FTA RESEARCH

FEDERAL TRANSIT ADMINISTRATION

Integrated Wheel/Rail Characterization through Advanced Monitoring and Analytics

OCTOBER 2019

FTA Report No. 0145
Federal Transit Administration

PREPARED BY
MTA/New York City Transit
2 Broadway, New York, NY 10004

IN COOPERATION WITH
KLD Labs
Dayton T. Brown
Plasser-American
National Research Council of Canada
New York City Transit Subway Group
New York City Transit Office of Strategic Innovation and Technology

U.S. Department of Transportation
Federal Transit Administration

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DISCLAIMER

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Federal Transit Administration
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1200 New Jersey Avenue, SE
Washington, DC 20590

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

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13. ABSTRACT This report documents a multi-year, multi-member collaborative research effort to demonstrate machine-vision enabled wheel/rail characterization, monitoring and analytics. A unique suite of data acquisition equipment was employed. In-track laser wheel scanning, wayside Lateral over Vertical (L/V) force measurement, Truck Bogie Optical Inspection (TBOGI), and Track Geometry Car (TGC) track inspection technology were combined with a Data Collection Consist (DCC) in revenue service equipped with on-board accelerometers, acoustic and propulsion energy recording devices, and a bogie with two instrumented wheel sets. The effort primarily targeted two required FTA Solicitation categories: Operational Safety & System Resiliency. Enhanced operational safety was demonstrated through data collection supporting analytics to proactively assess conditions to enhance system safety. Conditions were monitored by the wheel/rail characterization and analytics systems. Comparisons of "before event" system data signatures with "after event" system data signatures accurately identify track flaws and damage and failure points to accelerate repairs and service recovery following an event.			
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The Data Collection Consist and wheel scanner owe their successful operation to the members of the #7 Line Car Desk Rapid Transit Organization (RTO) and Corona Car Maintenance Facility Team. Without their support and schedule flexibility each day, the successes of our research efforts could have been seriously reduced.

Cooperation of Subways Car Equipment Engineering and Maintenance of Way (MOW) Track Engineering was excellent in facilitating the acquisition of real-time data from vehicles in revenue service in a safe and well-managed manner.

Acknowledgments would not be complete without mention of the Federal Transit Administration (FTA) Office of Research, Demonstration and Innovation and the MTA Grants Group for working in a supportive manner over the entire wheel/rail research period of performance.

Abstract

This report documents a multi-year, multi-member collaborative research effort to demonstrate machine-vision enabled wheel/rail characterization, monitoring and analytics. A unique suite of data acquisition equipment was employed. In-track laser wheel scanning, wayside Lateral over Vertical (L/V) force measurement, Truck Bogie Optical Inspection (TBOGI), and Track Geometry Car (TGC) track inspection technology were combined with a Data Collection Consist (DCC) in revenue service equipped with on-board accelerometers, acoustic and propulsion energy recording devices, and a bogie with two instrumented wheel sets. The effort primarily targeted two required FTA Solicitation categories: Operational Safety & System Resiliency. Enhanced operational safety was demonstrated through data collection supporting analytics to proactively assess conditions to enhance system safety. Conditions were monitored by the wheel/rail characterization and analytics systems. Comparisons of "before event" system data signatures with "after event" system data signatures accurately identify track flaws and damage and failure points to accelerate repairs and service recovery following an event.

EXECUTIVE SUMMARY

A multi-member collaborative research team led by the New York City Transit (NYCT) Office of Strategic Innovation and Technology (OSIT) and hosted by the NYCT Department of Subways Maintenance of Way (MOW) Track Engineering and Car Equipment Engineering (CEE) groups was awarded a multi-year research grant from the FTA Office of Research, Demonstration and Innovation to demonstrate machine-vision enabled wheel/rail characterization and analytics to enhance operational safety and system resiliency.

This research effort employed a unique suite of state-of-the-art automated data collection equipment, including:

- In-track automated laser wheel scanning (WheelScan®) equipment at the Corona Car Wash on the #7 Flushing Line
- Wayside Lateral over Vertical forces (L/V) and Truck Bogie Optical Geometry Inspection (TBOGI) data acquisition devices located N/O 103rd St Station on the #7 Line
- On-board automated track inspection technology (existing) on the NYCT Track Geometry Car (TGC)
- An 11-car Research Data Collection Consist (DCC) in regular revenue service equipped with on-board accelerometers, acoustic and propulsion energy recording devices, and a bogie equipped with two instrumented wheel sets (IWS)

The project was initiated on August 5, 2015. After contracting, procurement, construction, and commissioning, the WheelScan® and DCC systems were fully operational in April 2017, and the TBOGI and L/V wayside systems were operational six months later. The demonstration period successfully continued through November 30, 2018.The project was completed within the original budget at a total cost of $4,631,869, which included $3,617,948 in FTA funding and cost-sharing by team members totaling $1,013,921. The total duration of the project is 52 months, ending on November 30, 2019.

The value of the research and evidence of potential for swift recapture of the research project investment was demonstrated with an estimated savings of approximately $10 million identified within the first two years following initiation of the research work, as shown in Table ES-1. This savings was associated with improved wheel service life and movement at NYCT's Corona Car Shop, away from non-optimum wheel maintenance and inspection practices, supported by the automated laser wheel scanning system and the DCC performance data.

However, the relatively short duration of the research period of performance proved insufficient to fully evaluate the total effectiveness of the suite of measurement systems to accumulate sufficient wheel and rail wear data and vehicle performance data to act upon and subsequently realize and quantify a number of longer-term improvements. More time and data monitoring will be required for that to occur.

Table ES-1

Evidence of Swift Recapture of FTA and Team Member Investment in Research Effort

Break Out of SMS Truck-Related Work with Estimates for Non-Optimum (Off-SMS Cycle) Wheel Work	
Labor Estimate	
797	Man hours for truck work in SMS cycle/car
$35.00	Hourly wage estimate
$27,895	Total labor cost/car for truck SMS
506	# cars in #7 Line fleet
$14,114,870	Total SMS cost for labor on truck work
50%	Estimate of labor (% SMS truck labor) for non-optimum wheel change
$7,057,435	
Material Estimate	
$55,413	Material cost/car for truck SMS work
506	# cars in #7 Line fleet
$28,038,978	Total materials cost for truck work in SMS cycle
10.00%	Estimate of wheel and axle costs in SMS cycle material
$2,803,898	
Estimated cost avoidance of one wheel change between SMS Cycle: $9,861,333	
Avoids one non-optimum wheel change by end of Year 2 of six-year SMS cycle	
Avoidance of 30-day mid-cycle manual inspections of entire #7 line fleet required by Office of System Safety after 2017 derailments	
Saving from elimination of extra 30-day cycle of manual wheel inspections: $240,000 per year in shop labor costs	

Table ES-2

Additional Project Efforts

Party Paying for Additional Effort	Description of Additional Work	Estimated Cost of Effort
NYCT Car Equipment Engineering	LTK/ARM Curve & Guard Rail Study	$400,000
NYCT MOW Track	34th Street Curve Rail Grinding 4/10–16, 2017; 11/11–12/2017;3/9–48, 2018	$127,016
Perpetuum	Perpetuum On-Board Energy Harvesting and Wheel Sensor Proof of Concept	$429,360
ConEd	ConEd/CUNY/NYCT Regenerative Braking Energy Study	$462,446
DOT RAILTEAM University Transportation Center	University of Delaware Wheel Wear White Paper	$34,000
New York State Energy Research and Development Authority) & City University of New York)	NYSERDA/CUNY & ConEd/NYCT Bi-Directional SubStation Feasibility Study	$486,321
Estimated total of additional efforts enabled by FTA wheel/rail research		$1,939,143

The collaborative wheel/rail research effort played an enabling role in a number of additional activities (totaling $1,939,143) undertaken at NYCT during the research work. Each activity incorporated data streams from the work that heretofore had not been available from a revenue train. Those additional efforts are shown in Table ES-2.

The project was featured in *Trains* (October 2017), and research progress was disseminated regularly through presentations at U.S. Industry conferences, trade journal articles, and open WebEx meetings throughout the research period, as follows:

- May 2016, WRI Integrated Wheel/Rail Characterization through Advanced Monitoring and Analytics
- January 2017, TRB Rail profile design for Curve N/O 34th on NYCT/MTA's #7 (Flushing) Line
- June 2017, WRI Integrated Wheel/Rail Characterization through Advanced Monitoring and Analytics
- August 2017, ICRI Case Study: Investigating and Testing Accelerated Wheel/Flange Wear
- October 2017, APTA/AREMA Wheel/Rail Interface Group – presentation at NYCT's Corona Car Shop
- April 2018, WRI FTA Research, Project NY-26-7113, Wheel/Rail Characterization, Monitoring, and Analytics
- June 2018, APTA NYCT Maintenance Innovation Using Research
- July 2018, CUTR Standards Working Group Meeting, Philadelphia
- March 2019, APTA N&V, presentation of FTA wheel/rail research effort
- June 2019, WRI Integrated Wheel/Rail Characterization through Advanced Monitoring and Analytics, research project review
- October 2019 (planned), World Congress on Railway Research (WCRR) presentation, Monitoring and Managing Wheel/Rail Forces by Using Instrumented Wheelset Technology

Research results from the project were numerous and varied. Data from each of the inspection systems were regularly transmitted to an FTP server accessible by all research team members, each of whom analyzed and reported on their respective data sets. An overall effort to integrate these data streams and analytics was undertaken by a team member (wheel/rail interaction specialist) from the National Research Council of Canada. This work began in earnest in April 2017 and continued until completion of the demonstration phases of the project into late November 2018.

Figure ES-1 illustrates how the data streams from each system could feed into and support various research outcomes and is a good visualization of what the research team was able to study with its unique suite of data acquisition equipment on a revenue train and active subway line. Although each tool has its own limited diagnostic capabilities and is valuable in its own right, the integration of these into one suite with multiple cross-correlations supported advanced analytics in the pursuit of the research objectives.

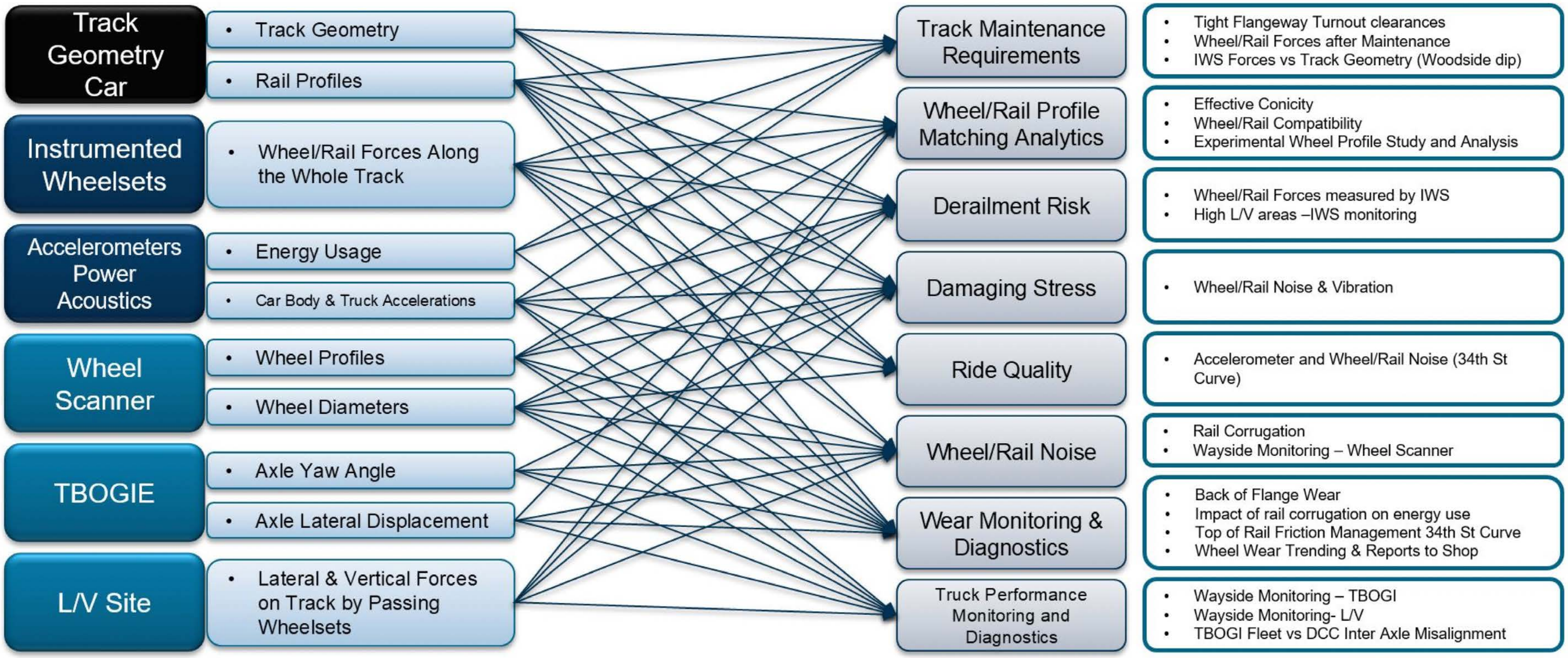


Figure ES-1 *Summary of potential linkages between technologies and analytics*

Research highlights and value estimates include the following.

Two restraining rail climb derailments in January 2017 led to a focus on the interaction of new and worn wheels with restraining rail components. The instrumented wheelset demonstrated that the as-installed condition at a turnout is associated with much higher lateral forces and a higher risk of restraining rail climb-outs when compared with the worn and well-lubricated conditions. One significant recommendation that followed is to review the existing restraining rail design and possibly develop a design that better matches the worn wheel population. The estimated value per occurrence of proactively avoiding derailments was 1) minor/no injury derailment – $25,000 for restraining rail climb-out derailment, and 2) major derailment resulting in injury or death – severity dependent, but could be $1 million or more.

Higher train speeds through restrained curves and turnouts increase wheel forces and derailment risk. Recommendations are to reduce such risks, including speed limits at some locations. These can be easily applied as the #7 Line moves to ATO (automatic train operation, also known as Communications-Based Train Control, CBTC). Quantifying the estimated value of increasing safe train speeds has not been estimated by any group at NYCT, primarily because until the total saved time in a daily operating period exceeds the equivalent of a complete round trip (1 hour 15 minutes on the #7 Line), the ability to operate an additional trip with existing equipment would not result. However, managing higher safe speeds within acceptable limits derived from analysis of actual lateral and vertical forces associated with actual track geometries and actual wheel conditions can result in shorter customer point-to-point transit times and ensure that speeds and system conditions do not result in unacceptable increased risks leading to derailments.

Several issues with wheel wear and wheel shape were uncovered. Some wheels were discovered to encounter heavy back-of-flange wear that results in a lower back-of-flange angle, which may contribute to increased risk of restraining rail climb. A new calculation was implemented in the WheelScan® system, such that wheels can now be monitored for this condition and proactively addressed as necessary. A step increase in wheel wear, both flange and back-of-flange, occurred in January 2018, believed to be the result of lubricator/friction management failure experienced under the coldest weather conditions. Wheel wear data from 2018 winter operations caused NYCT OSIT to revisit the performance properties of materials being widely employed for friction management (for rail lubrication as well as top of rail (TOR) friction management). Newly re-trued, unworn wheels were seen to incur high rates of flange wear over about the first three months of running and then declined to a much lower, almost zero, rate of wear thereafter. A new wheel profile was designed to mimic the worn shape and was installed on 20 wheels for testing on the #7 Line with the expectation of providing a significant extension (e.g., >20%)

to the wheel truing interval. The unworn wheels encounter very high effective conicity values, especially in tight-gauge track. Contrary to experience elsewhere, this means that the worn wheel is less likely to experience ride stability problems than the freshly re-trued, unworn wheel.

