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QUANTIFICATION OF RAIL DISPLACEMENTS UNDER LIGHT RAIL TRANSIT FIELD LOADING CONDITIONS

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ABSTRACT

While timber crossties are widely used in North America, the popularity of concrete crossties has increased significantly in recent years. Concrete crossties require the use of premium elastic fastening systems to have a proper and stable system.

The primary role of fastening system is to attach the rail to its support preserving track geometry. For this reason, past research has focused on its development and behavior. Even though a large amount of research has been conducted on heavy-haul freight railroad systems, little work has been conducted to focus on rail transit systems. Therefore, a field analysis of the behavior of fastening systems under rail transit system loading conditions has been executed, focusing on light rail transit loading conditions.

To perform this study, revenue service field data were collected on a light rail transit system. The instrumentation used and how it was installed on site are described in this paper. The critical quantitative metric discussed in this study is the relative displacement of the rail with respect to the concrete crosstie. Analyzing vertical and horizontal displacements, as well as rotation, the performance of the fastening system can be evaluated. For this purpose, different sites on the same rail system were selected for study, comparing both curve and tangent track geometry. In addition to this, the movement of the rail under every axle of the light rail vehicle has been studied in detail.

In summary, an analysis of how the rail performs in terms of displacement under light rail transit loading conditions has been completed. Based on field data, the analysis allows the reader to understand how the rail displaces under the given loads when it is installed in a ballasted concrete crosstie track and restrained by elastic fastening systems.

INTRODUCTION

Rail displacements are a major concern in terms of track performance. Keeping the appropriate level of serviceability in the track is a key to increasing the time between maintenance cycles and reducing cost. Irregular track geometry might cause accelerated deterioration in the track due to higher impact loads. In addition to this, excessive rail displacements could generate adverse safety impacts related to the operation of the line, demanding the use of reduced speeds, therefore, affecting the efficiency of the system.

Both in North America and internationally, the most common type of track infrastructure is ballasted. Over the last decade, the usage of concrete crossties has increased at an accelerated rate due to its capacity to perform at a satisfactory level in cases when timber crossties cannot [1]. Rail transit systems have opted for the generalized use of concrete crossties ensuring a superior ride quality [2]. In addition to this, the variability of the loading conditions due to the changing operation speeds, the different static loads of the cars and maintenance-of-way equipment, as well as environmental and extreme weather conditions, cause uncertainty in the demand on the track that leads to the adoption of concrete crossties [2].

Using concrete crossties provides an overall higher stiffness of the track, as the conformed system is more rigid. This places a higher demand on the fastening system, requiring higher performance to maintain the integrity of the track. Fastening systems must ensure the ability to maintain track gauge and prevent excessive rail movement that might cause accelerated failure of other components of the superstructure of the track [3]. Hence, the requirement of premium elastic fastening systems is a characteristic of concrete crosstie ballasted track.

Extensive research has been done for this type of track under freight railroad loading conditions, but not for rail transit systems. For this reason, this research aims to evaluate the performance of fastening systems under light rail transit loading conditions as well as to propose a methodology for future cases.

METHODOLOGY

In order to quantify the actual demand inferred by light rail vehicles on the track, this project and its data are based on field measured data. The field instrumentation used for this project, which is introduced in the next section, allows for the quantification of different loading demands on the track. For the purpose of this paper, rail displacement data as well as input load data have been quantified. Simultaneously, the number of axles as well as the train operating speed has been recorded for every of the train passes that has been analyzed.

Rail displacement has been quantified as relative to the crosstie. The intention of capturing the relative displacement to the crosstie instead of the total displacement of the track is to better assess the fastening system performance. Therefore, the measured displacement of the rail will be only the movement that is allowed by the fastening system. Vertical and horizontal displacements of the base of the rail, as well as rail rotation, were measured. Displacements are measured under every axle and between trucks where, theoretically, uplift of the rail can be found.

