Rail

The most feasible of the flat rail testing rigs utilizes a short length of rail that is passed underneath each rail wheel. The rails are moved forward and backward to simulate track conditions. Single wheel versions of oscillating test machines have been built and are in use; however, they have primarily been used for testing rail strength or joint bar fatigue.

Relevant Design Information

The oscillating rail concept considers the use of a short length of rail on a bearing platform longitudinally displaced beneath a rail wheel. While antiquated versions of this concept rely on mechanical actuators to oscillate the rail, at least one modern version of this concept has been created that uses hydraulic actuators to apply normal loading on the wheel and position the rail (Figure 6). However, no known full truck testing machines of this type have been designed or produced.

Concept Benefits

- Equivalent behavior to conventional rail
- Single wheel versions have been previously implemented
- Simple to implement
- Depending on design, differential speeds possible
- Superelevation and rail cant are possible

Concept Drawbacks

- Low speeds only
- Steady-state testing not possible

Concept Score

The poor concept scores for this design reflect the anticipated performance with regard to high speed testing.

Table 20. Full-Truck Oscillating Rail Rig Scoring

Test Conditions	Specific Testing Aspect	Oscillating Flat Rail, short stroke (~1-2m)	
Standard Components Usage	**Fielded Rail**	5	Easily used
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	5	Yes, may need provisions added for constraint system
Loads at Speed (Freight)	**<40 mph**	1	Cannot achieve high speeds
	40-80 mph	0	
	> 80 mph	0	
Loads at Speed (Passenger)	**<70 mph**	1	Cannot achieve high speeds
	70-140 mph	0	
	> 140 mph	0	
Test Article Constraints	**Angle of Attack**	5	Similar to single wheel design
	Laterally Unconstrained Bolster	3	Minimal constraints needed
	Lateral Position Hold	5	Similar to single wheel design
Special Conditions	**Cornering**	3	Differential speeds possible, but not curved rails
	Rail Cant	5	Proven design
	Superelevation	5	Possible
	Two-point Contact	5	Equivalent rail geometry
	Switch Simulation	3	Longer piece of switch track must be used
Data Collection	**Steady State Tests**	1	Not possible due to small length of rail
	Strain (Force) Measurement	4	Proven design
	Displacement / Velocity Measurement	5	Proven design
Implementation	**Current or past studies of the concept**	3	Similar to single wheel designs
	Similarity to Typical Rail	5	Equivalent rail geometry, except curved rail
	Actuators	5	Equivalent to single rail
	System Complexity (number of system components)	4	Moderate
Totals (Importance x Implementation Rating)		287	VT score
		335	FRA score

4.5.2 High Speed Shooting Rail

The attributes of this concept are similar to what was described in Section 3.4.2. This design would utilize two rails that pass through adjustable guides that constrain the rail under the rail truck assembly (Figure 22).

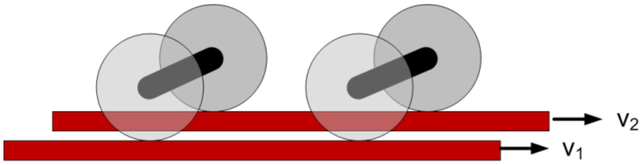


Figure 22. Stationary truck, track in motion

Relevant Design Information

The greatest limiting factor of this type of design, as with the previous design, is the difficulty associated with the acceleration of the rail to elevated test speeds. For example, consider the acceleration of a single, 115 lb/yd rail (very light rail) to a speed of 220 mph. Neglecting the weight of guide bearings or other necessary components for such a device, and assuming a constant acceleration of the rail, it is found that regardless of the length of rail, the force required is 60 kip (the time it takes to accelerate to speed varies depending on the length). If a 50-foot section of rail was chosen, the acceleration of the rail needed (just to *reach* 220 mph) is 31 times the acceleration of gravity. For this reason, high speed testing on such a rig is exceedingly improbable.

Concept Benefits

- Contact mechanics are typical.
- Differential speeds are theoretically possible.

Concept Drawbacks

- Huge loads would be required to accelerate the track to high speeds.
- Constraining the rail would be difficult depending on the speeds and conditions required.

Concept Score

The scores of this design reflect the drawbacks previously discussed: huge loads are required to reach high speeds for this concept and the rail guide system will likely be very complex and will add significantly to the friction forces that need to be overcome.

Table 21. Full-Truck Shooting Rail Rig Scoring

Test Conditions	Specific Testing Aspect	Shooting Flat Rail, long stroke	
Standard Components Usage	**Fielded Rail**	3	Fielded rail too heavy
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	5	Yes, may need provisions added for constraint system
Loads at Speed (Freight)	**<40 mph**	2	Refer to calcs
	40-80 mph	1	
	> 80 mph	0	
Loads at Speed (Passenger)	**<70 mph**	1	Refer to calcs
	70-140 mph	0	
	> 140 mph	0	
Test Article Constraints	**Angle of Attack**	5	Similar to oscillating flat rail design
	Laterally Unconstrained Bolster	3	Minimal constraints needed
	Lateral Position Hold	5	Similar to oscillating flat rail design
Special Conditions	**Cornering**	3	Differential speeds possible, but not curved rails
	Rail Cant	5	Similar to oscillating flat rail design
	Superelevation	5	Possible
	Two-point Contact	5	Equivalent rail geometry
	Switch Simulation	2	Piece of switch track may be used
Data Collection	**Steady State Tests**	2	Longer rails allow better steady state conditions
	Strain (Force) Measurement	4	Similar to oscillating flat rail design
	Displacement / Velocity Measurement	4	Contactless measurement technologies must be utilized
Implementation	**Current or past studies of the concept**	0	No literature available
	Similarity to Typical Rail	5	Equivalent rail geometry, except curved rail
	Actuators	1	Massive forces needed over a great distance
	System Complexity (number of system components)	1	Very complex facility req'd
Totals (Importance x Implementation Rating)		250	VT score
		296	FRA score

4.6 Modified Rail (Crown and Gauge Face)

The final concept for testing a full truck involves using modified rails (continuous rail bands). As previously outlined for the single wheel and wheelset versions, this concept was developed to incorporate the contact mechanics' benefits of the flat-rail design, but allow the capability of obtaining higher test speeds. In this configuration, at least two longer rail bands (or four shorter bands under each wheel) will be used as the rail surface. These bands pass under the rail wheels similarly to how an automotive rolling road test rig performs (Figure 23).

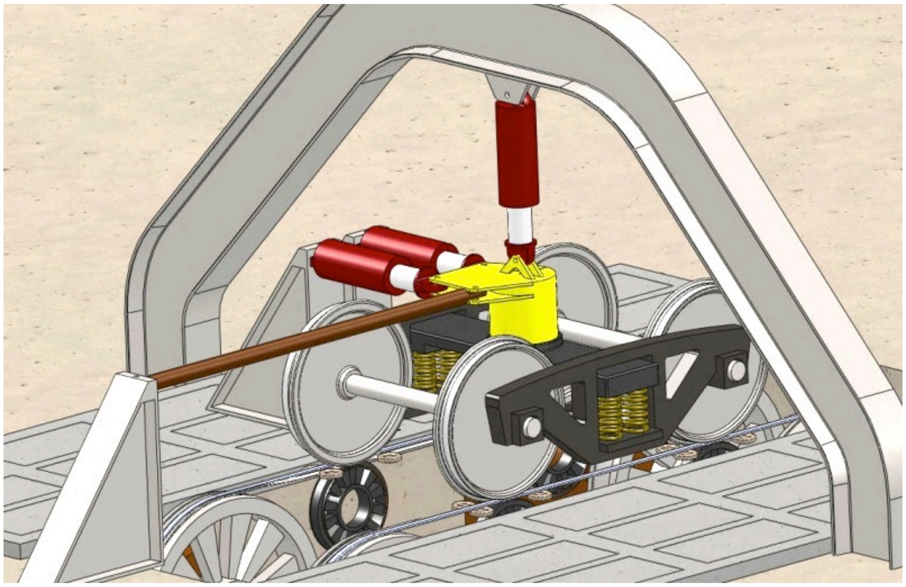


Figure 23. Full truck roller rig with modified rail crown as the rail surface

Relevant Design Information

Although this configuration uses a modified rail crown, the roller diameters should be large enough to allow deflection of the rail elastic region. Additionally, it can be seen in the previous figure that two bands are being used to recreate the rail profile that includes the gauge face. This band interface could likely interfere with the predicted performance of the wheels on the rail and would require significant study.