A wheel flange wear problem was noticed in early 2016 and traced back to the newly-opened track between 34th St–Hudson Station and Times Square in Fall 2015, leading to considerable focus on this track section. As a long (1,200 ft) and relatively sharp (650 ft radius or 8 degree) curve, it proved to be the site of considerable noise and recurring rail corrugation development. Rail corrugation developed rapidly on the low rail of the CC2 (upgrade) track but not on the high rail or either rail of the parallel (downgrade) CC1 track. Rail grinding was effective in removing corrugation but not in preventing its re-emergence. Noise measurements showed a strong peak at the value associated with the corrugation wavelength. Rail grinding dramatically reduced noise levels but they re-merged as the corrugation re-developed. Top-of-rail (TOR) friction management was recommended and is being trialed to determine its ability to mitigate rail corrugation, vibration, and noise. Improvements to lubrication and TOR friction management were implemented as a result of the increased scrutiny. Unfortunately, it has not yet been possible to claim success in having reduced wheel wear or corrugation rates. Studies of energy consumption showed that the removal of rail corrugation and re-profiling to a better contact shape resulted in a 5% reduction in energy use. This number, while significant, is smaller than expected. The reason is largely because the bulk of the energy is being consumed in surmounting the steep 2.5% grade and not in curving forces. A higher percentage reduction would be expected on track without grade.

Review of the rail profiles suggest that the high rail is consistently over-relieved from the template at the gauge corner. Even though the resulting rail meets the tolerance specification, the two-point contact condition that occurs from the over-relief contributes to ongoing high rates of wear at the gauge face and wheel flange. The estimated value of reduced #7 Line fleet wheel damage resulting from a more conforming wheel profile (the proposed Experimental Wheel Profile) in combination with improved friction management at the 34th St curve is predicted to be $8–10 million over a six-year service life.

High recurrence of rail grinding for removal of track corrugations can be eliminated. Each rail grinding activity at the 34th St curve cost approximately $127,000. Three rail grindings were performed by NYCT during the research period for a total cost of $381,000 for grinding the same section of track. Improved wheel/rail contact can eliminate or delay subsequent track replacement at a track replacement cost of an estimated $3.6 million for a 1,000-ft track section replacement.

A priority track geometry defect was found at a station platform on an open-deck steel elevated structure by the TGC but was not identified by the IWS. This suggests that refined analytics are required that consider IWS L/V force deviations at lower speeds.

Significant reductions in wheel/rail forces and vibration amplitudes discovered during wet weather suggest that considerable benefit could be achieved through the use of friction modifiers and enhanced application of friction management approaches.

Performance against Objectives

The research work completed during the extended period of performance addressed all the original project demonstration objectives and met the original evaluation criteria. With key results and findings and subsequent mitigation measures taken, the agency has met most of the objectives in some degree or form. However, follow-up research efforts will be needed to take full advantage of the findings and continued data collection and analysis. Table ES-3 summarizes the research team's performance against evaluation objectives. See the link in Appendix H for a list of additional research efforts reflecting a significantly expanded scope of follow-on research.

Table ES-4 provides a summary of the metrics defined for evaluation as part of this third-party review. The table includes original metrics, a synopsis of goals achieved, and recommendations for future work to further refine the metrics.

Table ES-3 *Project Performance against Evaluation Criteria*

Evaluation Criteria	Performance Measures	Key Results/Findings	Actions Taken by NYCT
Enhance Operational Safety	1. Mitigate equipment failure conditions 2. Correct conditions causing slow speed derailment risk 3. Correct conditions contributing to poor ride quality and steering instabilities	1a. Rail corrugation on 34th St curve 1b. Accelerated flange wear after milling 2a. Discovered new back-of-flange issues 2b. Higher L/V forces seen after track maintenance 2c. Cars seen with interaxle misalignments 3a. Discovered tight gage conditions and potential for instability	1a. Initiated TOR Friction Management 1b. Designs for "gently-worn" wheel profile for wear tests 2a. Reprogrammed wheel scanner to analyze whole back of flange 2b. IWS data monitored after track work 2c. "Bad actors" identified by TBOGI 3a. Examination of IWS and DCC vibration data
Infrastructure & Equipment Resiliency	1. Enable data collection, asset condition monitoring and documentation 2. Enable pre/post-incident asset condition documentation to accelerate safe event recovery	1a. Wheel measurement exception reporting and data archiving 1b. Wheel/truck/vehicle/consist identification 1c. Track location matching 1d. Vehicle location matching 2a. #7 Line pre/post event data mapping	1a. Automated wheel scan data reporting 1b. RFID vehicle asset tagging 1c. RFID indexed TGC track maps 1d. RFID indexed vehicle data maps 2a. RFID aligned TGC and DCC data maps exist
Reduce Energy Use	1. Reduce wheel/track conditions causing hunting 2. Reduce vehicle propulsion energy needs	1a. Discovered high interaxle misalignment issues 1b. Discovered locations where hunting heightened 1c. 7% energy penalty seen with corrugated rails 2a. Friction management reduced energy needs	1a. TBOGI enables "bad actor" identification 1b. IWS data reveals vehicle "hunting" signatures 1c. DCC traction energy monitored 2a. DCC traction energy monitored
Increase Asset Service Life (Reduce Planned Capital Costs)	1. Facilitate extensions of wheel/track service life and asset life cycle costs	1a. Wheel life improved from initial <2 yr (2017) to > 3 year (2018) 1b. Rail grinding needs at 34th St curve persisted	1a. WheelScan data monitoring and reporting 1b. Better TOR Friction Management needs identified
Asset Condition-Based Monitoring & Maintenance (Reduce Asset Ownership Costs)	1. Facilitate maintenance of wheel/rail asset condition monitoring & documentation 2. Enable co-ordinated condition-based maintenance of wheels, track and truck components	1a. Documentation of locations, equipment, data collection, and wheel measurements 1b. Maintenance forecasting and condition-based shop scheduling 1c. Wear trending identified period with significant reductions in wheel life 2a. Condition-based maintenance of wheel services and replacements	1a. RFID tags and readers employed on #7 Line 1b. WheelScan wheel wear data trending employed 1c. Prompted testing of "worn wheel" profiles 2a. WheelScan Data trending enables condition-based maintenance
Improve Customer Service & Experience	1. Reduce wheel/rail noise 2. Improve vehicle safety and operational continuity 3. Improve vehicle ride characteristics	1a. Higher noise areas identified 1b. Noise may be addressed when certain levels reached 2a. Identify areas of excessive forces and greatest risk 2b. Enhanced proactive decisions to reduce safety concerns 3a. Manage performance for improved ride characteristics	1a. DCC use of external microphones 1b. Noise levels monitored by DCC acoustics gear 2a. IWS data used to identify excessive forces 2b. Real-time track and vehicle performance data analysis 3a. DCC monitors acoustics and vibrations

Table ES-4 *Metric-Based Evaluation Summary*

Subway System Safety Improvement					
Incident Type	**Phase II (As-Is) 12 mo**	**Phase III (After)**	**R&D Result**	**Instrument or Method Used**	**Recommendations**
Accidents or incidents	Historical record	Extrapolation of examples evidence reduction	NYCTA reported reduction in wheel climb derailments as result of available data from research activity	NYCT Incident Reports	Continue to monitor accidents and any related incidents, including driver feedback; create database and link to maintenance activities
Red conditions	Historical record	Extrapolation of examples evidence reduction	Data not available to asses all red conditions; not enough elapsed time since implementation allowed for in-depth analysis	Analytics, TGC, IWS, TBOGIE, L/V	Evaluate rate of change of Red and Yellow instances; in particular, define dates when actions implemented or changes in policy undertaken
Risk mitigation	Historical measures	Measured risk reduction	Using data acquired through system implementation allows for reduced risk, as demonstrated by identifying several potential new safety parameters	Analytics, TGC, IWS, wheel scan, TBOGIE, L/V	Implement additional risk mitigation thresholds based on additional higher-order analytics; include maintenance actions undertaken for reference; monitor trends and rate changes in defining data variables
Subway System Resiliency					
Element	**Phase II (As-Is) 12 mo**	**Phase III (After)**	**R&D Result**	**Instrument or Method Used**	**Recommendations**
Wheel rail noise	DB before	DB After	Grinding implementation on corrugated curve reduced noise, noise reduction able to be quantified	Microphones and accelerometers, DCC Suite	Strongly recommended to analyze noise data on production basis, particularly changes over time; correlate data with maintenance actions such as grinding, rail replacement, and friction management.
Energy use	Historical	Energy Use After	Energy data acquired but not analysed to date; heuristically, noted that energy somewhat reduced but cause could not be attributed to any specification	Instrumented traction motors DCC suite	Strongly recommended to analyze energy data on production basis, particularly changes over time; correlate data with maintenance actions such as friction managing and rail grinding
Maintenance events (pre and post)	Historical	Maintenance records after	Due to limited time from implementation to action, metric not evaluated	Analytics, NYCT data	Recommended to evaluate levels of annual maintenance (normalized with tonnage or use levels) and correlate with any maintenance philosophy changes and implementation
Component life cycles	Historical	Re-estimated component Life predictions	Data available to evaluate potential extensions in life cycle for wheels and rails; data supported changes in maintenance approaches that showed significant increases in life cycle	Calculations and estimations	Continue to monitor rates of degradation and resulting life cycles for wheel, rail, and other track/vehicle components; correlate to maintenance actions

Table ES-4 (cont'd.) *Metric-Based Evaluation Summary*

Subway System Effectiveness					
Equipment and car condition			Data collected clearly provides ability to assess equipment component and overall condition; to date, no actions taken; potential safety and maintenance thresholds on identified	Analytics, IWS, wheel scan, TBOGIE, L/V	Analyze various data sources and use higher- order data analytics to define car/equipment condition indices that are function of measured data to monitor car/ equipment condition seamlessly and continuously
Ride quality			Ride quality addressed through combined data inputs from several measurement systems; no direct measure of ride quality exists at car body, should be investigated; metrics can be developed from available data to assess ride quality and act accordingly	Analytics, IWS, TBOGIE, L/V	Use higher-order analytics to develop ride quality metric for available data sources that can be monitored continuously and autonomously and alerts provided when thresholds exceeded
Acceptance by NYCT operating units		Adoption in procedures	NYCT operating units have started to review resulting data and potential maintenance and safety thresholds for further implementation	Analytics, NYCT data	Develop justification for all recommended changes in philosophy and training materials for NYCT departments
Financial Measures and Other Benefits					
Element	**Goal**		**R&D Result**	**Instrument or Method Used**	**Recommendations**
Reduced life cycle costs (wheels)	10% increase wheel life		Analyses showed that an extension in wheel life can be directly attributed to data and analysis resulting from this research effort, with potential annual savings of $7,500,000	Wheel scan, Analytics	Refine life cycle cost calculations based on analytic results of degradation rates and refined costs. Expand to include secondary and tertiary benefits
Lower life cycle costs (rail)	10% increase rail life		Not all rail was analyzed; subset data and analyses showed that more than $160,000 can be saved annually for rail	Analytics, TGC	Refine life cycle cost calculations based on analytic results of degradation rates and refined costs; expand to include secondary and tertiary benefits
Lower cost of asset ownership			Total cost of asset ownership not evaluated; time to implementation too short to capture reduced life cycle costs; analyses for wheel and rail support significant reduction in cost of asset ownership	Analytics	Perform total cost of asset ownership study based on results of further analytics

Third-Party Independent Evaluation

The University of Delaware's (UD) Railroad Engineering and Safety program conducted an independent third-party review of the project. Overall, UD believes that the project was a success and clearly illustrated the potential that these new data acquisition systems could offer to rail operators. The activity showed a successful implementation of the measurement systems themselves. Integration of a wide variety of connected systems carries a unique set of challenges. The team was able to overcome these challenges and provide a large stream of inspection data, as well as start the process of interrelating the data.

UD also believes there was insufficient time available within the research effort's period of performance to fully evaluate the effectiveness of the measurement systems (a longer timeframe is required to act on the data and realize the improvements and to see the actual results in the data); it is still possible to assess whether the program shows progress in addressing these objectives and setting the stage for further evaluation and implementation.

UD reported that the study demonstrated the ability to collect very large quantities of data and to use basic threshold level analysis to obtain useful information and improve safety. It also demonstrated the ability to use engineering knowledge, experience, and judgment in conjunction with the data to obtain valuable and meaningful insights from both safety and maintenance points of view. However, it also showed the need for a higher-order level of analysis of the data to include:

- Trend and forecasting analysis
- Correlation of different measurement systems to extend the basic analyses and perform root cause investigations
- Identification of non-obvious relationships between different measurement streams and safety and/or maintenance issues
- Optimization of maintenance and associated asset management
- Conversion of data into information

The opportunity for broader data analysis can be found in the complete "Third-Party Independent Review and Evaluation" in Appendix I (see link). Supplemental analysis of wheel-wear data should be a focus of any follow-up activity, and there is significant opportunity to apply improved data analysis techniques, e.g., data analytics or "big data" techniques, to further use these data to better understand the interrelationships between the measured parameters, component degradation, maintenance, and safety.

UD believes that this research effort can directly lead to the implementation of new and improved safety and maintenance standards and processes. Although many of the above parameters have the potential for use as safety standards, nearly all direct and indirect measurements have the potential for new maintenance procedures or standards. For example, the measurements associated with the WheelScan® wheel profile measurement system can be used as safety standards and maintenance standards and offer a real opportunity for optimization of the current wheel truing and replacement practices. Further measurements, such as IWS forces, L/V ratios, track geometry, and angle of attack, give insight on equipment and component condition and could be used to create thresholds at which a component must be serviced or replaced. However, creating new safety standards is not as simple, since only parameters that directly affect or reduce derailment risk would be useful as a safety standard. L/V ratio and wheel condition are two such parameters.