Dynamic rail loads have been measured in parallel with the rail displacements. Based on previous University of Illinois at Urbana-Champaign (UIUC) research [4] using strain gauges applied on the rail, both vertical and lateral loads can be measured in a similar fashion to a Wheel Impact Load Detector (WILD), albeit on a smaller scale. Static loads of the different axles were provided for comparison. Based on the recorded field data, an analysis of the results can be conducted, understanding how the system behaves under load. This study was conducted at both a tangent and a curve site.

As part of the path forward of this study, analytical and finite element models (FEM) will be used in order to predict the track behavior given the measured inputs. Laboratory tests might be included to support future conclusions.

FIELD INSTRUMENTATION SETUP

Revenue service loading and displacements were measured using the following types of instrumentation:

- Linear Potentiometers - Used to measure rail base displacements (vertically and horizontally). The maximum stroke length used is 1.181 inches (30 mm) with and repeatability of ±0.00008 inches (±0.002 mm). The model that has been used is Novotechnik TS-0025.
- Portable Displacement Measurement Device (PDMD) - Rapidly deployable bracket with 6 linear potentiometers fixed to it. The different metrics measured with PDMDs were the horizontal displacement of the base of the rail, and the vertical displacement of it, both in the field and the gauge side of the rail. Vertical displacement of the base was measured on both sides in order to calculate rotation of the rail. All three metrics were collected twice, once at each side of the fastening system. PDMDs are affixed to the selected crosstie, placing the tip of the potentiometers on the rail base. These brackets are non-permanent, being placed on site only for the measurement, then taken out after completing the field data collection.

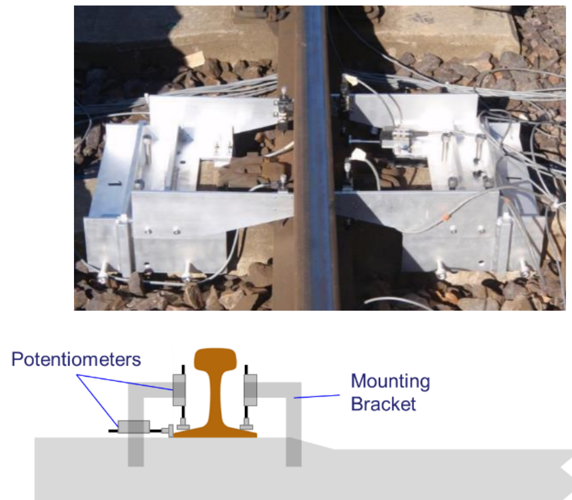

Figure 1. Portable Displacement Measurement Device installed on-site and sketch

- Rail Strain Gauges - Used to measure the forces in the rail induced from applied loads. Strain gauge bridges are applied to rail web and flange. As the collected information is the strain of the rail under the given loading conditions, using the proper calibration factor, the actual dynamic force is measured. Vertical and lateral input loads in both rails are recorded.
- Automated Compact Data Acquisition (cDAQ) System manufactured by National Instruments (NI). Used to record data coming from potentiometers and rail strain gauges. Can be triggered manually or via laser sensor activation. For the purpose of this work, the system was triggered manually.

FIELD SITES

Locations

The scope of work for this project has been limited to one light rail transit system. The partner agency for this project is St.

Louis MetroLink, where two different sites were installed with field instrumentation.

The first site, known as curve site or pilot site, is a curve located in Belleville, IL. This curve has a maximum allowable speed of 45 mph (72 km/h) with a 6° curve, 955 ft (291 m) of radius and a superelevation of 5.25 in (133 mm). The balance speed of the curve is 35.4 mph (57 km/h). Both low and high rails have been instrumented with PDMDs and rail strain gauges. Data from 36 trains has been used for this analysis.