Concept Benefits

- Continuous, steady-state testing of wheels
- Uses a rail crown for testing with the optional addition of a gauge face band; this will allow for investigation of wheel-rail interaction under real operating conditions, including flanging events.

Concept Drawbacks

- Possible plastic deformation of the rail crown will greatly reduce the time between belt replacements.
- Stress on rail may exceed the limits of the material at higher loads and speeds.
- Rail band placement and control may be difficult.

Concept Score

Although this test design is unlike anything in the rail industry, automotive rolling dynamometers show significant similarities, although at much lighter loads and, typically, speeds less than 180 mph.

Table 22. Full-Truck Deformable Band Roller Rig Scoring

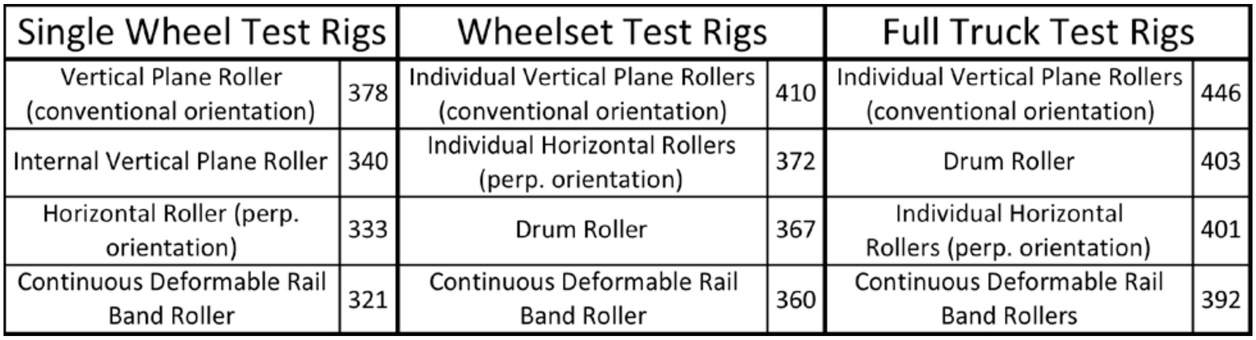
Test Conditions	Specific Testing Aspect	Continuous Deformable Rail Band Rollers	
Standard Components Usage	**Fielded Rail**	2	Must be modified
	Fielded Wheels / Wheelsets	5	Yes, but cannot be instrumented
	Fielded Truck	5	Yes, may need provisions added for constraint system
Loads at Speed (Freight)	**<40 mph**	4	Automotive rolling roads exist, but high loads and high speeds are uncertain
	40-80 mph	3	
	> 80 mph	2	
Loads at Speed (Passenger)	**<70 mph**	4	Automotive rolling roads exist, but high loads and high speeds are uncertain
	70-140 mph	3	
	> 140 mph	2	
Test Article Constraints	**Angle of Attack**	5	Proven design for automotive applications
	Laterally Unconstrained Bolster	3	Minimal constraints needed
	Lateral Position Hold	5	Proven design for automotive applications
Special Conditions	**Cornering**	5	Differential speeds possible, possibly curves
	Rail Cant	5	Deformable rail bands may be tilted
	Superelevation	5	Possible
	Two-point Contact	4	Second band required but allows for same linear speed at both contact points
	Switch Simulation	0	Implausible condition
Data Collection	**Steady State Tests**	5	Similar to automotive testing
	Strain (Force) Measurement	4	Proven technologies exist
	Displacement / Velocity Measurement	5	Similar to automotive testing
Implementation	**Current or past studies of the concept**	2	Similar to automotive testing
	Similarity to Typical Rail	4	Similar geometry but not real rail
	Actuators	4	Similar to automotive testing
	System Complexity (number of system components)	3	Similar to automotive testing
Totals (Importance x Implementation Rating)		338	VT score
		392	FRA score

5. Concept Scoring Summary

Although the concept scoring may not capture every detail of all the concepts up for evaluation, it does provide researchers with a good marker of how different concepts compare. More importantly, the pros and cons of each concept give designers good guidance on what the most important aspects of a design are likely to be. Through this concept scoring process, a small set of rig possibilities is likely to offer the greatest possibility of success for this rig design.

The top four highest-scoring design concepts for each of the three test rig categories are listed below in Table 23.

Table 23. Top four scores for each design type



Single Wheel Test Rigs		Wheelset Test Rigs		Full Truck Test Rigs	
Vertical Plane Roller (conventional orientation)	378	Individual Vertical Plane Rollers (conventional orientation)	410	Individual Vertical Plane Rollers (conventional orientation)	446
Internal Vertical Plane Roller	340	Individual Horizontal Rollers (perp. orientation)	372	Drum Roller	403
Horizontal Roller (perp. orientation)	333	Drum Roller	367	Individual Horizontal Rollers (perp. orientation)	401
Continuous Deformable Rail Band Roller	321	Continuous Deformable Rail Band Roller	360	Continuous Deformable Rail Band Rollers	392

The vertical plane roller is the clear winner for each category. The main reason for the high score of these designs is the vast literature available on them. However, the potential of the horizontal roller design to overcome the shortcomings of a conventional roller do make that concept more appealing than may be apparent in the final scores.

6. Mathematical Modeling

A mathematical model has been developed as a part of this project to help with the detailed design stage and to better understand the dynamic behavior of the system. The model is able to capture the essential dynamic behavior of a truck on curved track under general conditions of speed, curvature, and superelevation; the main purpose of developing this dynamic model is to gain insight into various design factors. Various design configurations can be studied using this model and their effects can be determined. In addition to that, the model will be used for specifying different components, actuators, and sensors, as well as getting a better understanding of the displacements and velocities, force ranges, and any other factors that are important for the detailed design stage.

The dynamic model is capable of simulating a conventional passenger truck's dynamic behavior on a curved track for various model variables. The effect of different wheel-rail profiles, different track geometry (curvature, gauge, and superelevation), and different truck geometry can be studied at various test speeds using this model.

As mentioned above, the model gets constant forward velocity, track geometry (degree curve, superelevation), wheel-rail profile, geometric and material properties of various parameters like truck and track dimensions, a creep model, masses and inertias, rail and suspension stiffness and damping as inputs and calculates wheelset lateral displacement, acceleration, AoA and normal forces, truck and carbody lateral displacements accelerations, and other parameters such as creepage, creep forces, and moments as outputs.

The model consists of two wheelsets, a truck frame, four rails, and a point mass representing half of the carbody. Each rail has one state for its lateral displacement; each wheelset has five states for its lateral displacement, lateral velocity, yaw, yaw rate, and spin. The truck frame has four states for its lateral displacement, lateral velocity, yaw, and yaw rate. The carbody has two states (lateral displacement, and lateral velocity), resulting in a total number of 20 states.

6.1 Wheelset dynamic model

The wheel-rail profile has a significant effect on the dynamic behavior of the truck. The current dynamic model uses the AAR wheel-rail profile, but other wheel-rail profiles can be easily implemented into the model. The wheel-rail profile information, including Wheelset rolling radii, roll angle, and contact angle, have been extracted from Nagurka, M. L., 1983. "Curving performance of rail passenger vehicles." Mechanical Engineering. Cambridge, Massachusetts Institute of Technology.