Table ES-5 illustrates the potential for an agency setting safety and/or maintenance standards or procedures from the data acquired by these different measuring systems. NYCT will be evaluating the incorporation of measurements of parameters impacting safety and maintenance from the new data available on the #7 Line, as shown in Table ES-5:

- Safety parameters and thresholds as directly measured by the systems
- Maintenance parameters and thresholds as directly measured by the systems
- Ridership performance parameters and thresholds
- Component degradation relationships
- Relationships between energy use, noise, vibrations, accelerations and other parameters
- Other intra-measurement relationships that can enhance safety and operations, including derived parameters

Research Team and Third-Party Independent Research Evaluator Recommendations

Based on the results of the NYCT Project, the project report, and the conclusions presented in the full UD independent review, the recommendations are that NYCT pursue the following to identify and quantify added value (monetary) and collateral (non-monetary) benefits following completion of the research effort. Recommendations are as follows:

- Subway System Safety Improvements
  - Curve & guard rail study
  - Implement tests of a new wheel profile and better friction management
  - Explore monitoring vehicle operating performance data analysis “before and after” track maintenance

- Subway System Resiliency
  - Develop capability to map and record track geometries and corresponding DCC vehicle/track performance data on the #7 Line
- Subway System Effectiveness
  - Understand and monitor vehicle and track conditions directly impacting ride quality
- Financial Benefits
  - Increased effective daily use of laser scanner in Corona Shop vehicle maintenance and scheduling
  - Catalyzed Regen braking studies to investigate energy efficiency improvements (ConEd/NYCT Regen Braking Energy Collaboration, October 2018)
  - Reduced lifecycle costs of wheels and reduced lifecycle costs of rail

Table ES-5

Establishment of Maintenance and Safety Standards from Measured Parameters

Instrumentation	Parameter	Maintenance	Safety
NYCT **Track Geometry Car**	Track geometry parameters	Yes	Yes
	Track quality index	Yes	No
	Rail profile	Yes	No*
	Rail wear rate	Yes	No
	Rail life prediction	Yes	Yes
	Rail corrugation	Yes	No
	Video recording	Yes	No
KLD **Automatic WheelScan®**	Wheel wear parameters	Yes	Yes
	Wear rate (flange thickness)	Yes	No
	Wheel maintenance prediction	Yes	Yes
	Wheel replacement prediction	Yes	No
	Wheel climb risk (wheel flange angle)	Yes	Yes
	Effective conicity	Yes	No
NRC Canada **Instrumented Wheelset**	Forces (lateral, vertical, longitudinal)	Yes	Yes
	L/V ratio (wheel climb risk)	Yes	Yes
	Dynamic impact loads	Yes	No
WID **TBOGI**	Angle of attack	Yes	No
	Inter axle misalignment	Yes	No
	Rotation	Yes	No
	Misaligned/skewed trucks	Yes	No
	Tracking position	Yes	No
	Tracking error	Yes	No
	Shift	Yes	No
ISI **L/V System**	L/V ratio (wheel climb risk)	Yes	Yes
DTB **Microphones**	Noise levels	Yes	No
	Wheel/rail noise	Yes	No

Instrumentation	Parameter	Maintenance	Safety
***DTB* Energy Monitors**	Propulsion energy usage	No	No
	Traction motor current	No	No
***DTB* Accelerometers**	Acceleration	Yes	No**
	Ride quality	Yes	No

Green highlights are direct measurements supported by \ instrument suite. Yellow highlights are analytical results/information that can be supported by data collected from instrument suite.

**Rail gage face angle, which can be measured as part of rail profile, has potential for safety monitoring.*

***In some high speed rail application, truck acceleration used as safety factor, but not commonly used for metros or transit systems.*

Tasks for Continued Research and Future Study

The program was a successful demonstration of the implementation and potential use of the selected instrumentation and measurement systems; however, there was insufficient time and resources for a more comprehensive assessment of the data and its potential impact on safety, operations, and maintenance. As such, the research team and UD recommend follow-up activity focusing on data analysis, individually and in an integrated fashion, to develop key implementation functions such as:

- Completing a trial of a wheel profile designed to mimic some aspects of the worn wheel shape that was initiated on the DCC at the close of the research effort
- Implementing a scientific friction management trial of friction modifiers to evaluate their contribution to reduced corrugation development, forces in curves, noise and vibration
- Establishing a data warehouse (rather than the current FTP site) to manage the large volumes of data and facilitate subsequent alignment, extraction, and analysis
- Developing a software system to automatically analyze and report on trends, maintenance needs, and alarms
- Continuing analysis to determine the cause of excessive wheel wear and its asymmetry

Thus, it is recommended that additional analysis and automated analytics research effort be explored as a follow up activity to include parallel analyses using:

- Engineering-based analysis approach
- Increased automation in data analytics
- Data science (“big data”) analysis approach

The focus of this follow-up study should be the development of the implementation functions noted in Table ES-5 that can be used not only by NYCT but by other U.S. transit and rail systems. The goal of such an activity would be to identify appropriate techniques and standards, demonstrate and quantify their effectiveness, and provide a platform for long-term implementation.

SECTION 1

Project Description and Goals

The Integrated Wheel/Rail Characterization and Safety through Advanced Monitoring and Analytics Project is a collaborative research and demonstration effort. The project goal is to prove the concept that it is both technically-feasible and cost-effective to implement and operate an automated, digital data-based information system incorporating analytics. The analytics provide information that is then used to foster decisionmaking that can be associated with wheel and track condition monitoring and condition-based maintenance.

Through enhanced management of the subway car wheel set profiles, track maintenance, and knowledge of the conditions of the wheel/rail surface contact, the benefits identified as a result of using the analytics are expected to be:

- Improved operational safety
- Enhanced system resiliency
- Post-event system service recovery
- Condition-based maintenance
- Optimized propulsion energy use

The research first modeled and verified wheel/rail conditions, developed analytics, and produced research results associated with New York City Transit (NYCT) subway vehicles and track segments on the #7 Line (Flushing Line).

This research and demonstration effort is supported by an innovative collaboration between the Federal Transit Administration (FTA) Office of Research, Demonstration and Innovation and the New York Metropolitan Transportation Authority via an NYCT-led collaborative research team that includes the following:

- **NYCT Operational Groups**, including Car Equipment Engineering (CEE), Division of Car Equipment, and Track Engineering (MOW Engineering), Maintenance of Way (MOW)
- **NYCT Office of Strategic Innovation and Technology** (OSIT), a NYCT office whose goal is to facilitate innovation at NYCT
- **KLD Labs, Inc.**, a New York technology company with machine vision technology used for wheel scanning and measurement systems who has already installed technology and software on the NYCT Track Geometry Cars (TGC)

- **Plasser American Corporation**, a Virginia company and NYCT research team partner with extensive machine vision technology and track measurement technology installed on NYCT TGCs
- **Dayton T. Brown**, a New York engineering service company skilled in on-board vehicle condition monitoring technology expertise and knowledgeable of the R188 car design
- **National Research Council (NRC) of Canada**, the Government of Canada's premier research and technology organization that operates as an independent and impartial research organization and serves as Canada's premier organization for multidisciplinary research and development activities

The research site targets one NYCT subway line (its vehicles, track, and maintenance facility) as a representative subset of the overall NYCT subway system and of other U.S. transit rail systems. NYCT leveraged earlier FTA–NYCT research team efforts involving automated track video technology to quickly build know-how around wheel/rail condition characterization and management to permit better-informed future investments and strengthen an agency's ability to deliver against forecasted value propositions in the areas of operational safety, system resiliency, after-event service recovery, energy efficiency, and asset management. This project was designed to support increased scalability to larger, full-system applications.

The project was structured into three phases. Table 1-1 provides a quick snapshot of the alignment of the research project with the required phases of work and the goals and objectives of the project.

Table 1-1

Proposal Alignment with Required Phases and FTA Objectives

Proposed Research Phases	Goals & Objectives
Phase I: Instrumentation of vehicles and collection of as-is and equipment evaluation	*Research Development and/or Synthesis Phase:* • Develop and showcase promising technologies, methods, practices, and techniques that improve public transportation systems
Phase II: Optimization of Analytics Capability of System Phase III: In-track Demonstration of Improved Performance Achievable through Implementation of Integrated Wheel/Rail Performance Characterization and Analytics	*Demonstration Phases:* • Revenue service (full-scale demonstrations preferred) • Develop and showcase promising technologies, methods, practices, and techniques that improve public transportation systems *Operational Safety:* • Demonstrate new or improved technologies, practices, and techniques to reduce risks of transit-related injuries and fatalities *Infrastructure State of Good Repair and Equipment Resiliency:* • Continue to deliver service after an emergency • Foster quicker recovery from events • Has attributes of resiliency – robust–adaptive–ready

SECTION

2

Project Objectives

This effort represents an integrated suite of machine-vision-supported wheel, track, and truck measurement and data collection and analytics targeted to enable enhanced management of wheel/track characterizations and condition monitoring. The collaborative research team also sought to provide the ability to identify and quantify potential value and benefits directly associated with decisions made with wheel/rail data and analytics. In addition, some less quantifiable customer benefits arising from the research such as improved vehicle acoustics, ride comfort, and improved system reliability were captured.

A summary of the research demonstration objectives is as follows:

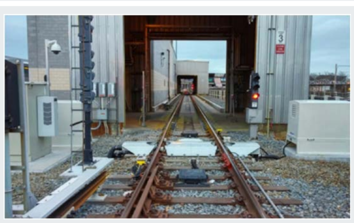
- Enhance Operational Safety
  - Identify and mitigate wheel/track conditions that contribute to equipment failure.
  - Identify and correct wheel/track conditions that could lead to either slow speed derailments or contribute to vehicle steering instabilities and poor ride quality.
- Enhance System Resiliency
  - Facilitate maintenance of current wheel/track data collection, and asset condition monitoring/documentation.
  - Accelerate post-emergency documentation of wheel/track asset conditions to accelerate recovery/repair prioritization and speed a system's safe return to service.
- Reduce Energy Use
  - Reduce wheel/track conditions that promote hunting.
  - Reduce subway vehicle propulsion energy requirements, especially as vehicles steer through curves.
- Reduce Planned Capital Costs
  - Facilitate extending wheel/track asset lifecycle costs by increasing the service life of wheels and extending the track service life.
- Reduce Cost of Asset Ownership
  - Facilitate maintenance of wheel/rail asset condition monitoring/documentation.
  - Enable coordinated condition-based maintenance of wheels, track, and truck components (create best value proposition).

- Improve Customer Service and Customer Experience
  - Reduce wheel/rail noise.
  - Improve vehicle safety/operational continuity.
  - Improve vehicle ride characteristics (wheels, track, and trucks).

Integrated, Machine-Vision Supported Wheel, Track, and Truck System

To achieve the research objectives, several measurement and data acquisition technologies were integrated into a comprehensive health and safety monitoring system that enabled integrated diagnostics for monitoring and maintenance planning. The integration of technologies and measurement capabilities is highlighted in Table 2-1.

Table 2-1 *Summary of Measurement Systems Employed*

Tool	Measurements Provided	Application/Analytics
NYCT track geometry recording car	Rail profile and track geometry measurements, including track gauge, track alignment and curvature, track profile, super elevation and geometry errors, as well as recording of detailed rail view and right-of-way video images.	Rail profile management (wear monitoring, trending, rail grinding) and track geometry monitoring and maintenance
	 *Source: NYCT*	
Automated equipment identification with RFID tags	Automatically identify car number and car end, enabling specific axle and wheel to be identified as they pass measurement site.	Basis for referencing all other vehicle based data records
Car body accelerations	Monitor vehicle response to track perturbations.	Provide indication of vehicle/ track interaction problems
In-track laser wheel scanner–wheel machine-vision system	Automatic digital measurements of wheel profiles. Capture condition of wheels for entire NYCT #7 Line fleet. Full wheel profiles will be captured. Typical measurements for entire fleet are flange width, flange height, hollow tread, rim thickness, back-to-back gauge, back-of-flange profile.	Wheel profile monitoring, wear trending, management of wheel re-truing activities to provide actual typical wheel profiles operating on NYCT #7 Line to help identify contact patch for each wheel profile
	 *Source: NYCT*	

Tool	Measurements Provided	Application/Analytics
Traction motor draw current monitoring on 11-car test consist (DCC)	Instantaneous energy consumption	Assessment of propulsion energy usage by trains and driver performance, impact of weather, modifications to wheels and/or rail, etc.
TBOGI – track-side truck wheel and rail dynamics measurement	Wheelset Angle of Attack and Tracking Position of all wheelsets of passing train, provide truck-based derived performance parameters–inter-axle misalignment, tracking error, rotation shift	Key parameters to help characterize wheel rail interface, wear rate of wheel and rail, rolling resistance. TBOGI identifies trucks with geometric issues (skewed, misaligned, improper tracking) that cause accelerated wheel and rail wear and can pose increased safety risk
	 *Source: NYCT*	
Instrumented wheelsets on DCC for wheel strain measurements	Forces between wheel and rail and contact patch position on wheel tread–for instrumented wheelsets only.	Vehicle/track health monitoring and to identify derailment potential (wheel unloading, excessive lateral forces)
	 *Source: NRC Canada*	
Wayside L/V force measuring system	Lateral and vertical forces for all axles passing that location.	Monitoring of truck performance and how it changes as result of planned track modifications (rail re-profiling, friction management etc.)
	 *Source: NYCT*	

Although each of these tools has its own limited diagnostic capabilities and is valuable in its own right, the integration of these into one suite with multiple cross-correlations supported advanced analytics in the pursuit of the research objectives. Figure 1-1 illustrates how the data streams from each system could feed into and support various research outcomes.

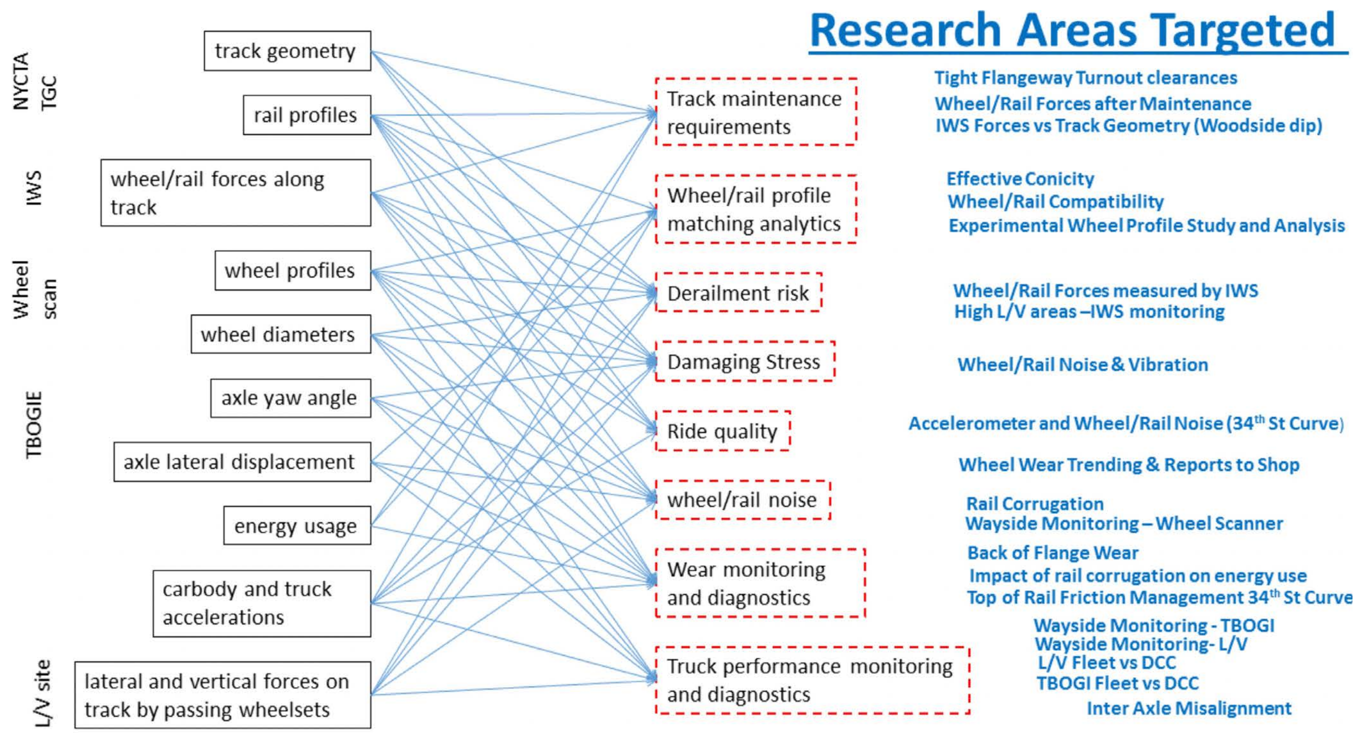


Figure 2-1 *Diagram illustrating potential linkages between technologies and analytics*

Project Work Schedule and Key Milestones

The original 24-month collaborative research effort's period of performance was extended to approximately 52 months, beginning with a Notice to Proceed on September 15, 2015, and concluding with a revised period of performance end date of November 29, 2019. Table 2-2 indicates the original phases of work (Phases I, II, and III) and numbered key milestones. Long lead items for the wheel profiling device and instrumented wheel sets were anticipated in the original planning, but Phase I delays were encountered early on due to difficulties with establishing the methods and processes for team member invoice payments working within MTA grants and NYCT organizations. This resulted in a Phase I delay of approximately nine months for procurement of big-ticket items such as the laser wheel scanner and Data Collection Consist (DCC) data acquisition equipment and their installation.