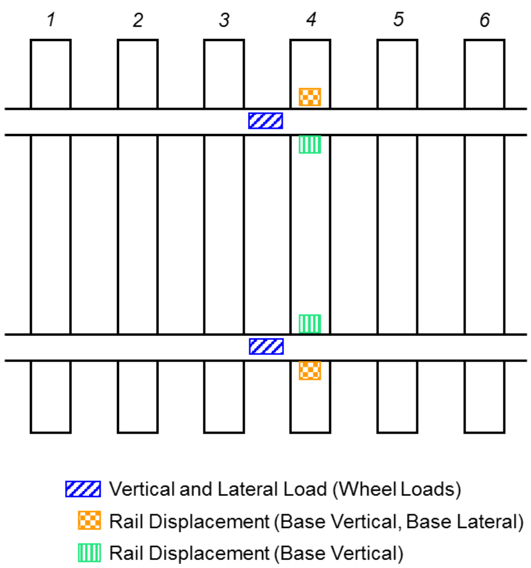

Figure 2. Curve site field instrumentation plan

The second site instrumented for this project was a tangent site, also on St. Louis MetroLink. This site was located in East St. Louis, IL, where track speed is 55 mph (88 km/h). Data from 6 trains has been collected for this analysis.

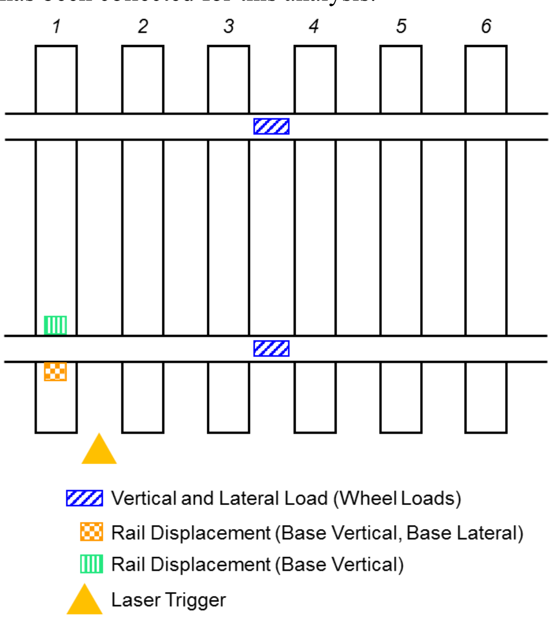

Figure 3. Tangent site field instrumentation plan

Track Characteristics

St. Louis MetroLink sites consist of concrete crossties and ballasted track. The concrete crossties used are the CXT 100-06, which are 8'3" (2,515 mm) long and are produced by LB Foster CXT Concrete Ties. The CXT 100-06 is a mono-block prestressed concrete crosstie. These crossties use a Pandrol Fastclip FE fastening system. The rail type installed is 115RE (standard rail size used) conforming to AREMA specifications as required by St. Louis MetroLink.