The model uses the Kalker's linear creep model to find the creep forces. At each wheel-rail interface, the longitudinal and lateral contact patch components of the creep force are calculated using the following equations:

$$FCPX' = -f33\xi x \tag{1}$$

$$FCPY' = -f11\xi y - f12\xi sp \tag{2}$$

And the spin creep moment acting normal to the contact patch is:

$$MCPZ' = f12\xi y - f22\,\xi sp \tag{3}$$

In the above formulas, the creep coefficients (f_{ij}) are functions of wheel-rail geometry, material properties, and normal load:

$$f_{11} = \left(\frac{F_N}{F_N^*}\right)^{2/3} f_{11}^* \quad f_{12} = \left(\frac{F_N}{F_N^*}\right) f_{12}^* \quad f_{22} = \left(\frac{F_N}{F_N^*}\right)^{4/3} f_{22}^* \quad f_{33} = \left(\frac{F_N}{F_N^*}\right) f_{33}^* \tag{4}$$

The magnitude of the resultant creep force cannot exceed the amount of available adhesion. Therefore, the resultant creep force is saturated using a modified Vermeulen-Johnson model:

$$\varepsilon = \begin{cases} \frac{1}{\beta}\left[\beta - \frac{1}{3}\beta^2 + \frac{1}{27}\beta^3\right] \ldots For\ \beta < 3 \\ \frac{1}{\beta} \qquad\qquad\qquad\qquad \ldots For\ \beta \geq 3 \end{cases} \tag{5}$$

$$\beta = \frac{1}{\mu F_N}\sqrt{(F'_{CPX})^2 + (F'_{CPY})^2} \tag{6}$$

And the creep forces are:

$$F_{CPX} = \varepsilon F'_{CPX}\ ,\ F_{CPY} = \varepsilon F'_{CPY}\ ,\ M_{CPZ} = \varepsilon M'_{CPZ} \tag{7}$$

Depending on the net wheelset lateral excursion, single-point or two-point contact can occur. Different situations of single-point and two-point contact can be seen in Figure 24.

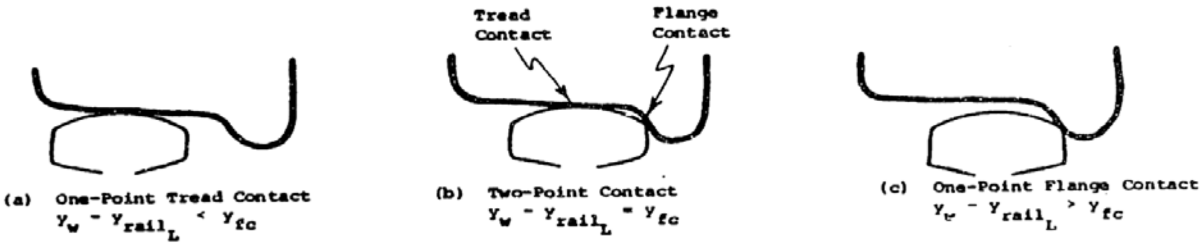


Figure 24.: Different Wheel-Rail contact conditions

Since normal forces change as flanging (two-point contact) occurs, as seen in Figure 25, the equations used for the single-point contact cannot be used for the two-point contact.

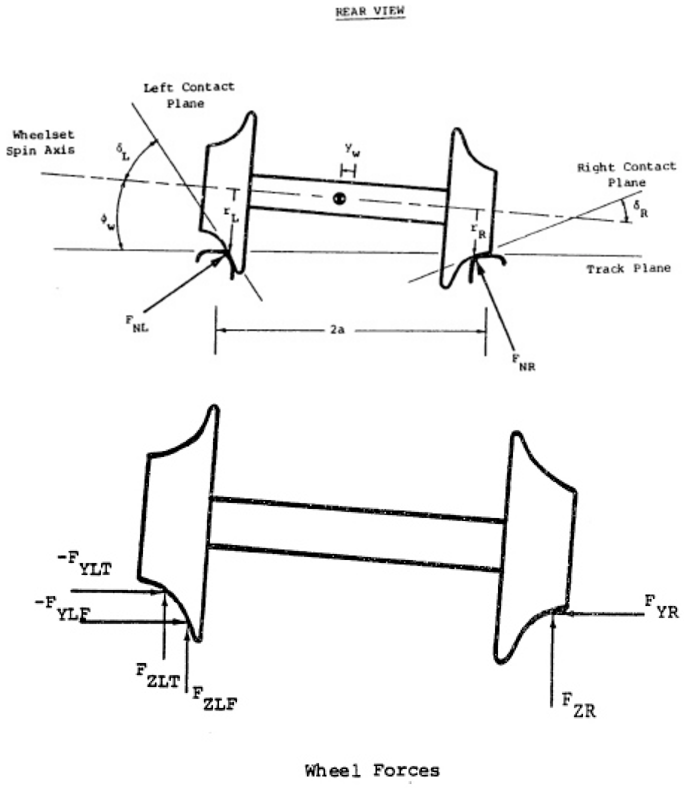


Figure 25. Single-point and two-point contact forces

The wheelset equations of motion for single-point contact are:

Lateral equation

$$\frac{W_w}{g}\left(\ddot{y}_w - r_o\ddot{\emptyset}_{SE}\right) = F_{CYL} + F_{CYR} + F_{NYL} + F_{NYR} + F_{susp_{yw}} + W_w(\varphi_d - \varphi_w) \qquad (8)$$

Vertical equation

$$\frac{W_w}{g}\left(\ddot{z}_w + a\ddot{\emptyset}_{SE}\right) = F_{CZL} + F_{CZR} + F_{NZL} + F_{NZR} + F_{susp_{yw}} - W_w \qquad (9)$$

Yaw equation

$$\begin{aligned} I_{WX}\left(\ddot{\psi}_w - \frac{\dot{V}}{R} + \frac{\dot{R}V}{R^2}\right) \\ &= -I_{WY}\dot{\theta}_w(\dot{\emptyset}_w + \dot{\emptyset}_{SE}) - a(F_{CXL} - F_{CXR}) \\ &- \psi_w\{(a - r_L \tan(\delta_L + \emptyset_w))(F_{CYL} + F_{NYL}) - a - r_R \tan(\delta_R - \emptyset_w))(F_{CYR} \\ &+ F_{NYR})\} + M_{CZL} + M_{CZR} + M_{susp_{zw}} - \emptyset_w(M_{CYL} + M_{CYR}) \end{aligned} \tag{10}$$

For the two-point contact, the equations of motion change into:

Lateral Equation

$$\frac{W_w}{g}\left(\ddot{y}_w - r_o\ddot{\emptyset}_{SE}\right) = F_{CYLT} + F_{CYLF} + F_{CYR} + F_{NYLT} + F_{NYLF} + F_{NYR} + F_{susp_{yw}} + W_w(\emptyset_d - \emptyset_w) \tag{11}$$

Vertical Equation

$$\frac{W_w}{g}\left(Z_w + \ddot{\ }a\ddot{\varphi}_{SE}\right) = F_{CZLT} + F_{CZLF} + F_{CZR} + F_{NZLT} + F_{NZLF} + F_{Susp\,Z_W} - W_w \tag{12}$$

Yaw Equation

$$\begin{aligned} I_{WX}\left(\ddot{\psi}_w - \frac{\dot{V}}{R} + \frac{\dot{R}V}{R^2}\right) \\ &= -I_{WY}\dot{\theta}_w(\dot{\emptyset}_w + \dot{\emptyset}_{SE}) - a(F_{CXLT} + F_{CXLF} - F_{CXR}) \\ &- \psi_w\{(a - r_{LT} \tan(\delta_{LT} + \emptyset_w))(F_{CYLT} + F_{NYLT}) \\ &+ (a - r_{LF} \tan(\delta_{LF} + \emptyset_w))(F_{CYLF} + F_{NYLF}) - (a - r_R \tan(\delta_R - \emptyset_w))(F_{CYR} \\ &+ F_{NYR})\} + M_{CZLT} + M_{CZLF} + M_{CZR} + M_{susp_{zw}} + \emptyset_w(M_{CYLT} + M_{CYLF} + M_{CYR}) \end{aligned} \tag{13}$$

As mentioned previously, each rail has one state (lateral displacement); for each rail, lateral stiffness and damping are considered, but since the mass of the rail is small compared with the mass of the vehicle, the mass of the rail is neglected. The equations of motion for the rail in single-point and two-point contact are as follows:

Single-point contact

$$m_r\ddot{y}_{rail_L} + c_r\dot{y}_{rail_L} + k_r y_{rail_L} = -F_{NYL} - F_{CYL} \tag{14}$$

Two-point contact

$$m_r\ddot{y}_{rail_L} + c_r\dot{y}_{rail_L} + k_r y_{rail_L} = -F_{NYLT} - F_{NYLF} - F_{CYLT} - F_{CYLF} \tag{15}$$

The truck that this model uses is a conventional passenger truck; it is modeled as a rigid frame attached to the wheelsets via a primary suspension and to the carbody via a secondary suspension system. Other truck configurations like force-steered trucks or the North American 3-piece freight truck are currently under development. In this model, it is assumed that the carbody is a point-mass and only its lateral motion is considered and the bolster is rigidly attached to the truck frame. The schematics of the truck suspension system are included in Figure 26.