As summarized in Table 2-3, the research performance period experienced slippage in each phase of the planned work. None of the reasons for this were of a magnitude that caused the research team to abort a targeted milestone or work effort, but some work efforts will continue past the date of the period of performance. Top-of-rail (TOR) friction management at the 34th St curve and the wheel profile experiment with a slightly worn profile will require much longer monitoring than the original research period would permit. A final eight months were added to allow for submission/payment of project invoices and maintenance of test equipment/instruments.

Table 2-4 provides a more detailed view of the progressive milestone efforts and their actual completion sequences and dates within the performance period.

Table 2-2

Original Work Schedule and Key Milestones

Phase I: Instrumentation of Vehicles and Collection of As-is and Equipment Evaluation
Project Kick-off Month 1
1. Month 5: DCC+ Research Consist instrumented with on-board recorders and initiate data collection
Gate Meeting 1 – Month 6 – Review of on-train data collection deliverables
2. Month 11: In-track wheel profile system commissioned, wheel profile data collection initiated
3. Month 12: Wayside L/V and TBOGI devices operational, data collection initiated
4. Month 14: Instrumented wheel sets installed and commissioned on DCC
5. Month 16: Integrated wheel profile, TGC, and way-side devices software integration complete
6. Month 18: Analytics functionality ready to support Phase II data collection of "As-Is"
Phase II: Optimization of Analytics Capability of System
Gate Meeting 2 – Month 19 – review of phase i deliverables and establishment of Phase II objectives
7. Month 20: Phase II "As-Is" data collection, analytics systems demonstration
Phase III: In-track Demonstration of Improved Performance Achievable through Implementation of Integrated Wheel/Rail Performance Characterization and Analytics
Gate Meeting Month 21 – Review of Phase II deliverables, establishment of Phase III objectives
8. Month 22: Phase III Modification A, Data collection, analytics systems demonstration
9. Month 23: Phase III Modification B, Data collection, analytics system demonstration
Gate Meeting Month 24 – Review of Phase III deliverables, review of final report

Note: Monthly progress reports published monthly; quarterly project reports published every calendar quarter.

Table 2-3

Actual Performance of Research Project Phases

Phase	Description	Planned Duration	Actual Duration
I	Instrumentation of vehicles and track with collection of "As-Is" vehicle & track data	18 mo	26 mo
II	Develop and optimize analytics capability of system	2 mo	4 mo
III	In-Track demonstrations of improved performance achievable with integrated wheel/track performance characterization and analytics	4 mo	22 mo

Table 2-4 *Project Milestones and Actual Completion Sequence*

Mile stone		Original		Milestone Completion Dates										
		Start Date	Completion Date	1-Oct-16 Revised Completion Fcst	1-Jan-17 Revised Completion Fcst	1-Apr-17 Revised Completion Fcst	1-Jan-18 Revised Completion Fcst	1-Apr-18 Revised Completion Fcst	1-Jul-18 Revised Completion Fcst	1-Oct-18 Revised Completion Fcst	1-Jan-19 Revised Completion Fcst	1-Apr-19 Revised Completion Fcst	1-Jul-19 Revised Fcst	1-Oct-19 Revised Fcst
1	**Notice to Proceed**	1-Sep-15												
2	**Phase I: Instrumentation of Vehicles**	15-Sep-15	1-Mar-17											
	Research consist instrumented with on-board recorders, initiate data collection		1-Feb-16	1-Nov-16	30-Dec-16 *Completed*									
	Gate Meeting 1 Month 6 – Review of on-train data collection deliverables		15-Apr-16	25-Aug-16 *Completed*										
	In-track wheel profile system commissioned, wheel profile data collection initiated		1-Aug-16	15-Nov-16	25-Jan-17	19-Jan-17 *Completed*								
	Way-side L/V and TBOGI devices operational; data collection initiated		1-Sep-16	15-Nov-16	1-Mar-17	20-May-17	*Completed*							
	Instrumented wheel sets installed and commissioned on DCC		1-Nov-16	15-Feb-17	1-Mar-17	31-Mar-17 *Completed*								
	Integrated wheel profile, TGC, wayside devices, software integration completed		2-Jan-17	25-Feb-17	1-Mar-17	1-Jun-17	30-Nov-17 *Completed*							
	Analytics functionality ready to support Phase II data collection of "as-is"		1-Mar-17	1-Mar-17	1-Mar-17	1-Jun-17	30-Nov-17 *Completed*							
3	**Phase II: Optimization of Analytics, Data Collection**	16-Mar-17	1-May-17											
	Review of Phase I deliverables; establishment of Phase II objectives		16-Mar-17				1-Nov-17 *Completed*							
	Phase II "as-is" data collection, analytics systems demonstrations		1-May-17				30-Nov-17 *Completed*							
4	**Phase III: Demonstration of Improved Wheel/Track Management**	1-May-17	1-Aug-17											
	Review of Phase II deliverables, establishment of Phase III objectives		15-May-17				10-Jan-18	15-Jan-18 *Completed*						
	Phase III Modification A: 34th St curve analytics & system demonstration		3-Jul-17				15-Mar-18	30-Jun-18	31-Jul-18	30-Nov-18	30-Dec-18	30-Dec-18 *Completed*		
	Phase III Modification B: Wheel profile change with analytics & system demonstration		1-Aug-17				15-Mar-18	30-Jun-18	30-Sep-18	10-Dec-18	30-Jan-19	30-Jun-19	10-Jun-19 *Completed*	
5	**Final Report**	1-Aug-17	1-Sep-17				31-Mar-18	30-Sep-18	30-Sep-18	15-Dec-18	28-Feb-19	30-Jun-19	30-Sep-19	

SECTION

3

Project Management

Originally a Stage and Gates Process approach was proposed for project management. Use of stages (phases) and review gates involves a formal stakeholder review of the successful completion of the current stage/phase objectives before the research progresses into the next stage/phase. This approach reduces risks associated with scope "creep" in which research efforts may migrate off the agreed-upon scope-of-work path and fail to address established objectives. As the wheel/rail research progressed, a less formal Stage and Gate structure was followed.

As the project progressed, weekly team WebEx meetings were held that permitted interaction/ communications involving the entire team and the FTA Project Manager on a frequent basis. The use of remote meeting technology and regularly-scheduled meetings and reporting schedules minimized any issues resulting from geographically-separated team members and supported communications and information-sharing during the project period. The team hosted FTA project management after Phase I efforts were competed to tour the research site and review the efforts completed and those planned for Phases II and III. A second on-site meeting with FTA, the research team, and key NYCT subway management and other industry participants was held in August 2018 to review and demonstrate the research work and frame the format of the final report.

Collaborative Research Team

Key project management strengths were discovered with the collaborative research approach. Employment of strong third-party technical talent/subject matter experts (other than those of NYCT) were seen as critical to the proper collection of meaningful data and a natural expansion of the research analysis from simply the assessment of obvious defects to an understanding that such research could offer a much wider data-driven contribution to proactive management and improvements of an operational system. The research effort drew heavily upon the technical talents of the National Research Council (NRC) of Canada, KLD Labs, Dayton T. Brown, and Plasser American Corp., all companies and organizations currently active in serving the rail industry.

A valuable lesson learned was that a carefully-considered and proactively-constructed collaborative research team assembled by any transit agency may assist agencies under significant resource constraints (financial, human resources, and innovation/technology experience). Research efforts supported by collaborations do not require that all necessary resources and knowledge be sourced from a single agency, group, or organization.

The research project was managed in accordance with FTA's requirements for a research demonstration, which involved working with the FTA Project Manager for overall project management and coordination during the period of performance. Included in this effort were the following:

- Management of FTA TrAMS (Transit Award Management System) by providing information and updates as required during the period of performance (quarterly status report, Federal financial report, milestones progress report, etc.)
- Development of a Project Management Plan (PMP)/Statement of Work (SOW)
- Development and maintenance of a project schedule and budget
- Initial kickoff meeting between project teams from FTA and NYCT OSIT
- Scheduled quarterly status report meetings
- Status report at the end of Phases I, II, and III
- Draft and final project report
- Draft and final evaluation report
- Participation in presentations to FTA and at least one transit industry group
- Support to FTA on knowledge transfer to the transit industry

SECTION 4

Budget Management

Research and demonstration costs are shown in Table 4-1. The research team targeted completing the research on or slightly below budget, and, at the time of this report, final costs were still being collected. The team met the originally-committed cost share commitment of $1,013,921 (22.97%).

Table 4-1 *FTA Research and Demonstration Budget by Phase*

Original Budget	FTA Funds	Cost Share	TOTAL	Cost Share
Phase I	$2,835,115	$761,097	$3,596,212	21.16%
Phase II	$387,024	$104,314	$491,338	21.23%
Phase III	$395,809	$148,510	$544,319	27.28%
TOTAL	$3,617,948	$1,013,921	$4,631,869	21.89%
ACTUAL Expenditures	$3,617,948	$1,013,921	$4,631,869	21.89%

Table 4-2 lists additional efforts arising from NYCT project management's leveraging of project data and analytics work as well as permitting DCC vehicle availability for additional instrumentation to advance other efforts at no additional cost to FTA. The original budget included $235,000 of contingency funding. Through careful project budget management and the use of NYCTA agency labor and KLD Labs labor to replace some originally-budgeted contractor labor for installing the laser wheel scanner, the research team targeted accomplishing the research with some funds remaining. Table 4-2 shows the originally-budgeted levels of FTA funds and team member cost share commitments and additional efforts arising from NYCT project management leveraging of project data and analytics work and permitting DCC vehicle availability for additional instrumentation to advance other efforts at no additional cost to FTA.

Table 4-2 *Additional Project Efforts*

Party Paying for Additional Effort	Description of Additional Work	Estimated Cost of Effort
NYCT Car Equipment Engineering	LTK/ARM Curve and Guard Rail Study	$400,000
NYCT MOW Track	34th St Curve Rail Grinding 4/10–4/16/17; 11/11–11/12/17; 3/9-48/18	$127,016
Perpetuum	Perpetuum On-Board Energy Harvesting and Wheel Sensor Proof of Concept	$429,360
ConEd	ConEd/CUNY/NYCT Regenerative Braking Energy Study	$462,446
DOT Rail Team University Transportation Center	University of Delaware Wheel Wear White Paper	$34,000
NYSERDA (New York State Energy Research & Development Authority) & CUNY (City University of New York)	NYSERDA/CUNY & ConEd/NYCT Bi-Directional SubStation Feasibility Study	$486,321
Estimated total of additional efforts enabled by FTA Wheel/Rail Research		$1,939,143

SECTION 5

Research Results

At the project's outset, it was believed that, by bringing together the various data streams from the systems summarized in Table 2-1, unique capabilities, understandings, and conclusions could be developed. Figure 2-1 is a diagram Illustrating that data from the various systems can be combined in numerous ways to provide insights and information on phenomena such as wear, ride quality, safety, and others.

The remainder of this report focuses on the research analytics in seven categories:

- **Track Maintenance Requirements** – The track geometry car identifies standard geometry defects needing rectification, and instrumented wheelsets, rail profile measurements, car body accelerations, and possibly energy usage provide additional data for identifying problem locations and quantifying the benefits of remedial action.
- **Wheel/Rail Profile Matching** – Data collected by the separate rail profile and wheel profile measuring systems can be combined to identify combinations of shapes that promote wear, rolling contact fatigue, or poor ride quality. Car body accelerations, instrumented wheel sets (IWS), Lateral over Vertical (L/V) measurements, and wear trending are employed to quantify the impact of changes.
- **Truck Performance Monitoring and Diagnostics** – The wayside Truck Bogie Optical Geometry Inspection (TBOGI) system identifies poorly-performing trucks and wayside L/V site measures, a symptom of poor truck performance. If the wheel/rail profile analytics rule out wheel/rail profiles as a contributor, then the reason for poor performance can be attributed to the truck. These can be flagged for maintenance and in combination with truck inspection data and lead to the development of routine or automated truck diagnostics.
- **Derailment Risk** – The IWS can measure locations of wheel unloading or excessive lateral force that are indicative of potentially unsafe conditions, but only for the truck under which the IWS is mounted and the wheel profile that is installed. At the L/V site, it is possible to change friction conditions and possibly rail profile and then assess the safety criteria at that location for all passing cars. It becomes possible to consider what might happen when higher-risk track locations are combined with higher-risk truck conditions to deduce the highest-risk vehicle-track conditions.

- **Damaging Stress** – Whereas wheel/rail profile matching identifies one contributor to damage, other identifiers include track geometry perturbations and poor truck performance, which are identified with the Truck Bogie Optical Inspection (TBOGI), IWS, car body accelerations, and L/V measurements.
- **Ride Quality** – Ride quality can be measured through car body accelerations and the instrumented wheelset and is the result of track geometry, wheel/rail profile matching, and truck characteristics; it can be diagnosed through integration and analysis of wheel profile, rail profile, track geometry, and TBOGI data.
- **Wear Monitoring and Diagnostics** – Measurements of wheel and rail profiles provided by the Laser WheelScan® and track geometry car can be trended to identify problematic conditions, which can be then diagnosed using the contact patch analytics, car body accelerations, IWS, TBOGI, and WheelScan® data.

Track Maintenance Requirements

Several practical examples were encountered that illustrate how the data systems provided helpful and useful information related to track maintenance practices.

Guarded (Restrained) Turnout South of Willets Point

In January 2017, the restrained turnout S/O Willets Point was the scene of two restraining rail climb derailments occurring within 24 hours of each other. The point of climb, as evidenced by marks on the rail, occurred about 15 ft before the frog point. The inside wheel on the curve ran along the top of the guard rail until the wheelset reached the frog point, where it was able to take the through route and, thus, derail. In both cases, the car was near the end of the train and was the trailing truck of the car. Train speed was roughly 15 mph (posted speed), and the derailed wheels were at or near the thin flange condemning limit. The turnout had been renewed only two weeks prior to the derailments and had “perfect” geometry, cant, etc. There is no super-elevation in the turnout.