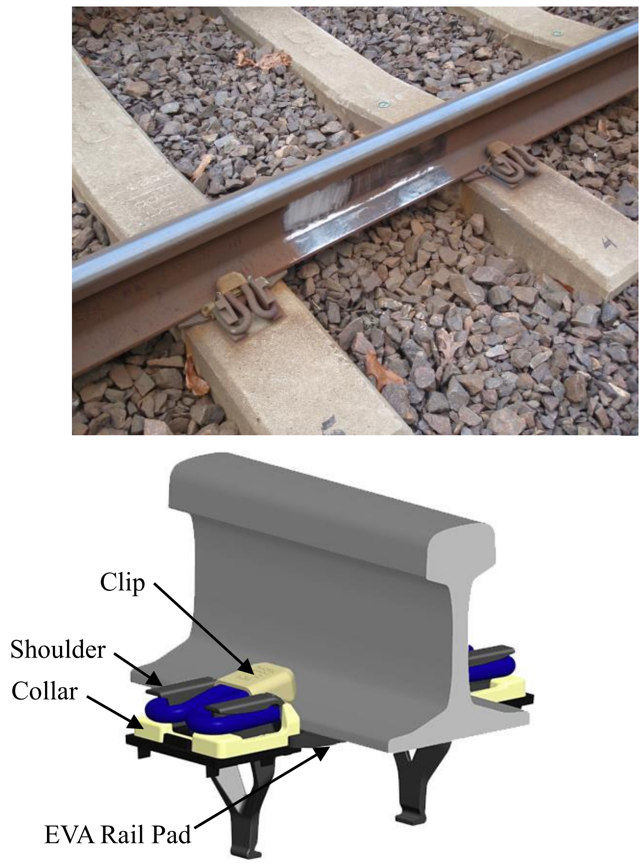

Figure 4. Pandrol Fasclip fastening system used on St. Louis MetroLink and drawing where components are identified

The Pandrol Fastclip FE is a premium fastening system manufactured by Pandrol Track Systems. Designed as a total system, all components are delivered to site pre-assembled on the crosstie [5]. The main parts of this system as described by Pandrol [5] are:

- Clip with toe insulator. This is the part of the fastener that restrains the rail from uplift.
- Cast shoulder for gauge retention. This component absorbs the lateral forces imparted to the rail, restraining it from horizontal displacements.
- Collar that provides lateral stiffness, helping in providing gauge retention (restrains horizontal displacement).

- Studded EVA rail pad that provides high impact attenuation. This is the component that absorbs downward vertical displacements.

Light Rail Vehicle

The light rail vehicles (LRVs) used in this system are Siemens SD-400 and Siemens SD-460. In general, LRVs have powered and unpowered trucks. For the cars used in this system, each vehicle has two powered trucks and one center unpowered truck, adding up to a total of 6 axles per car distributed in 3 trucks. The wheel static load ranges from 6.49 kips (28.87 kN) to 9.59 kips (42.66 kN) in the empty condition (AW0), having heavier loads for the powered axles (Table 1). The specific static loads for each wheel are given in Table 1 for AW0 and AW3 (crush load conditions), assuming that all the wheels are equally loaded when the train is in AW3 loading conditions.

Table 1. AW0 and AW3 static wheel loads for St. Louis MetroLink light rail vehicles

Axle	Static Wheel Load AW0	
	Left Wheel	Right Wheel
	kips (kN)	kips (kN)
1	9.56 (42.50)	7.55 (33.58)
2	9.59 (42.66)	7.43 (33.05)
3	6.97 (31.00)	6.80 (30.25)
4	7.29 (32.43)	6.49 (28.87)
5	7.84 (34.87)	9.21 (40.97)
6	8.04 (35.76)	9.14 (40.66)

Axle	Static Wheel Load AW3	
	Left Wheel	Right Wheel
	kips (kN)	kips (kN)
1	12.46 (55.42)	10.45 (46.48)
2	12.49 (55.56)	10.33 (45.95)
3	9.87 (43.90)	9.70 (43.15)
4	10.19 (45.33)	9.39 (41.77)
5	10.74 (47.77)	12.11 (53.87)
6	10.94 (48.66)	12.04 (53.56)

The static loads provided in Table 1 were provided by St. Louis MetroLink engineering staff.

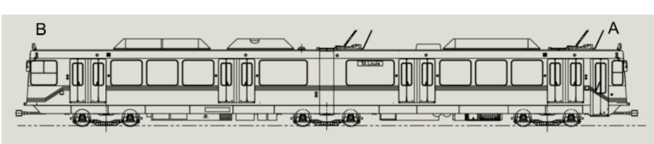

Figure 5. Drawing of LRV used on St. Louis MetroLink

The normal trainset consists of two coupled vehicles in ABBA configuration, adding up to 12 axles per train pass. The BA configuration of one car is shown in Figure 5.