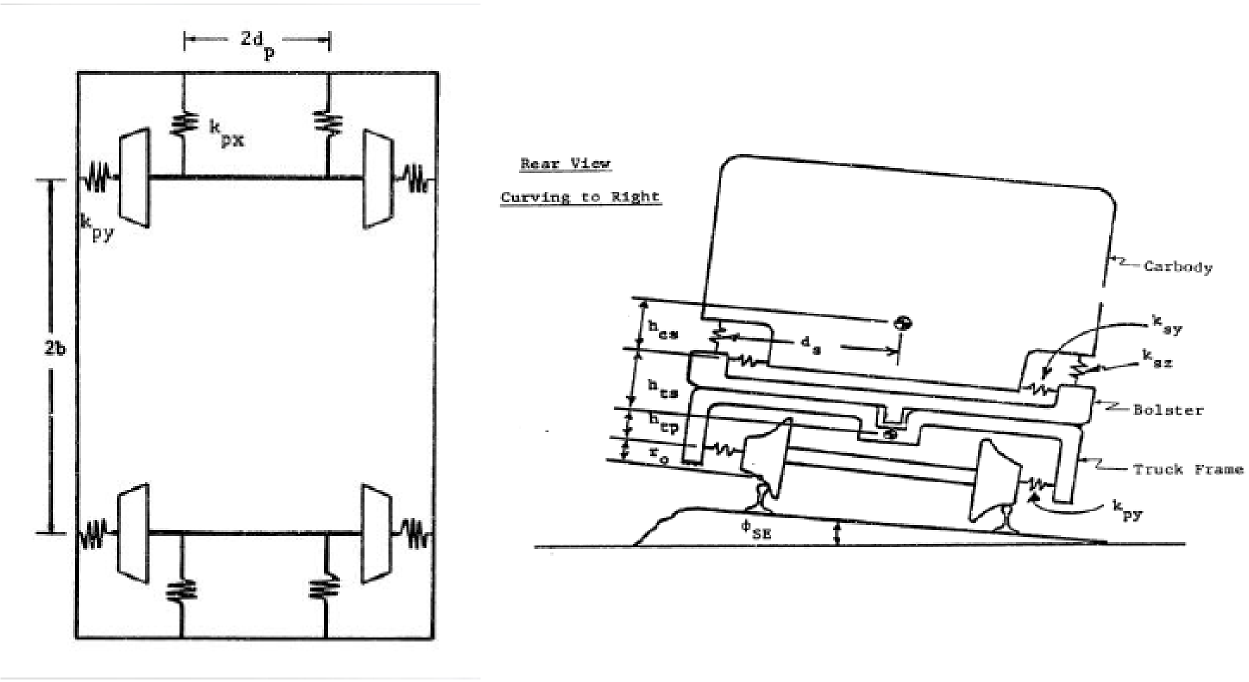


Figure 26. Suspension configuration of the modeled truck

Individual model components like the equations of motion for the wheelsets, truck, carbody, and the rails, as well as the primary and secondary suspension equations and creep forces, are assembled together and the full truck dynamic model is constructed. Matlab is used for programming the dynamic model and ODE23 is used as the solver for the state-space system.

6.2 Case studies

In the second part of this report an example is presented to show the capabilities and the outputs of the model. This example studies the effects of speed, track curvature, and track superelevation on the dynamic response of a truck as it negotiates a right-handed curve. The different numerical values required to model the system can be found in Table 24.

Table 24. Numerical values of the model

Wheel/rail parameters		**Geometry**			
$f_{11T}\,(lb)$	1.09e6	$r_o(ft)$	1.167	$h_{ts}(ft)$	1.48
$f_{12T}\,(ft-lb)$	8615	$a(ft)$	2.32	$h_{tp}(ft)$	0.52
$f_{22T}\,(ft^2-lb)$	82	$b(ft)$	3.75	$h_c(ft)$	2.375
$f_{33T}\,(lb)$	1.18e6	$d_p(ft)$	1.92	$l_s(ft)$	23.75
$f_{11F}\,(lb)$	7.34e5	$h_{cs}(ft)$	2.90	$d_s(ft)$	3.71
$f_{12F}\,(ft-lb)$	6820	**Wheelset and carbody**		**Truck**	
$f_{22F}\,(ft^2-lb)$	2	$W_w(lb)$	4054	$W_F(lb)$	4697
$f_{33F}\,(lb)$	6.71e5	$I_{wx}(slug-ft^2)$	28	$I_{Fx}(slug-ft^2)$	1166
λ	0.05	$I_{wz}(slug-ft^2$	547	$I_{Fz}(slug-ft^2$	1251
μ	0.30	$W_c(lb)$	70190		
Primary Suspension		**Secondary Suspension**			
$k_{px}(lb/ft)$	1.35e5	$k_{sy}(lb/ft)$	19500		
$c_{px}(lb-sec/ft)$	574	$c_{sy}\,(lb-sec/ft)$	1420		
$k_{py}(lb/ft)$	7.50e5				
$c_{py}(lb-sec/ft)$	620				

Twelve different cases have been studied using the model, and the results were compared for the verification of the dynamic model and better understanding of the effects of changing speed, superelevation, and curvature on the behavior of the system. The model is able to plot net wheelset excursion (in), wheelset lateral acceleration (Gs), wheelset yaw (deg), rail lateral displacement (in), truck frame lateral displacement (in), truck frame yaw (deg), and normal forces (lb) versus time[1]. The following table summarizes the characteristics of different cases.

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[1] The code is currently under development to be able to plot versus distance (instead of versus time) along the track.

Table 25. Different case studies

Simulation	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
Balance Speed (mph)	42.3	59.9	42.3	59.9	42.3	59.9
Superelevation (inches)	2.91 (3°)	5.82 (6°)	2.91 (3°)	5.82 (6°)	2.91 (3°)	5.82 (6°)
Speed (mph)	5		10		50	
Degree Curve (degree)	2.5					
Simulation	**Case 7**	**Case 8**	**Case 9**	**Case 10**	**Case 11**	**Case 12**
Balance Speed (mph)	29.9	42.4	29.9	42.4	29.9	42.4
Superelevation (inches)	2.91 (3°)	5.82 (6°)	2.91 (3°)	5.82 (6°)	2.91 (3°)	5.82 (6°)
Speed (mph)	5		10		80	
Degree Curve (degree)	5					

For the first case, all the plots are presented here to show the capabilities of the model, but the rest of the cases are only compared with one another.

Figure 27 shows the net wheelset excursion for the leading and the trailing wheelsets; as shown in the figure, the leading wheelset moves toward flanging in 1.8 seconds (s); it starts flanging for 2 s and then it goes through a single point tread contact phase for about 3 s after which it reaches its steady-state phase and remains flanging for the rest of the time.