Although the subject of a separate project at NYCT, this FTA effort focused energy on understanding how the DCC and other tools could be used to contribute understanding to those occurrences. A review of the instrumented wheelset data, specifically the peak L/V forces through that turnout, provides a very interesting picture (Figure 5-1). The maximum values occurred around New Year’s Day, having risen from lower levels in April 2017 and declining to lower levels into Summer 2018. This is a bit surprising, as increasing flange wear is believed to contribute to wheel climb derailments. Clearly, there is some other factor offsetting ongoing wear of the IWS wheels, most likely friction conditions.

At the time of the derailments, the friction conditions were known to be very "dry"—that is, there was no evident lubrication in place on any of the components, but especially on the restraining rail. Subsequent track inspections—for example, in August 2017 [1]—found some lubrication of the restraining rail to be present. A review of the temperature at that time found that the coldest weather, when lubrication systems are most likely to have failed or turned off for maintenance or other operational reasons, coincides with the period of highest forces (Figure 5-2). But there are other instances during hotter weather when some high values are encountered, so clearly there are other factors at play.

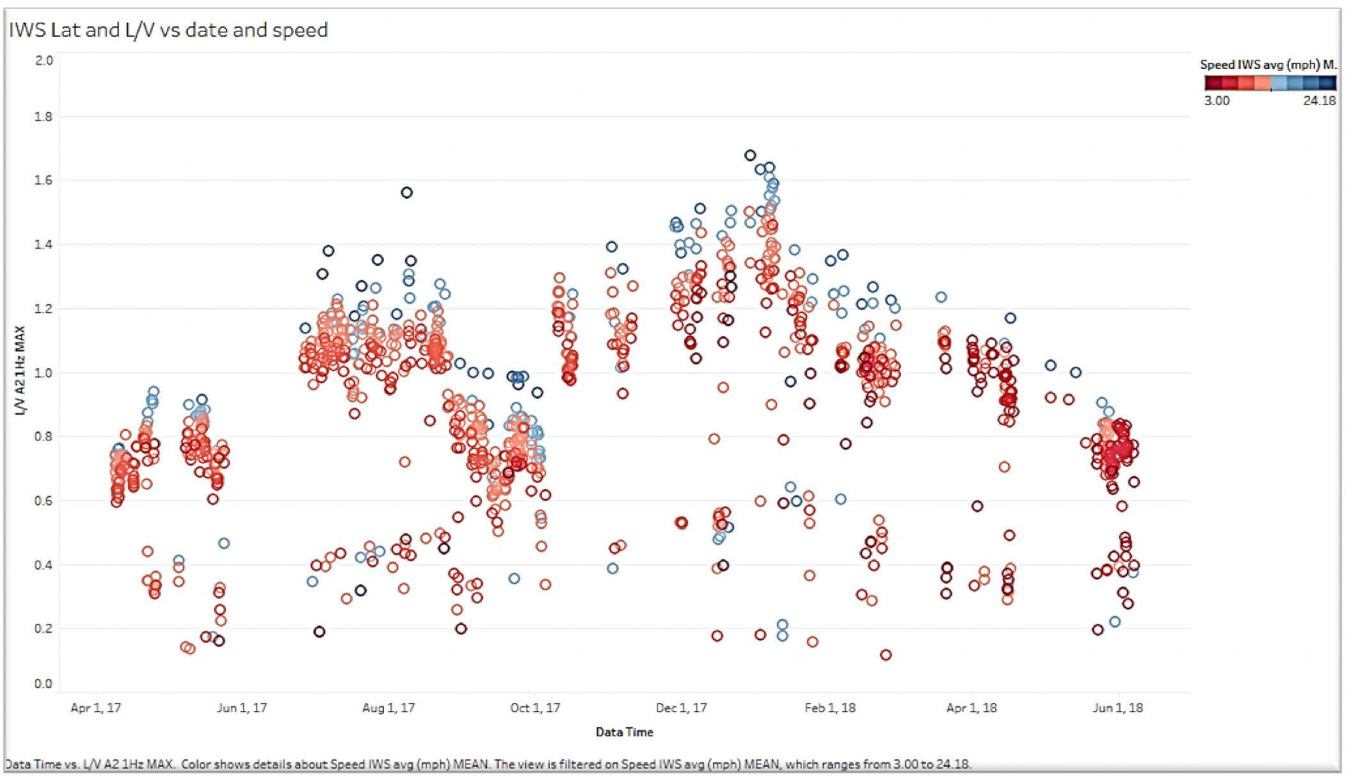
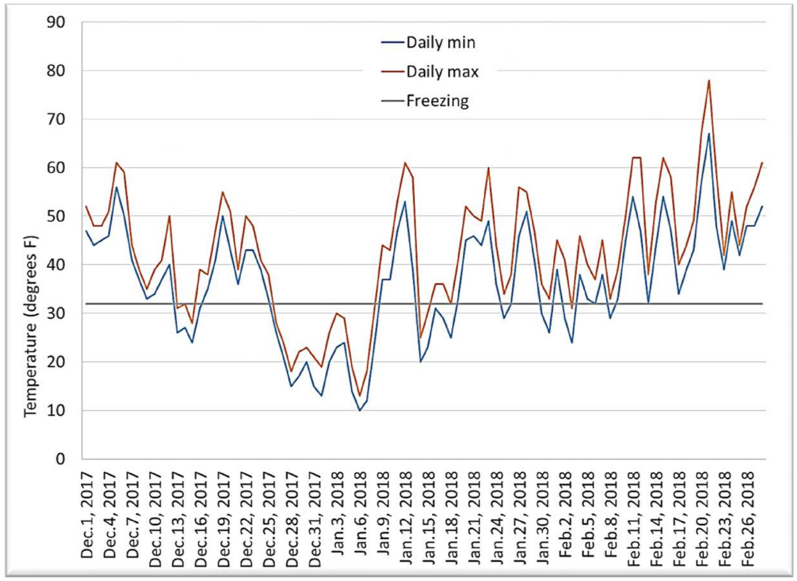


Figure 5-1 *Peak L/V values measured through restrained turnout S/O Willets Point on CC2*

Figure 5-2

Historical temperature data for New York City, with lowest temperature occurring around New Year's Day 2018



New Guard Rail Installation North of Willets Point

Monitoring of the IWS found that the L/V levels at the turnout N/O Willets Point increased over the course of one day from "normal" values of less than 0.5 to much higher levels greater than 1.5 (Figure 5-3) (see link in Appendix A, "Practical Examples of Performance Issues Identified on Line #7). A review of maintenance records determined that the increase coincided perfectly with the installation of a new guard rail at that location. This finding added urgency to ongoing discussions about the causes of guard (restraining) rail climb derailments S/O Willets Point.

Also evident in the data is a strong effect of rain/water on forces. Serving to significantly reduce friction levels, both light and heavy levels of water on the rail will reduce both lateral forces and L/V levels.

Data analytics identified the force signature of the flange back contact, as shown in the above two time/history plots of lateral forces. Without flange back contact, the lateral forces on turnouts behave as on a regular curve. The increased lateral forces on the curve have opposite signs, with east rail always negative. With flange back contact, the low rail force becomes very high and changes sign. On April 24, 2017, a new stock rail and guard rail were installed, and the flange way width was recovered to the design value. That change moved contact back to the guard rail, and the low rail L/V ratio jumped from about 0.5 to 2.5 on the April 24 run. The guard rail force could be expected to increase, but the high L/V was not known before. As shown, the L/V values remained high through May. The curiously low values on April 25, May 5, and May 22 were found to correlate with high levels of precipitation (25mm, 45mm, and 17mm rains, respectively). Rain significantly reduces friction levels.

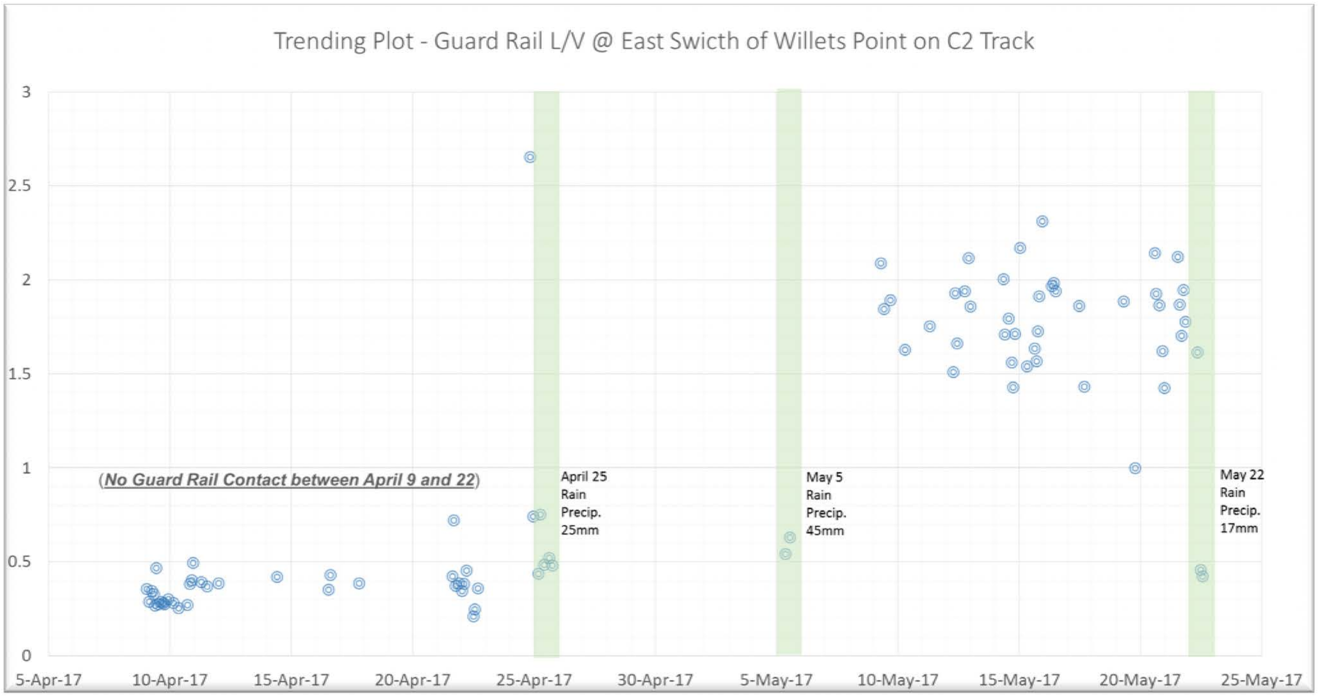


Figure 5-3 *Peak low/restraining rail L/V values measured by IWS at turnout N/O Willets Point*

The reduced forces encountered during rainy periods illustrates the potential benefits of top-of-rail (TOR) friction management, where friction control agents are applied to moderate friction levels and eliminate excessive wheel-rail creep forces, especially lateral forces in curves and turnouts. Accelerations are also measurably reduced by rain, reinforcing the expectation of lower forces, track damage, wear, risk, and noise as a result of friction management.

Wheel-Rail Forces at Curve N/O 34th St–Hudson Yards Curve

A rapid increase in wheel flange wear in 2016 was quickly traced to the opening of a new section of track between 34th St–Hudson Yards and Times Square. That track section includes a 650-foot radius and 1,200-foot-long curve, which was shown through modeling [2] to be the dominant location for wheel wear on the entire Line #7. New high and low rail profiles were designed and ground into the track in April 2017. Lubrication has been reviewed and adjusted several times since then. TOR friction management was installed in 2018. Reduction in wheel wear as a result of the new rail profiles, better lubrication, and friction management will be followed by NYCT after the end of this project's period of performance.

In addition to the wheel flange wear issue, the curve N/O 34th St–Hudson Yards Station is the site of heavy corrugation on the low rail of the CC2 track (upgrade). Accordingly, analysis of the noise and vibration measurements have been particularly intensive on this track section. The failure of treatments to date to curtail rail corrugation is illustrated in Figure 5-4. Although grinding is effective in removing the corrugation, it returns fully developed within about four months, contributing to high levels of vibration and noise. Analysis of the rail profiles shows that grinding has been only modestly successful in achieving the designed shape and that the friction management (lubrication and TOR) practices have been "spotty." Unfortunately, there was no prolonged period during this study for which the profiles and TOR were substantially functional, even though both have been improved over the last several months. Once the rail has been re-ground (October 2018), it should be assured that the friction management is working well and then the noise and vibration values monitored to determine whether the corrugation development rate has been significantly reduced.