DATA COLLECTION

The data collected includes horizontal and vertical displacements, as well as rotation under the 12 axles and between trucks of each train pass. In total, 18 data points have been recorded for each displacement and for each train measured. Recording of data was done with the cDAQ through the linear potentiometers mounted on the PDMDs and the rail strain gauges. The sampling rate used was 2,000 Hz. A calibration factor has been used to transform the raw voltage data recorded to displacement in inches. This is the relation between the mechanical stroke length of the potentiometer, which is 1.181 inches (30 mm) and its maximum output signal in terms of voltage (2.5 V). The obtained signal has been processed employing a harmonic filter and performing a baseline correction to obtain the desired displacement results.

RESULTS

Curve Site

A total of 36 train passes were analyzed for the curve site, measuring displacements in high and low rail. Results are presented using box plots to be able to visually evaluate the displacements' distributions. Box plots are used to present the data, placing the central 50% of the total data inside the box, defined as inner quartile range (IQR). The median is shown to separate the two central quartiles. In addition to this, whiskers and crosses are used to represent maximums, minimums and outliers.

Peak results are presented in Figure 6 for horizontal, vertical field, and vertical gauge displacements of high and low rail at the curve. For lateral displacements, movement towards the field side has been considered as positive. As a reference for vertical displacements, upward values were taken as positive.

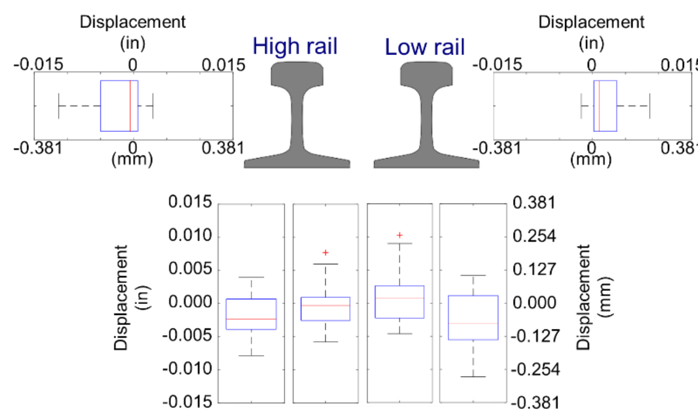

Figure 6. Displacements in curve site by rail and by potentiometer

Considering lateral movement of the rails, displacement toward the field side is predominant, with almost 75% of the values as positive in high and low rail. In general, gauge opening is found under train passes on the curve site. Residual lateral displacement towards the gauge side is found, due to friction at the wheel-rail interface. When comparing absolute values, the maximum displacement towards the gauge side found was 30% of the maximum positive displacement. Maximum measured displacements toward the field side are 0.0113 (0.29 mm) in and 0.0086 in (0.22 mm) for high and low rail, respectively.

Vertical displacements in the field side distributed similarly for high and low rail in the curve. The majority of the dataset showed downward displacements. Uplift displacements up to 40% of the highest negative vertical displacements were recorded for the field side vertical displacement in both rails. Largest vertical downward displacements recorded on site are 0.0111 in (0.28 mm) and 0.0078 in (0.20 mm) for the low rail and high rail, respectively.

Results for gauge side vertical displacements of the base showed that the uplift of the rail is equal or higher than the downward movement. This information, in addition to results for the vertical displacement in the field side, proves rotation of the rail towards the field side in high and low rail.

In order to achieve a better understanding of the behavior of the rail under wheel pass, the results were discretized by wheel and axle, from 1 to 12, being wheel 1 the first to pass over the instrumented site.

Given the consistent nature of the results for both of the cars of the train, the following plots represent the measured displacements of each axle of one car. A schematic of how the results have been grouped is shown in Figure 7.