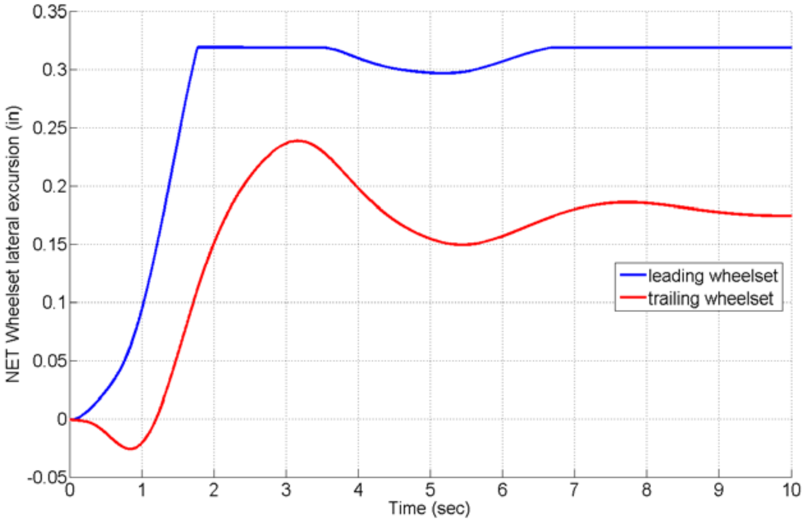

Figure 27. Net wheelset excursion for Case 1

Figure 28 shows the wheelset lateral acceleration; since the wheelset angular velocity drops suddenly as the flanging start a negative acceleration can be seen at the same time the flanging happens.

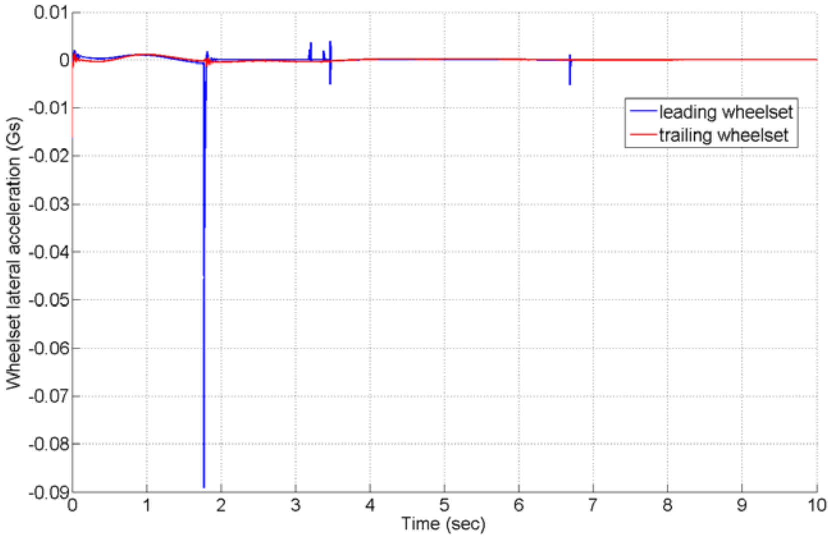

Figure 28. Wheelset lateral acceleration for Case 1

Figure 29 shows the wheelset yaw. As shown, as the wheelset enters flanging, the flanging forces turn the wheelset and reduce the yaw angle. The figure also shows that at 3.7 s, the wheelset is in tread contact phase, the flanging forces disappear, and the yaw angle starts to increase.

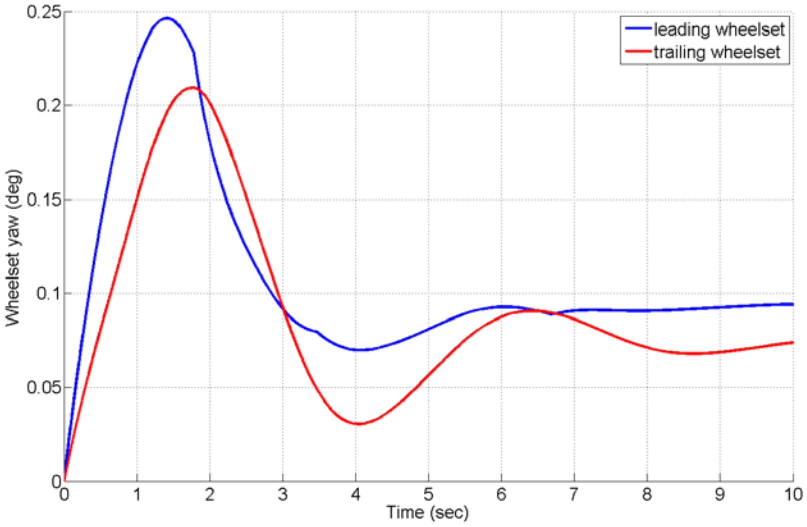

Figure 29. Wheelset yaw for Case 1

Figure 30 shows the right and left wheel lateral displacement. When the left wheel starts flanging (flange hits the rail), it causes the left wheel to displace suddenly; the flanging forces are transformed through the wheelset axel and cause the right rail to displace in the opposite direction.

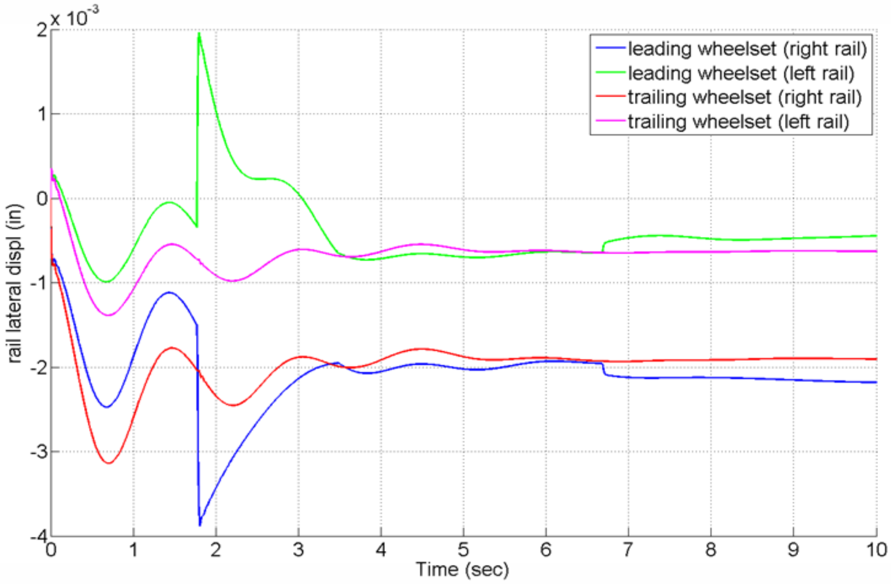

Figure 30. Rail lateral displacement for Case 1

Subsequently, the lateral displacement of the wheelsets causes the truck frame to move laterally (Figure 31).