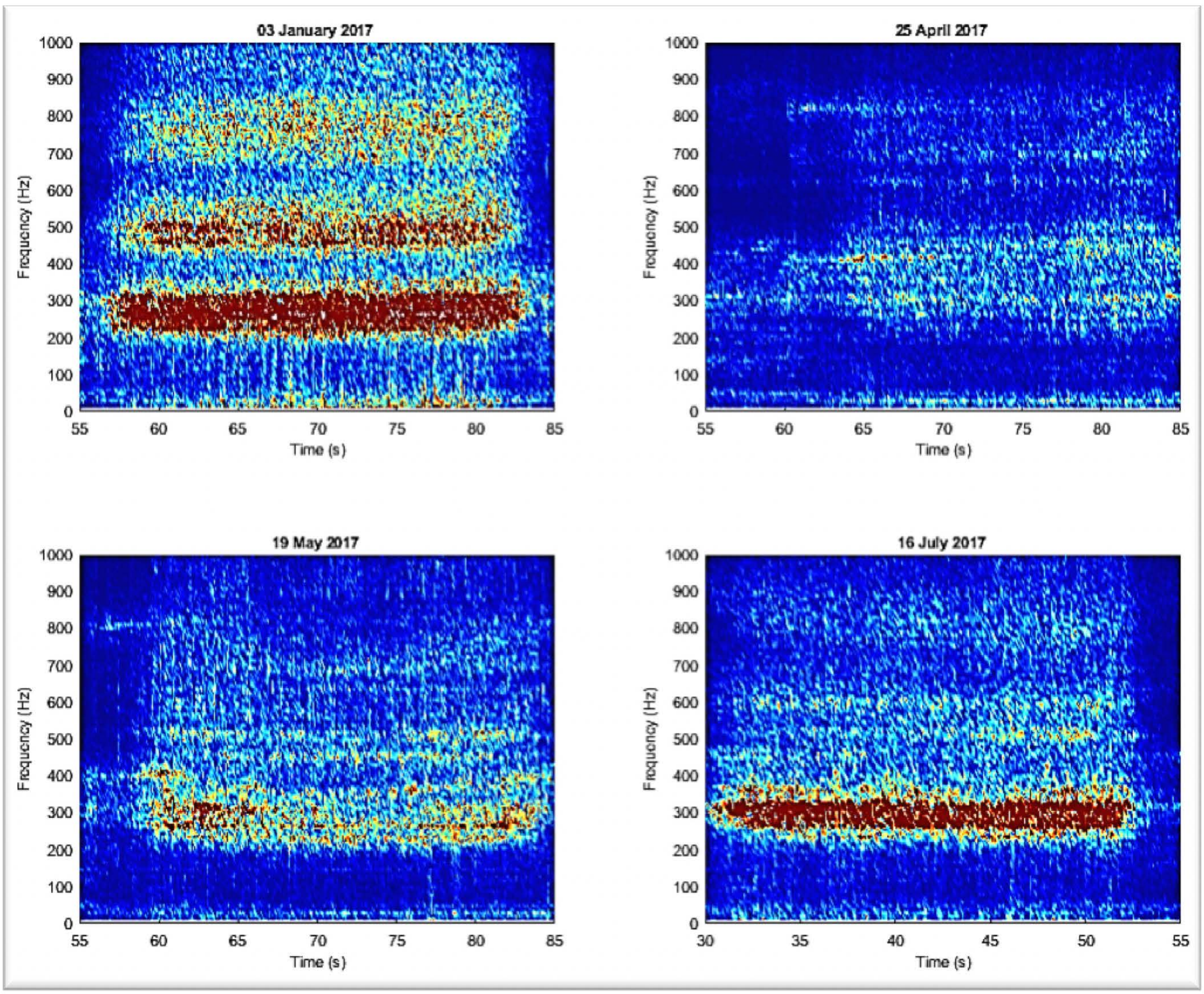


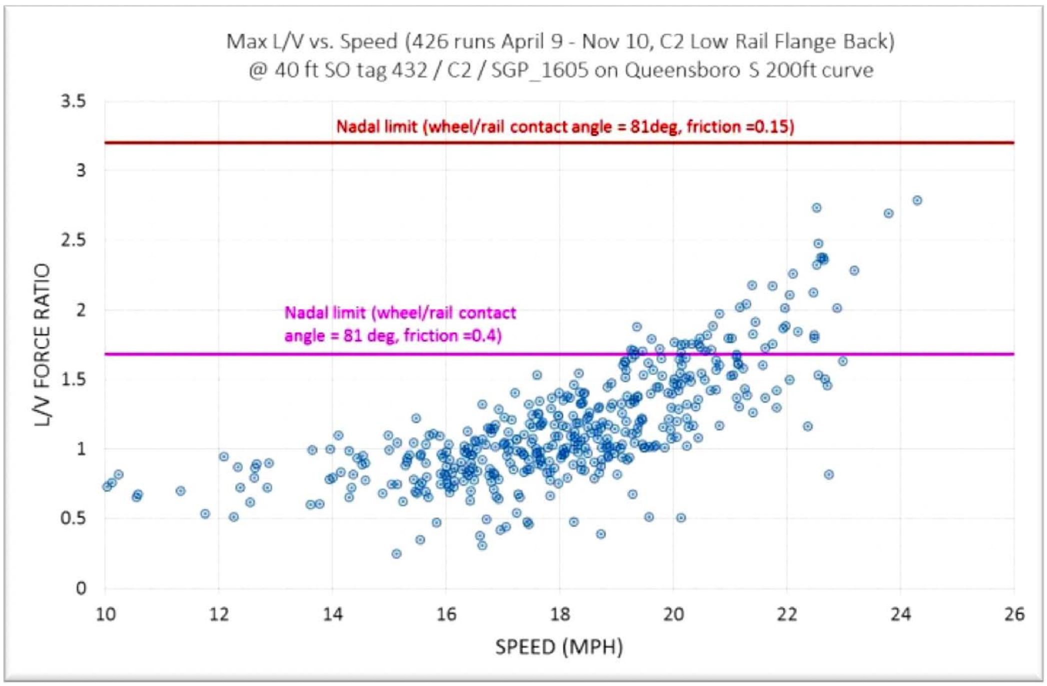
Figure 5-4 *Rail corrugation persistently returned after each rail grinding cycle and friction management applied*

Sharp Curve South of Queensboro Plaza

The sharp restrained curve between Court Square and Queensboro Plaza was identified by the IWS as a location of high L/V forces. Subsequent analysis identified train speed to be an important factor in those forces (see Figure 5-5). A recommendation was made that train speed should be limited to 15 mph (balanced speed) to avoid high L/V force on the restraining rail that might precipitate a guard rail climb.

Figure 5-5

Variation of L/V with speed on C2 Track South of Queensboro Plaza



Priority 1 Defect at Woodside Station

A Priority 1 track geometry defect (dip on track surface) was identified by a track geometry car inspection in October 2017. IWS data showed that there was a vertical force peak at the same location (Figure 5-6, blue trace). After the defect was corrected, the vertical force peak disappeared, which confirmed effectiveness of the maintenance activities (Figure 5-6, red trace).

Figure 5-6

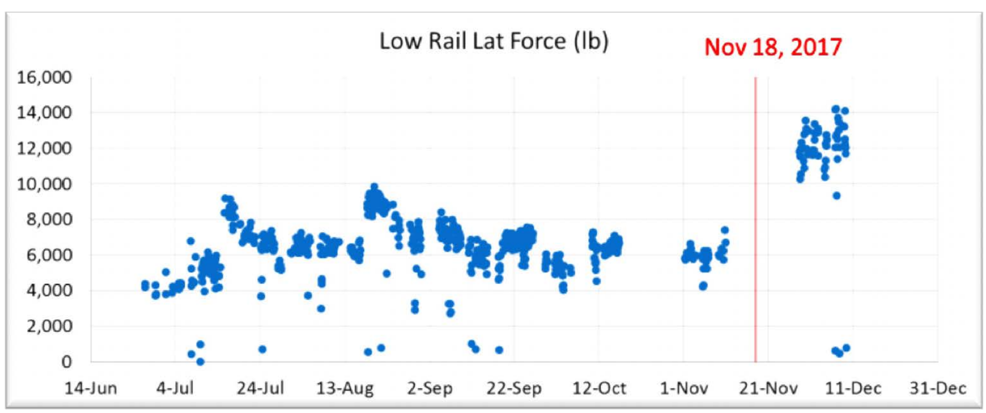
Vertical dip measured by geometry car at Woodside Station on CM track

Switch 441B N/O Queensboro Plaza

By trending the IWS data (Figure 5-7), it was found that the lateral force on leading low rail increased by more than 50% in November 2017 at switch 441B N/O Queensboro Plaza. This corresponds to track maintenance activities—specifically, replacement of the switch point, stock rail, guard rail, and frog of that switch on November 18, 2017, due to rail and frog point defects. This is similar to the case at N/O Willets Point Station. In both cases, the replacement of the guard rail at a turnout will recover the flangeway clearance to its design value, which causes a transfer of lateral force from high rail to the flange back.

Figure 5-7

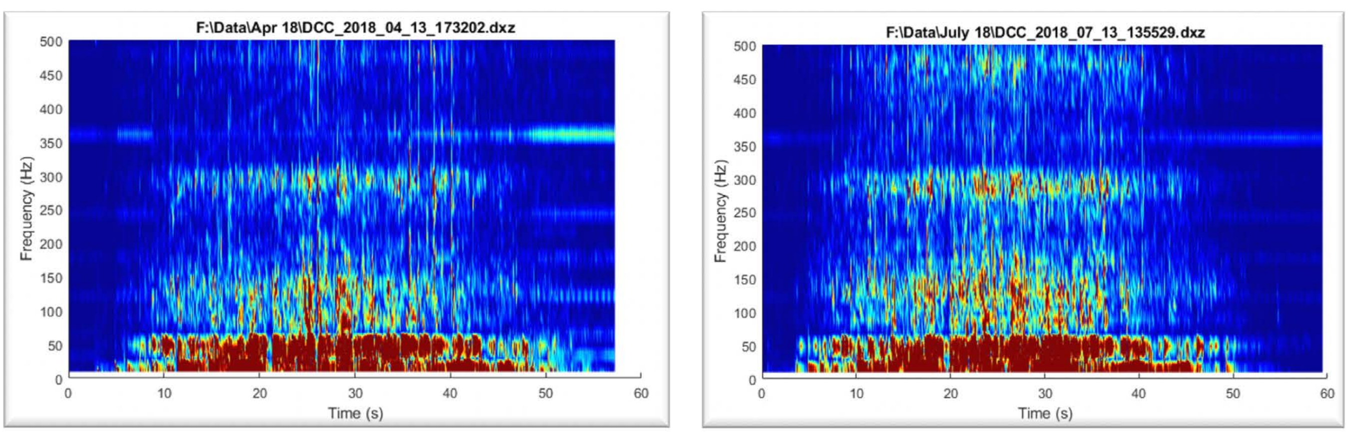
Lateral force variation at Switch 441B, with sudden increase occurring as result of its renewal



Loose Screw Spikes between 40th/46th St Stations on Track C1

The straight section of track between the 40th/46th St stations was identified by MTA track forces as having long clusters of loose spikes (Figure 5-8). Review of the vertical vibrations (Figure 5-9) found no noticeable change between April 2018 and June 2018 after the spikes had been replaced.

Figure 5-8
Loose spikes on track C1 between 40th/46th St stations



April 13, 2018

July 13, 2018

Figure 5-9 *Vertical vibration signature for trains running on track C1 between 40th/46th St stations*

Conclusions

Data from the DCC and wayside systems demonstrated the following:

- Impact of friction on forces and noise – the DCC and forces measured can be used to assess the effectiveness of current friction management practices and highlight areas in need of attention.
- Significant reductions in forces and accelerations on days with high precipitation, suggesting that TOR friction management could have a strong impact in reducing forces, track damage, wear, corrugation, and noise.
- Ability of the instrumented wheelset to identify areas of high lateral forces and excessive vertical forces to direct maintenance forces to track areas in need of attention.
- Usefulness of accelerometers in assessing corrugation levels.
- Usefulness of noise measurements on the DCC for identifying the effectiveness of wayside noise mitigating techniques such as friction management.

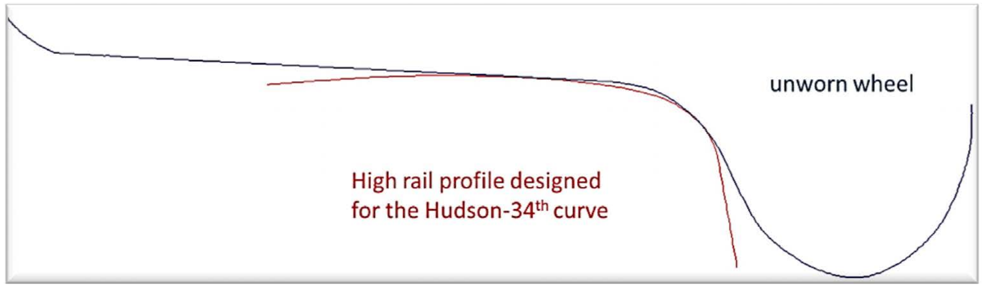
Wheel/Rail Profile Matching

The KLD WheelScan® collects 14,000–17,000 wheel profiles monthly, with most wheels being measured three or more times per month. Meanwhile, rail profiles are regularly collected by the track geometry car. Wheel and rail trends in themselves are valuable for identifying wear issues associated with local track conditions or particular vehicles. By bringing together the wheel profile data, compatibility issues can be examined that might reveal the causes of wheel-rail performance problems such as wear, corrugation, RCF, noise, and ride quality.

The emergence of accelerated wheel flange wear in 2015 eventually was traced back to the 650-ft radius, unguarded (unrestrained) curve N/O 34th St–Hudson Yards. Its radius, long length, and poorly lubricated state contributed noticeably to wheel wear. A suggested improvement was the design of improved rail shapes for those curves. In a 2016 project for NYCT-MTA, new high and low rail profiles were designed to best match with the existing population of worn wheels and then ground in April 2017 onto the CC1 and CC2 tracks. Outside of numerical modeling, it has not (yet) been possible to quantify the benefit of the designed profiles because they were never accurately installed into track (always over-relieved; see link in Appendix B, "Techniques for Assessing Wheel-Rail Profile Compatibility") and because of the inability to quantify a change in wheel wear.

But the new rail profile, even if properly ground, would not perform well against the unworn NYCT wheel. As seen in Figure 5-10, it is clearly a poor match with the designed rail. Heavy two-point contact exists against the high rail of curves, leading to high rates of wheel and rail wear, poor steering, and higher noise. For this reason, a "test wheel" was designed for trial on the NYCT Flushing Line (#7 train).

Figure 5-10
NYCT's current unworn wheel overlaid on rail shape designed for unrestrained curve N/O 34th St–Hudson Yards



Test Wheel Profile Design for NYCT's Flushing Line (#7 Train)

NYCT's current wheel has three notable shortcomings:

- Strong two-point contact with current worn curve rails (Figure 5-10).
- Wears very quickly during its early life, losing 4–5 mm of flange width within first 3–4 months of running (see Figure 5-39).
- Low flange angle of 67 degrees; as a result, has elevated risk of derailment (see Figure 30 in Appendix A, "Practical Examples of Performance Issues Identified on Line #7").

The test wheel was designed to address all these shortfalls (Figures 5-11 and 5-12) as follows:

- Mimics shape of worn wheel in throat region that is critical for steering in curves.
- Flange angle increased to 70 degrees; ideally, would have been 72 degrees or more, but greater flange angles do not match well with current worn rails (cause second point of contact low down on gauge face) and would likely lead to disappointing performance; if wheel shape actually to be changed fleetwide in the future, sharper flange angle should be considered.
- Initial flange width is 2.2 mm less than current worn wheel to avoid excessive conicities that contribute to truck hunting and avoid heavy impact with frog nose.

As a result of these changes, the wheel is expected to immediately match with the current worn rails and, thus, not rapidly wear in.

In comparison with the current unworn NYCT wheel, the test wheel provides a single point of contact, with a large fraction of the high rails on the curve N/O 34th St–Hudson Yards (Figure 5-13).