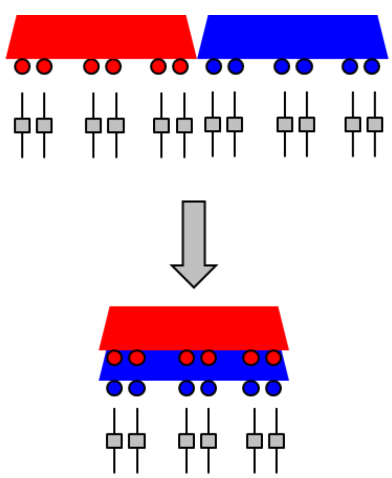

Figure 7. Axles grouping sketch

Displacements discretized by axle within a car are shown in Figures 8 to 13.

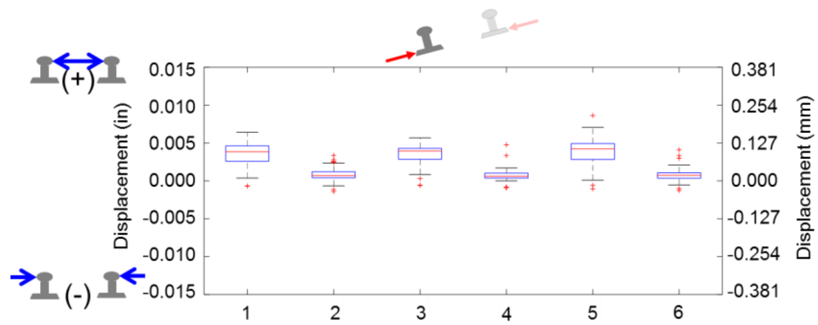

Figure 8. Horizontal displacements in low rail and by LRV wheel (1-12)

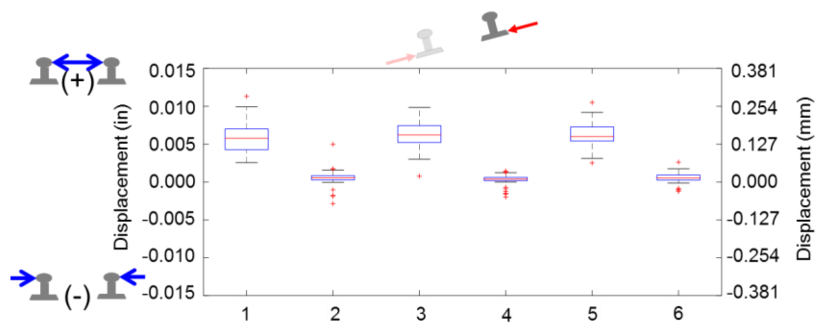

Figure 9. Horizontal displacements in high rail and by LRV wheel (1-12)

As can be seen in Figures 8 and 9, when lateral displacements under each wheel load were obtained, a defined pattern could be observed in high and low rail. While the leading axles cause the highest displacements on the system, trailing axles inferred minor disturbance in the rail. This gives an overview of the dynamic behavior of the rail in the curve under dynamic loading of cars. While leading axles force themselves through the rail in the curve, trailing axles come along before the rail has time to recover to its original position.

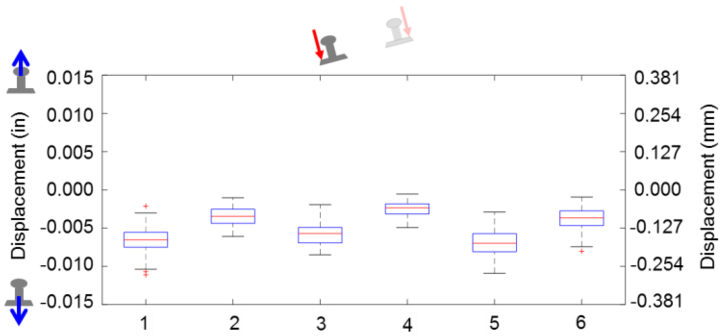

Figure 10. Field side vertical displacements on low rail by LRV wheel (1-12)