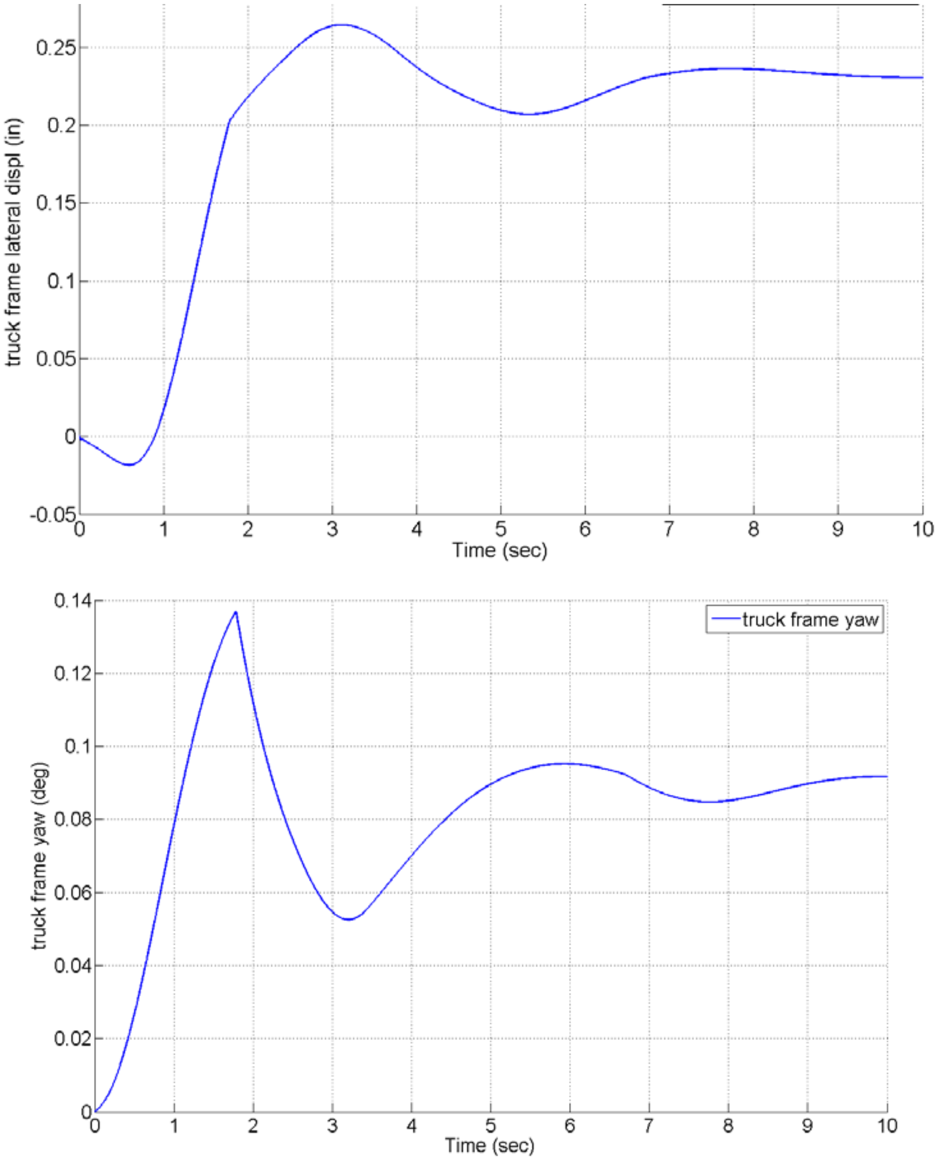

Figure 31. Truck frame lateral displacement and yaw

Figure 32 shows the normal forces for the leading wheelset as it negotiates a curved track; this figure shows that the right wheel is always in tread contact as expected; the left wheel enters flanging at time 1.8 s, and the normal force then is a combination of tread normal force (red line) and flange normal force (magenta line).

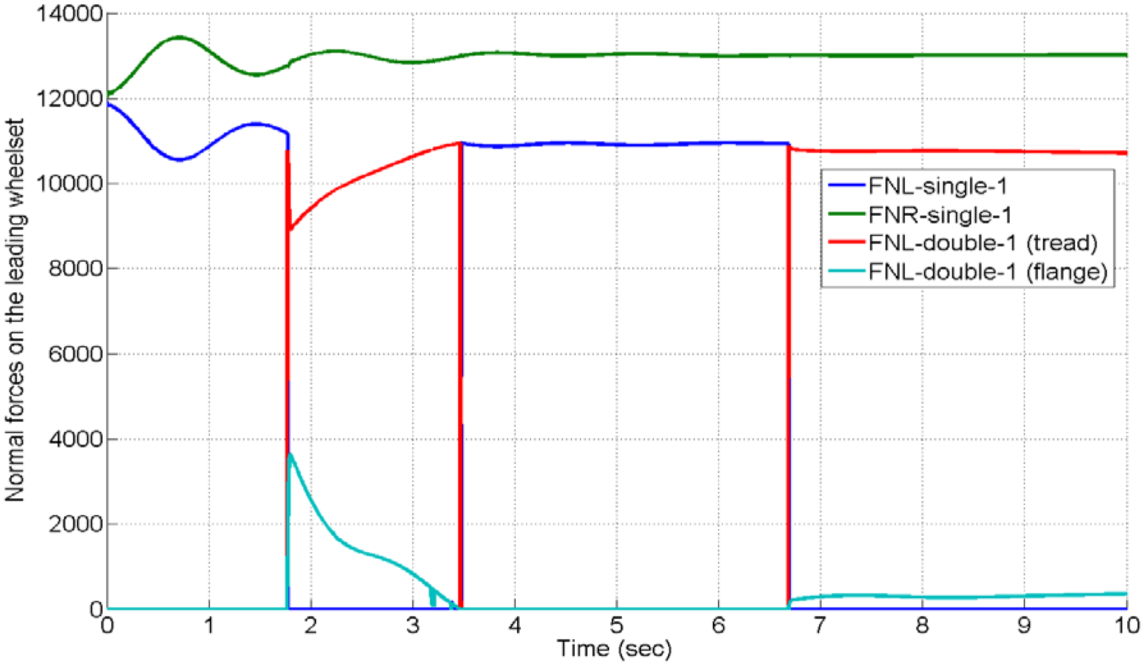

Figure 32. Normal forces on the leading wheelset

To study the effect of speed on the dynamic behavior of the model, Cases 1 and 5 are compared with each other; as can be seen in Table 26, all the conditions except for speed are the same in both cases.

Table 26. Case 1 and Case 5 parameters

Simulation	**Case 1**	**Case 5**
Balance speed (mph)	42.3	42.3
Superelevation (inches)	2.91 (3°)	2.91 (3°)
Speed (mph)	5	50
Degree Curve (degree)	2.5	

For the lateral displacement of the wheelsets, increasing the speed causes the leading wheelset to start flanging faster and to keep flanging the whole time; the trailing wheelset goes through more oscillatory movement before it reaches its steady state position, as is shown in Figure 33.

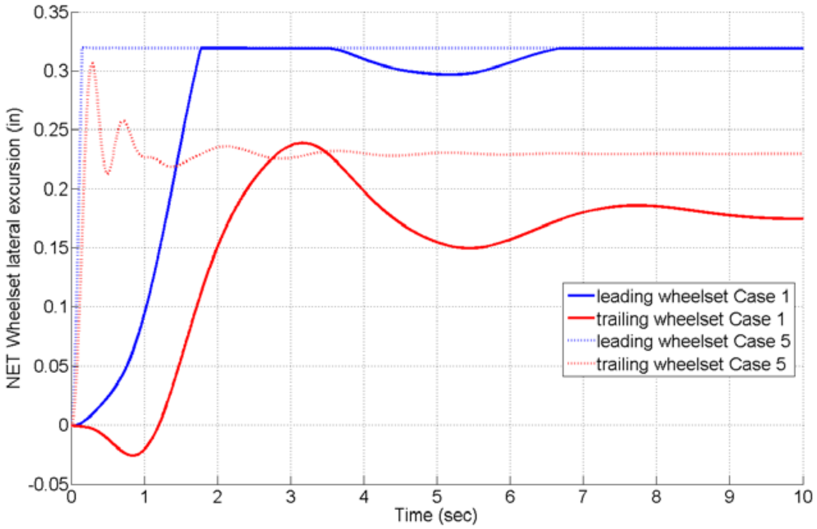

Figure 33. Net wheelset lateral excursion Case 1 and Case 5

A comparison of these figures shows that the right rail normal force is greater when the speed is lower and decreases as the speed increases; unlike the right wheel, normal forces (tread and flange) for the left wheel increase as the speed increases because of the increased centrifugal forces, as shown in Figure 34.