Figure 5-11

Test wheel profile designed for MTA Line #7 fleet

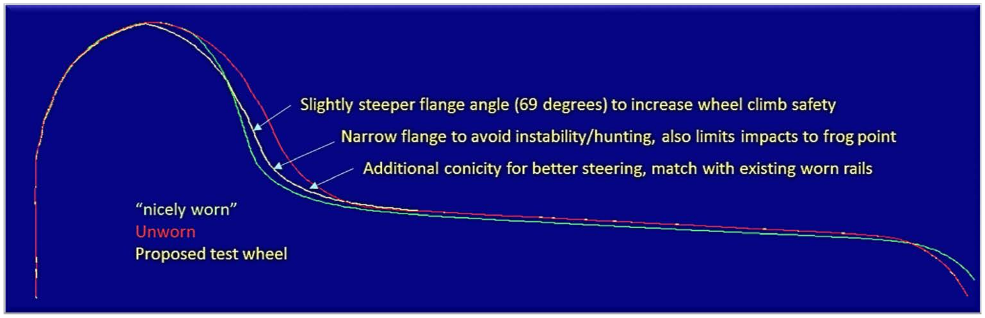
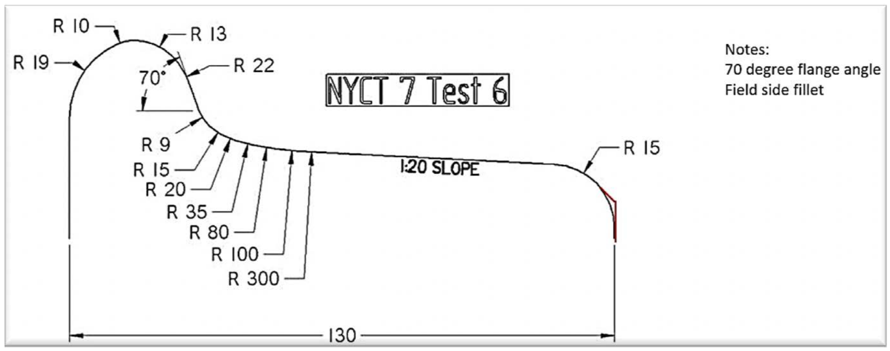


Figure 5-12

Details of NYCT test wheel profile



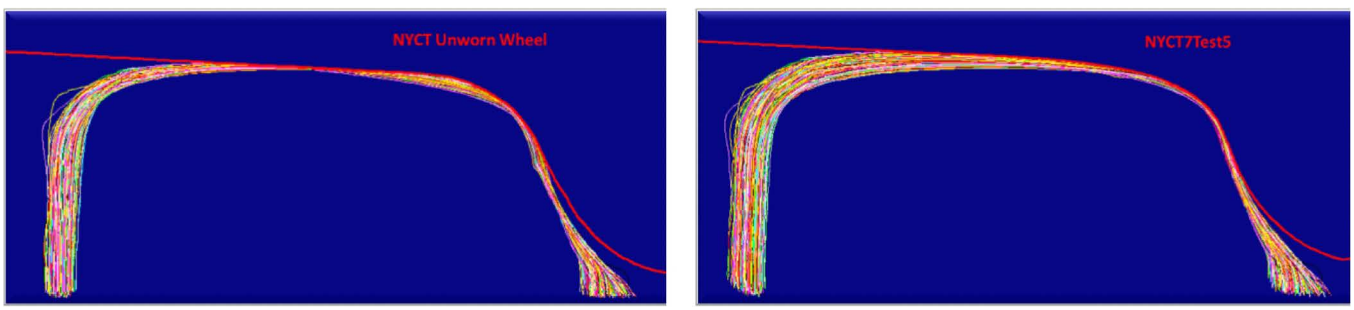


Figure 5-13 *Overlay of NYCT unworn (left) and test wheel (right) on high rails of curve N/O 34th St–Hudson Yards*

Wheel-Rail Profile Analytics

Appendix B, "Techniques for Assessing Wheel-Rail Profile Compatibility," outlines several different methods for matching and analyzing wheel and rail profiles and assessing their performance capabilities, as summarized below.

Conformality brings together the wheel and rail (as in Figure 5-10) and determines whether there are one or two points of contact and whether the profiles match closely in shape (called conformality) or are non-conformal. The benefits and disadvantages are outlined in Table 5-1. As shown, transit systems should aim for a 1-point conformal contact. This recommendation applies to the new and worn condition. Figure 5-14 shows how the test wheel matches with the measured rails on the curve N/O 34th St–Hudson Yards. There is a large distribution because of variations in the rail shape, but the average is a one-point conformal contact.

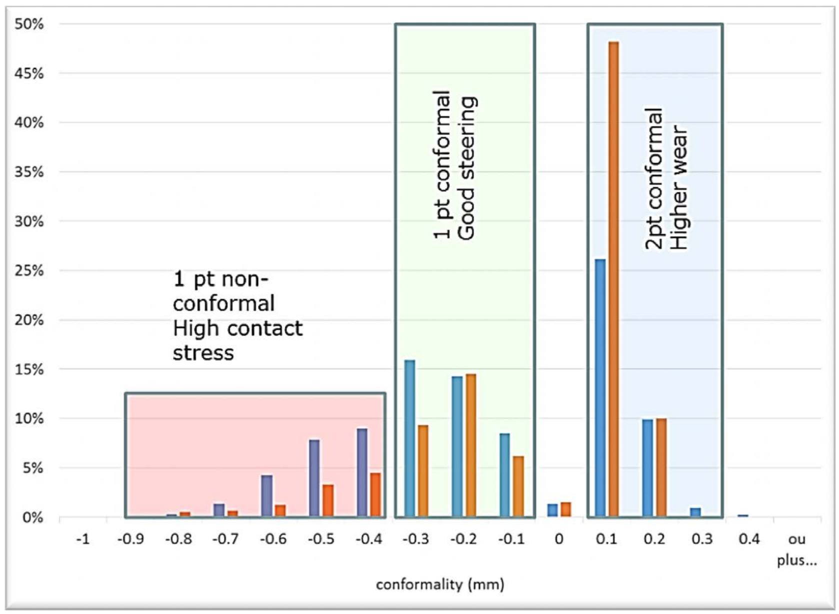
Table 5-1

Advantages and Disadvantages for Conformal/ Non-conformal and 1pt/2pt Contacts

	1pt	2pt
Conformal	Good steering, adequate control of stress; ideal for transit systems	Needed on freight railroads to control stress without sacrificing too much in steering and wear
Non-conformal	Good steering but excessive contact stress leads to rolling contact fatigue and gauge corner defects	Avoids loading of gauge corner, but suffers heavy wear and higher lateral forces; common new condition on many railroads.

Figure 5-14

Conformality distribution for designed wheel running against measured rails on curve N/O 34th St–Hudson Yards

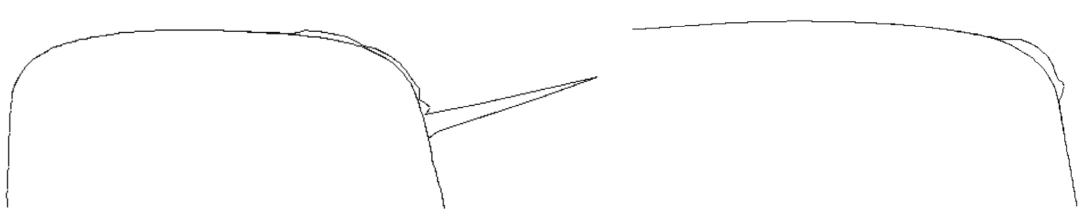


Additional conformality examples are provided in Appendix B, where that analytic is used to show how the rail shape changes through the curve and to assess the matching with the unworn, designed, and heavily-worn wheels.

Pummelling employs a curving simulation to calculate the position and forces of wheels on rails, then calculates distributions of forces (e.g., L/V ratio), contact stress, and wear index. An example is shown in Figure 5-15, illustrating the distribution of frictional work for 50+ trucks running on the average worn and designed rails from the Hudson–34th curve. The designed shape on the right significantly reduces the expected gauge face and wheel flange wear.

Figure 5-15

Calculated frictional work for 50+ trucks running on average worn and designed rails from Hudson–34th curve



Effective conicity is a calculation most often applied to stability in tangent track and shallow curves. Technically, it represents the amount of rolling radius differential that develops as the wheelset shifts laterally from its "neutral position" with a specific pair of rails at a specific value of track gauge. Since a rolling radius difference causes a steering moment, λ more practically represents the amount that steering forces change as the contact points on the two wheels shift in response to the axle shifting by small amounts. High λ values are associated with vehicle instability (known as "hunting") and resulting poor ride quality, deterioration of truck components (including wheel flanges and dampers), an oscillating wear pattern on rails, and sometimes track fastener damage. Appendix B shows an example of an area of high conicity coinciding with a region of measured high lateral accelerations on the DCC.

Details of the effective conicity calculation are given in Appendix B. An example of the results is shown in Figure 5-16, which shows that a controlling factor for λ is the flange gap, the clearance between track gauge and the wheel flanges. When track gauge is tight, λ can be especially high. Unworn wheels with thicker flanges have higher calculated effective conicity values than wheels with worn flanges.

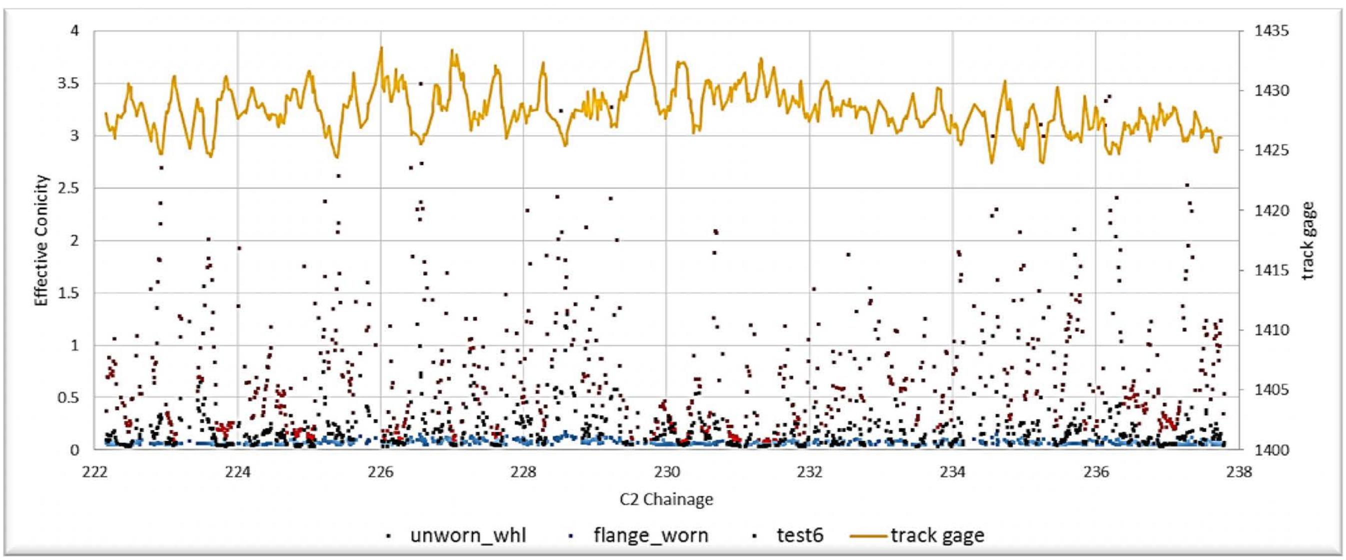


Figure 5-16 *Calculated effective conicity values for three wheels running over measured profiles from Line #7 between 40th/46th St*

Shakedown index assesses the probability of rolling contact fatigue resulting from certain combinations of wheel-rail profiles. It is most often used in concert with simulations (e.g., pummeling). Since the #7 Line does not appear to be suffering unduly from rolling contact fatigue, it is not particularly relevant to this study, but it might apply on other lines with different combinations of wheel and rail profiles, speeds, etc.

Wear coefficient, introduced in Figure 5-15, assesses the amount of energy dissipated in the wheel/rail contact though simulation. An example that compares the performance of the unworn and worn wheels running through the curve at 34th St–Hudson Yards is given in Figure 5-17.

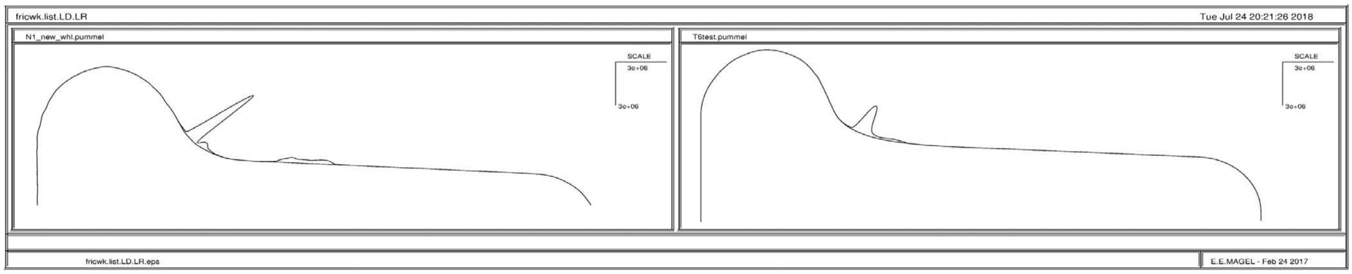


Figure 5-17 *Wear distribution (sum of T-gamma) determined by pummeling unworn wheel (left) and Test6 designed wheel (right) through Corona curve (C2 398-403)*

Summary

Several analytics have been introduced for matching of wheel and rail shapes. Performance estimates—for example, with respect to wear rates, noise, forces, and contact fatigue—are then possible. Several applications of these analytics were then made to:

- Validate that the designed test wheel is compatible with the worn population of rails on the curve N/O 34th St–Hudson Yards and that the rail profile designed for that curve in early 2017 still matches the worn wheel population of 2018.
- Illustrate the correlation between effective conicity and poor vehicle stability, highlighting that tight gauge is a significant deterrent to good high speed performance in tangent track.
- Assess the accuracy of rail profile grinding undertaken on the curve N/O 34th St–Hudson Yards.
- Show how the new wheel profile design can be expected to wear less than the current unworn wheel.

For the Future

Ideally, automated algorithms would be in place to undertake these analytics on a regular basis throughout the system to identify "hot spots"—those contributing to poor ride quality, high rates of wear, excessive lateral forces, and high derailment risk. These analytics are also key to identifying optimal rail profile designs. Similarly, poor wheel profile performance can be predicted and an ideal new wheel shape converged upon. Hopefully, ongoing monitoring and field testing will enable the benefits of the improved rail profiles installed at the curve N/O 34th St–Hudson Yards and the new test wheel design to be determined.

Truck Performance Monitoring and Diagnostics

The TBOGI and L/V instrumentation are located on track C2 line just north of the 103rd St (Corona) station (see Figure 5-18). The L/V is located on a short, unrestrained curve of 1780-ft radius (3.2 degrees), with a super-elevation of 2.75 inches and a posted speed of 50 mph. Due to its proximity to the station, it is likely that the head end of the trainset will run slower than the trailing end through that site. After passing the curve, and roughly 300 ft further along, the TBOGI is located on tangent track. In the span of one week, a given car might pass the wayside instruments as many as 130 times. Figure 5-18 shows the physical location of the L/V and TBOGI sites on MTA's Flushing Line (#7 train) in Queens.

Figure 5-18

Layout of wayside test sites

L/V Data

A comparison of L/V data between both cribs found that Crib 2 consistently measured lower values of lateral force and L/V but nearly the same V. To determine which of the two cribs to use, the lateral force on the trialing wheelset was examined. In this relatively mild curve, those values should be near zero. Plotting the lateral forces on the low rail for trailing wheelsets only (Figure 5-19) shows that Crib2 best reflects this expectation. Any further analysis uses only the Crib 2 data set.

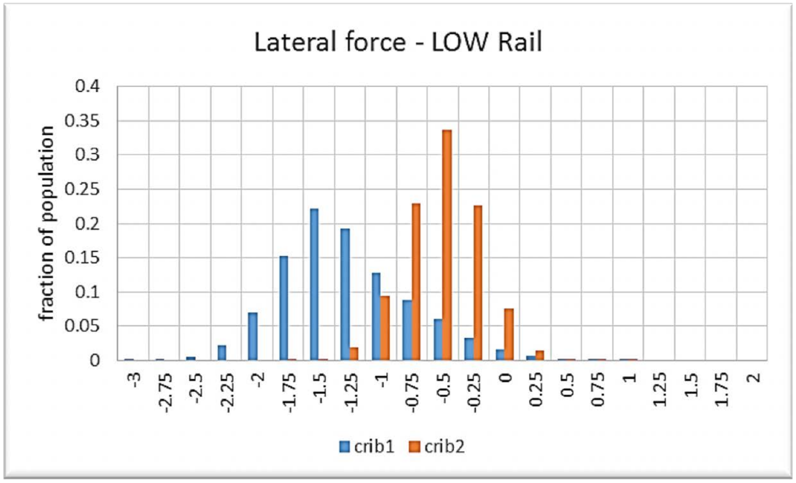


Figure 5-19

Plot of lateral forces for trailing wheelsets, as measured by Crib 1 and Crib 2

Motored vs. Non-Motored Trucks

The L/V data do not show any measurable differences in L/V forces for motored vs. non-motored trucks (Figure 5-20). That said, it is interesting to note that the IWS truck, which is non-motored, does not follow the distribution very well (Figure 5-21), tending towards lower (more negative) L/V values. Although the values are not so extreme as to be considered "outliers," they cannot be said to be representative.