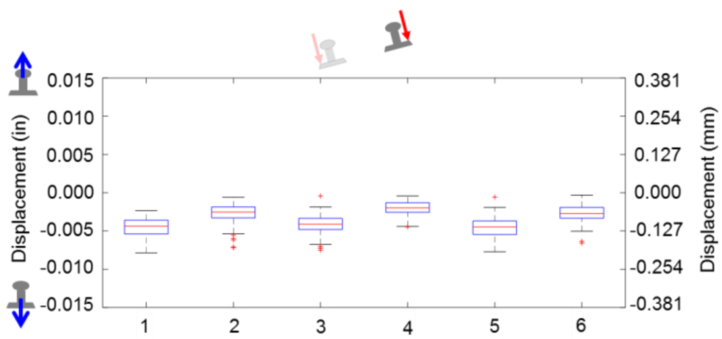

Figure 11. Field side vertical displacements on high rail by LRV wheel (1-12)

Vertical displacements on the field side are shown in Figures 10 and 11, where similar behavior to what was noted for lateral displacements was found. Again, the leading axle of every truck caused larger displacements while under the trailing axles the rail moved less. In this case, due to vertical loads being larger than lateral loads, displacements under trailing axles are noticeable.

Gauge side vertical displacements are represented in Figures 12 and 13, and show different behavior for low and high rail.

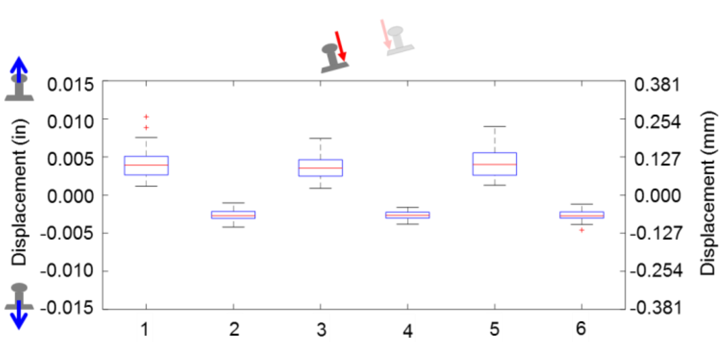

Figure 12. Gauge side vertical displacements on low rail by LRV wheel (1-12)

In Figure 12, vertical displacements on the gauge side for the low rail are shown by wheel. Movement in the low rail showed a clearly defined pattern, with positive displacements measured under leading axles while negative displacements were measured under trailing axles. As seen in previous results, the highest displacements in absolute value are found under the leading axles.

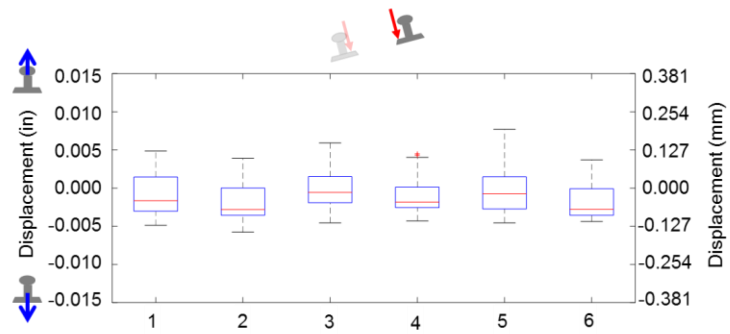

Figure 13. Gauge side vertical displacements on high rail by LRV wheel (1-12)

As show in Figure 13, displacements in high rail under wheel loads had two types of behaviors:

- Alternating negative and positive displacements for consecutive axles. Negative displacements were predominant under leading axles versus positive displacements being predominant under trailing axles.
- Negative displacements under all 12 wheel loads, finding larger displacements under leading axle wheel loads.