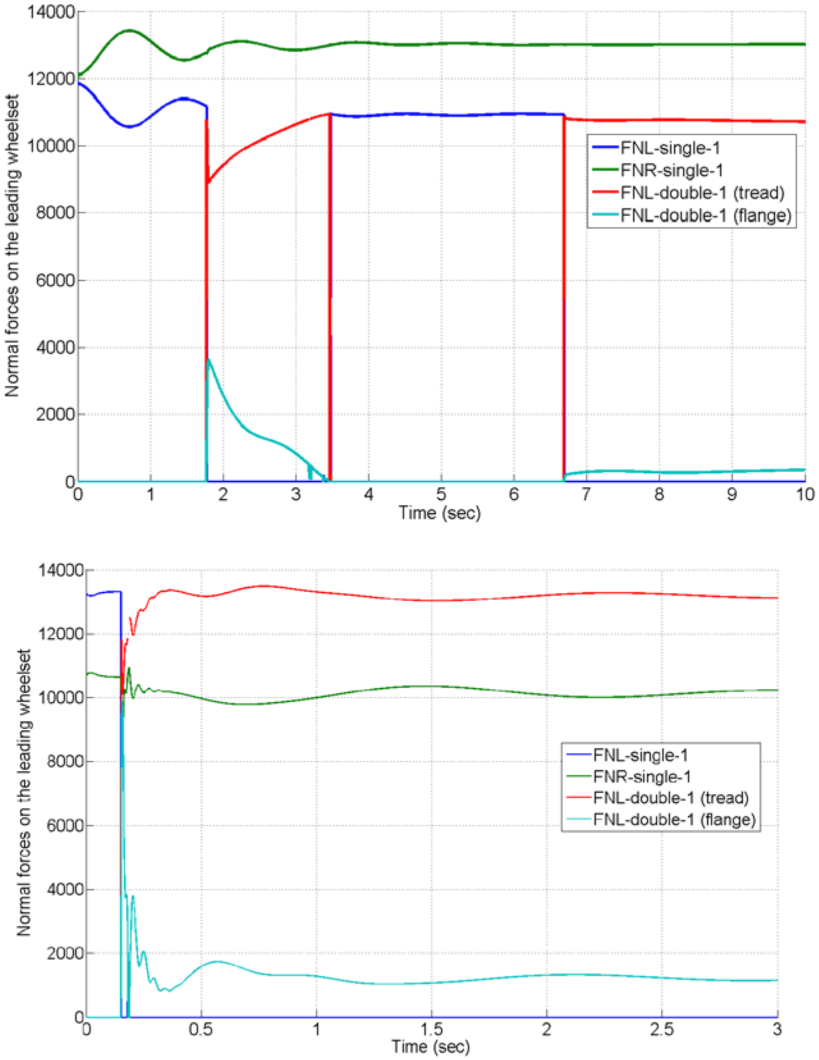

Figure 34. Normal forces on the leading wheelset Case 1 (top), Case 5 (bottom)

The effect of superelevation is studied by comparing Case 1 with Case 2. Characteristics of both cases can be found in Table 27.

Table 27. Case 1 and Case 2 Parameters

Simulation	**Case 1**	**Case 2**
Balance Speed (mph)	42.3	59.9
Superelevation (inches)	2.91 (3")	5.82 (6")
Speed (mph)	5	
Degree Curve (degree)	2.5	

As expected, increasing the superelevation of the track will cause less flanging at the outer wheel. In the event of increased superelevation, the leading wheelset flanges for only a couple of seconds and then goes to a single-point contact steady-state—unlike Case 1 which has a two-point contact steady-state, as shown in Figure 35.

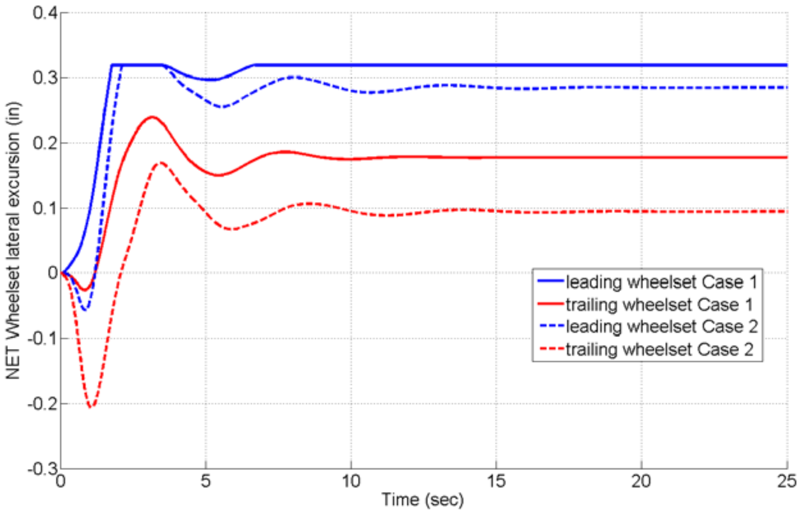

Figure 35. Net wheelset lateral displacement Case 1 and Case 2

The comparison of the normal forces show that the normal forces at the right wheel in Case 2 are greater than those in Case 1; and, as a result of superelevation, the normal forces at the left wheel in Case 2 are less than those in Case 1, as depicted in Figure 36.

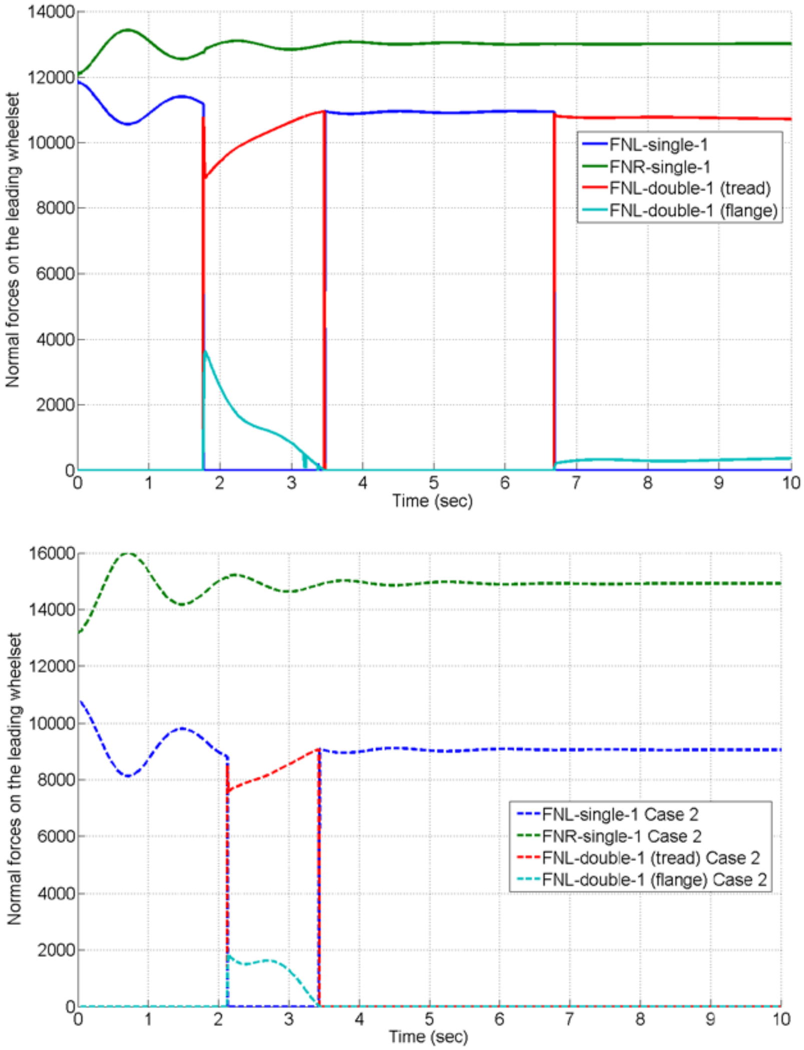

Figure 36. Normal forces on the leading wheelset Case 1 (top), Case 2 (bottom)

The last case studies the effect of track curvature on the dynamic behavior of the system; Case 1 is compared with Case 7. A brief comparison of the two cases is provided in Table 28.

Table 28. Case 1 and Case 7 Parameters

Simulation	**Case 1**	**Case 7**
Balance Speed (mph)	42.3	42.3
Superelevation (inches)	2.91 (3°)	2.91 (3°)
Speed (mph)	5	
Degree Curve (degree)	2.5	5

Figure 37 shows that as the radius of the curves get smaller, the leading wheelset reaches its two-point contact position sooner and remains in that position for the rest of the curve.

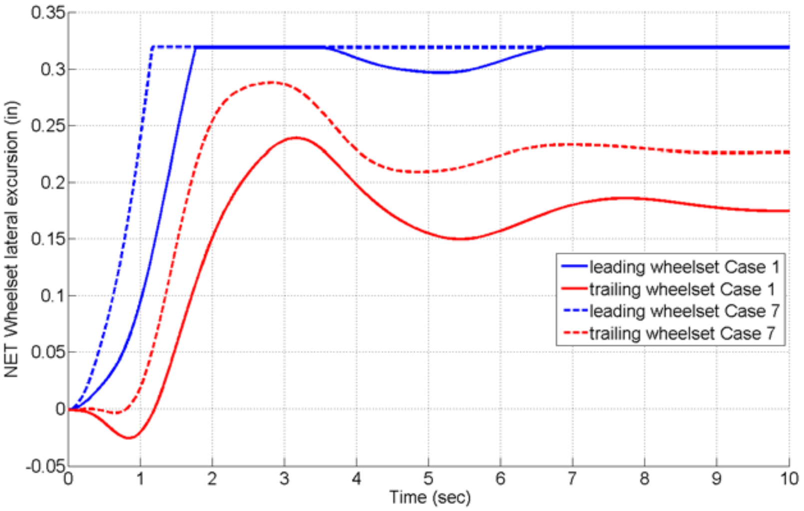

Figure 37. Net wheelset lateral excursion for Case 1 and Case 7

Normal forces at the right wheel decrease slightly as the curve radius is decreased, as clearly shown in Figure 38.

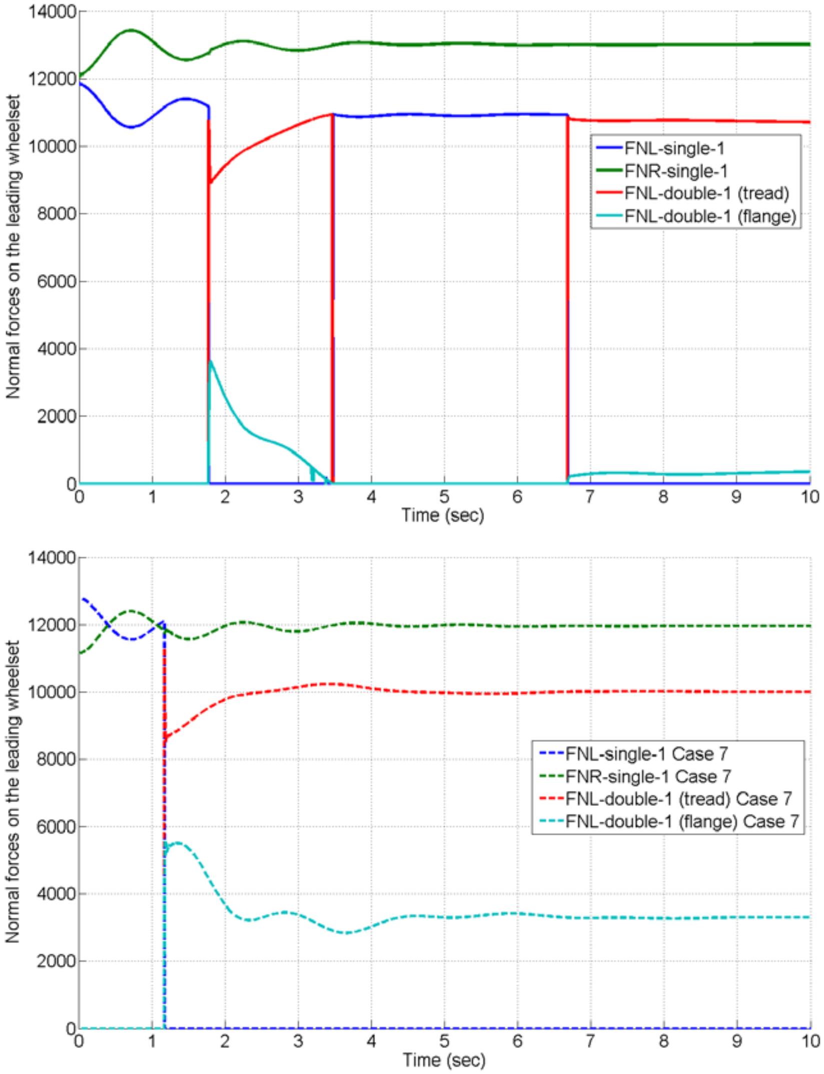

Figure 38. Normal forces on the leading wheelset Case 1 and Case 7

6.3 Modeling Summary

The case studies verified the model and now the outputs of the model can be used in the detailed design stage of the project to help specify the necessary components. The model can be used to study and get a better understanding of the effects of speed, curvature, superelevation, wheel-rail profile, and hunting dynamics. The model is currently under development to simulate different truck configurations.

7. Conclusion

The preceding discussions present and summarize various aspects of the design concept phase of this project, including the scoring and modeling work. The design concepts were originally intended to meet the three goals listed in Section 1:

1. Study traction ellipse
2. Measure all possible parameters of the dynamics
3. Allow testing with fielded and standard wheels and rails

A thorough review of past studies, evaluation of present and past roller rig test systems, and consultation with those involved in operating such systems have made us realize that the first and third goals cannot be achieved easily by the same test rig. The fundamental requirements of the two goals are not congruent. They require a system arrangement, actuation mechanism, and sensory suite that are different in their range of capabilities. Attempting to combine the two goals can result in a system that is either overly complex or not capable of achieving either goal successfully.

Study of the traction ellipse requires precision control and sensor resolution so small that it will be at odds with the large tolerances of typical railroad equipment. Production bearings, sideframes, bolsters, axles, and wheels are all designed for long life under a variety of harsh conditions. They are not commonly designed with the level of precision that is needed for repeatable and accurate measurement of wheel-rail contact dynamics. The fielded and standard component variability would introduce measurement variations that exceed those required for contact patch dynamics studies. Further, if one intends to study the effect of a standard or fielded component on a dynamic event, such as derailment, one is interested in the interaction of various truck components at a macro scale, not necessarily what happens at the contact patch.

It is, however, not lost on us that the U.S. railroads—and railroad practitioners worldwide—are highly interested in having access to a test facility that will allow them to study operational- and safety-critical events in an environment with far higher testing repeatability than the field. It is, however, recognized that one may not be able to test many dynamic events and rail and wheel conditions in the field with a sufficient degree of repeatability to conclusively study the effect of one event's specific effect on train operation. Such needs can only be realized by systems that are far more precise and sophisticated than the existing roller rigs that are predominantly used for wheel or rail life testing. The latter can be achieved with repeated cycles and brute force, whereas the former requires a high degree of precision. We believe that the gap between the existing systems and a rig that can allow duplicating field events in the controlled environment of the laboratory can be greatly bridged through a scaled design that allows precise measurement of contact forces, moments, displacements, and velocities beyond the current state of the art. The scaled system will serve as a stepping-stone by allowing us to better assess and control the high-risk elements of a full-scale test rig.

We recommend that FRA fund a project that is geared towards designing and fabricating a scaled rig for wheel-rail contact mechanics and dynamics studies. Once the efficacy of such a rig is proven, it may be followed by a more ambitious project of constructing a full-scale rig in the next decade.

8. References

1. Iwnicki, S., *Simulation of wheel-rail contact forces.* Fatigue & fracture of engineering materials & structures, 2003. 26(10): p. 887–900.
2. Marshall, M.B., *Experimental characterization of wheel-rail contact patch evolution.* Journal of tribology, 2006. 128(3): p. 493–504.
3. Iwnicki, S., ed. *Handbook of Railway Vehicle Dynamics*. 2006, Taylor & Francis Group: Boca Raton, FL.
4. Garg, V.K. and R.V. Dukkipati, *Dynamics of Railway Vehicle Systems*. 1984, Orlando, FL: Academic Press, INC.
5. Dukkipati, R.V., *A Parametric study of the lateral stability of a rail bogie on a roller rig.* Proceedings of the Instituion of Mechanical Engineers. Part F, Journal of rail and rapid transit, 1999. 213(1): p. 39–47.
6. Allen, P.D., *The critical speed of a railway vehicle on a roller rig.* Proceedings of the Institution of Mechanical Engineers. Part F, Journal of rail and rapid transit, 2001. 215(2): p. 55–64.
7. Iwnicki, S.D., *Validation of a MATLAB railway vehicle simulation using a scale roller rig.* Vehicle system dynamics, 1998. 30(3): p. 257–70.

Abbreviations and Acronyms

NS	Norfolk Southern
LIDAR	Light Detection and Ranging
AoA	Angle of Attack