Having found opposite behavior on the gauge side vertical displacement for high and low rail suggested that the attack angle of the wheel when entering the curve causes the train dynamics to have different effect on each of the rails. The light rail vehicles used in St. Louis MetroLink (Siemens SD-400 and Siemens SD-460) have rigid trucks, not allowing the individual steering of each axle. In addition, the rotation of the rail obtained was larger for the low rail.

Tangent Site

A more focused analysis was performed by UIUC researchers for the tangent site. Capturing data for 6 trains on one rail, the same study was performed. Horizontal displacement, as well as vertical displacement on the field and the gauge side of the base of the rail were measured with field instrumentation.

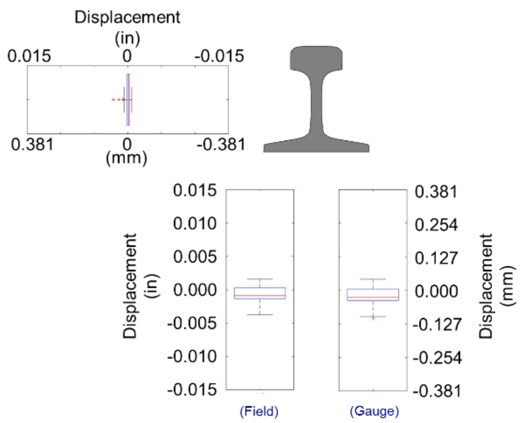

Figure 14. Displacements by rail and by potentiometer

Results of the conducted field instrumentation are represented in Figure 14. As was expected, rail at a tangent location under the same light rail transit loading conditions showed smaller displacements that when studied in curve. The maximum lateral displacement measured was 5 times smaller than maximum measured in low rail for the curve site analysis. Vertical displacements on field and gauge side showed similar distribution indicating that the rail did not rotate at the tangent site.

Displacements were found to be consistently smaller than for the curve site for negative displacements, as well as for uplift of the rail.

Table 2. Maximum measured displacements under light rail transit loading conditions

			Max.	Min.
			in*10^{-3} (mm)	in*10^{-3} (mm)
Curve	Low Rail	Horizontal	8.6 (0.22)	-1.7 (-0.04)
		Vert. Gauge	10.3 (0.26)	-4.6 (-0.12)
		Vert. Field	4.2 (0.10)	-11.1 (-0.28)
	High Rail	Horizontal	11.3 (0.29)	-3.0 (-0.08)
		Vert. Gauge	7.7 (0.20)	-5.8 (-0.15)
		Vert. Field	3.9 (0.10)	-7.8 (-0.20)
Tangent	Rail A	Horizontal	2.2 (0.06)	-0.5 (-0.01)
		Vert. Gauge	1.6 (0.04)	-4.2 (-0.11)
		Vert. Field	1.6 (0.04)	-3.7 (-0.09)

CONCLUSIONS

Displacements of the rail under light rail transit loading conditions were collected and analyzed by UIUC researchers. The study shows the behavior of the fastening system under the given loading conditions based on field measurements at a light rail transit system (St. Louis MetroLink).

Horizontal displacement of the rail was found to be consistently toward the field side under wheel loads, meaning that gauge opening occurs under a train pass. Larger displacements were measured at the curve site with respect to the tangent site meaning that this part of the track presents a higher challenge for the performance of the fastening system. Additionally, the curve site showed more complex rail dynamics under wheel loads.

Some specific conclusions for each of the analyzed track segments can be drawn:

For curve site:

- Gauge side alternates positive and negative values. In other words, rotation of the rail was found to occur under a truck (two axle) pass. Rail displacement under a train pass contributes to gauge widening.
- Leading axles of every truck caused the largest displacements on the system. The displacement of the rail primarily occurs under the leading axle, not allowing the rail to recover its original position before the trailing axle pass.
- Rotation of the rail was toward the field side.

For tangent site:

- Rotation of rail is much lower than expected, even negligible at times.
- Minor horizontal displacements were captured. The measured lateral displacement due to the rocking of LRVs did not have a relevant magnitude.

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