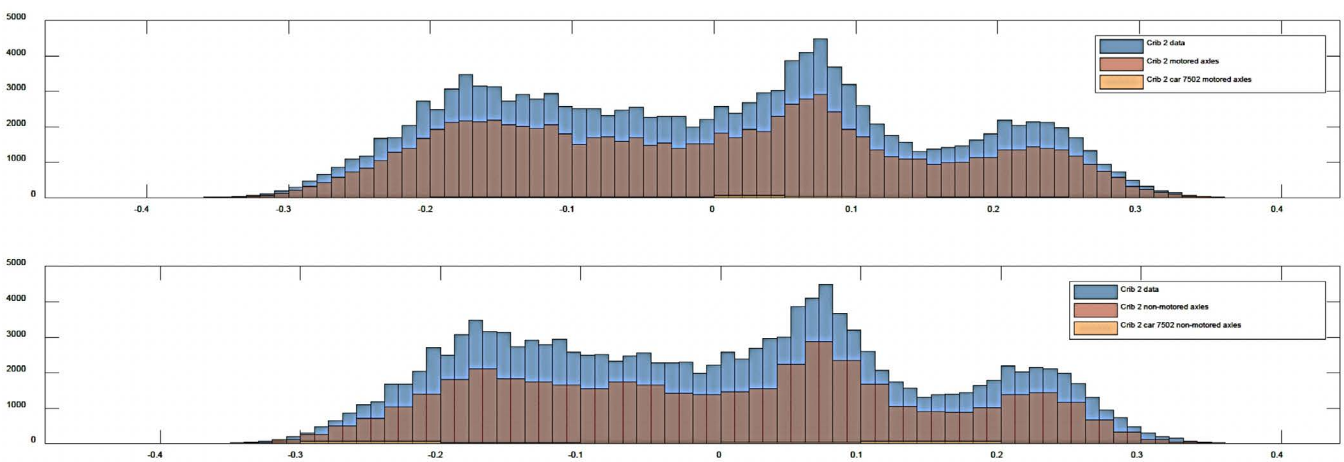


Figure 5-20 *Distributions of motored (top) and non-motored (bottom) trucks passing L/V site*

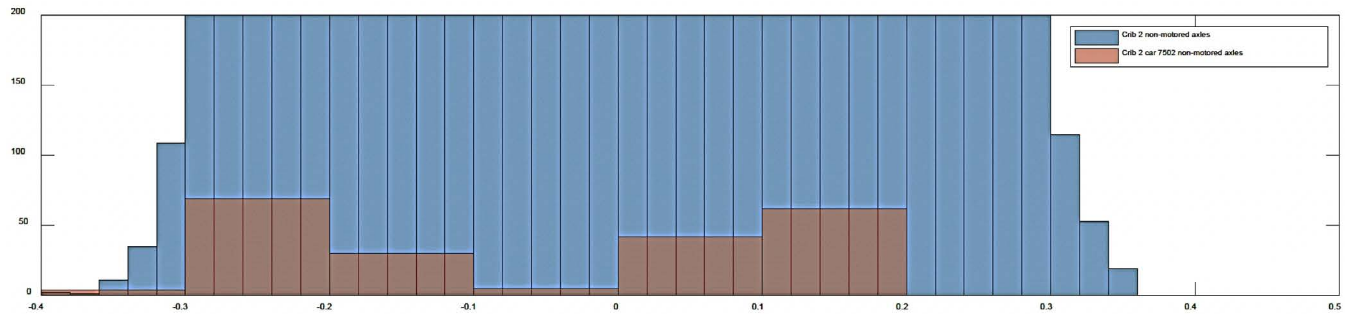


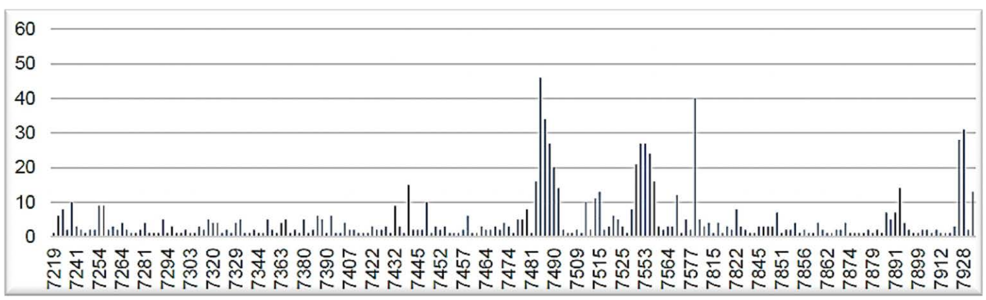
Figure 5-21 *IWS truck on Car 7502, exhibiting lower values of L/V than general population*

A search for L/V outliers proved interesting. Looking for cars that consistently exhibited L/V values exceeding the 99th percentile level of 0.294 (the highest values of high rail L/V) for the week of data examined revealed two well-defined clusters (see Figure 5-22):

- Cars 7486–7490 is a complete 6-car consist
- Cars 7551–7555 is a complete 5-car consist

Figure 5-22

Poorly-performing cars clusters

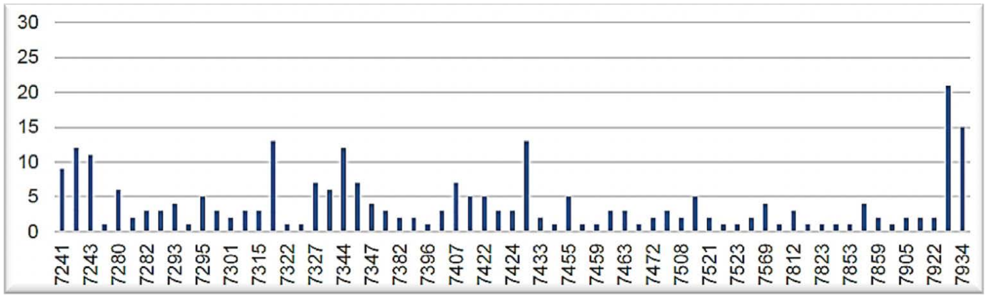


A review of the WheelScan® data reveals that nearly every wheelset on those two consists had been replaced between December 2017 and the end of January 2018. For all intents and purposes, most of the wheels on these two trainsets would be unworn. The poor match with current worn rails is likely a contributor to poor curving performance and higher lateral force.

The same approach was taken to look at trainsets that gave strong negative L/V values (those having the largest values of low rail L/V), with occurrences falling below the first percentile value of -0.264. These are shown in Figure 5-23; no clusters arise in this case. The WheelScan® data for all cars having 10 or more exceedances (7242, 7243, 7320, 7344, 7431, 7933, 7934) were examined, and it was found that all had well-worn wheels at the time of the L/V measurements. In fact, the car with the most exceedances (7933) was re-trued just three days later.

Figure 5-23

Outlier cars with strong negative L/V values



Summary

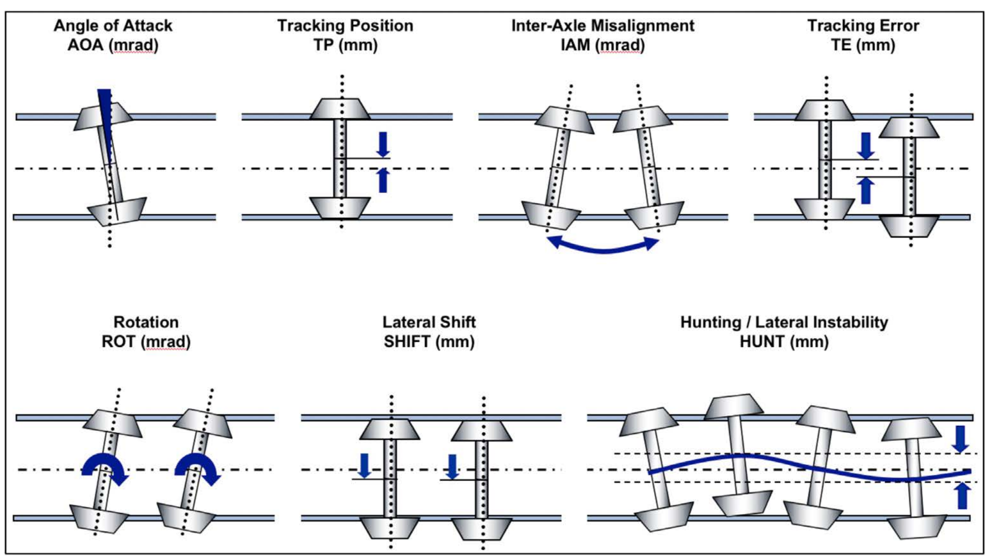
Outlier wheelsets can be effectively identified as those that are repeatedly measured as having high force levels. Those outliers can then be targeted for inspection and maintenance. With greater experience, it may be possible to relate force signatures to some specific maintenance action. In this project, only wheel shape and (in the next section) correlation with TBOGI results was reviewed. A review of the L/V outliers suggests that both brand new and end-of-life wheels perform worse than wheels at a "mid-life" worn shape.

TBOGI Results

The TBOGI measures the Angle of Attack (AOA, in mrad) and Tracking Position (TP, in mm) of each wheelset of a passing train. From the AOA and TP measurement of the two wheelsets of a truck, several truck performance parameters are derived, as shown in Figure 5-24 and described in more detail in Appendix E, "WID Report" (see link). TBOGI also provides derived truck performance parameters, described in more detail in Appendix E.

Figure 5-24

TBOGI parameters



On tangent track, both wheelsets of a truck should have an AOA of 0 mrad and a TP of 0 mm. The TBOGI dataset spans the interval of November 2, 2017, to June 18, 2018, and comprises a total of 348,461 valid truck passes (i.e., no invalid image data or missing AEI tag) captured from 978 unique trucks. Table 5-2 provides statistics of each TBOGI measurement for the entire dataset. All acronyms that end with _L refer to Leading Wheelsets, and all acronyms that end with _T refer to Trailing Wheelsets. The averages of TP_L and TP_T are practically zero, which is desirable. The AOA_L and AOA_T have a symmetric bias of 0.29 mrad, which is unusually large for this parameter. The average IAM (0.58 mrad) corresponds to exactly the expected value of AOA_L – AOA_T.

The 3.2-degree (1,780-ft radius) curve preceding the TBOGI site is deemed a "mild" curve, wherein the wheelsets will take a yaw angle with the rail. As the truck exits the curve and transitions through the spiral and then onto the tangent, both wheelsets should return to their nominal AOA of 0 mrad. The measured average AOA for the lead and trail wheelsets shown in Table 5-2 (0.29 and 0.29 mrad, respectively) and may be indicating that a group of wheelsets have not completely returned to a zero AOA position by the time they have reached the TBOGI system.

Table 5-2

Statistics of TBOGI Measurements, Entire Dataset

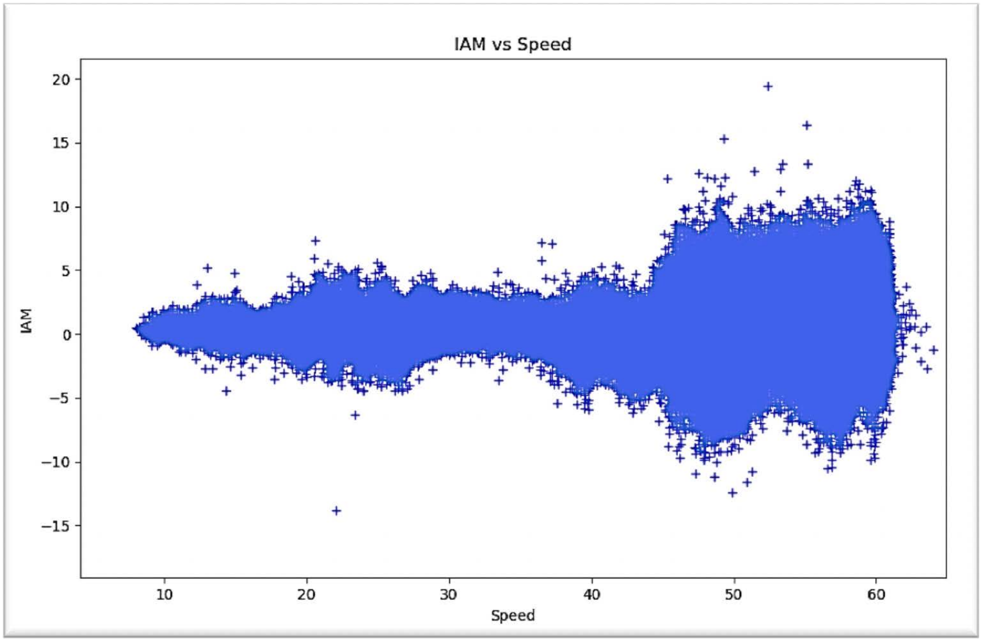
	AOA_L, mrad	AOA_T, mrad	TP_L, mm	TP_T, mm	IAM, mrad	TE mm	SHIFT mm	Rot, mrad
Average	0.29	-0.29	0.01	-0.01	0.58	0.01	0.01	NA
Σ	1.78	1.72	1.63	1.53	2.15	1.51	1.36	NA
Max	12.3	14.9	8.6	7.0	19.4	12.9	7.5	10.5
Min	-9.1	-12.8	-17.1	-14.8	-13.8	-15.5	-14.5	-8.0

In WID's experience, drawn mostly from working with freight and heavy haul railways, the Standard Deviation (σ) of TP_L and TP_T for the Line 7 fleet are very low. The lower values may be the result of the trucks having a more elaborate suspension design and a uniform fleet maintained to higher standards. The standard deviation of the AOA_L and AOA_T and, consequently, interaxle misalignment (IAM) are, however, much higher than measured at any other railroad in WID's experience.

Typically, TBOGI exceptions are characterized by high repeatability, even over different speeds, which was not the case at NYCT. Figure 5-25 shows a scatter plot of the IAM vs. speed data points for the entire dataset that confirms there is a speed dependency on the maximum values of IAM; the maximum IAM abruptly increases at speeds over 40 km/h (25 mph) to over 10 mrad. Tracking position was found to be unaffected by train speed.

Figure 5-25

IAM vs. speed scatter plot



The standard deviations for the angular measurements (AOA_L, AOA_T, and IAM) of data points having speed lower than 40 mph were found to be less than half those of higher speed data readings and more in line with WID's experience elsewhere.

Outliers were identified by Wayside Inspection Devices, Inc. (WID) as those repeatedly having values exceeding the 3σ threshold level for tracking error, shift, interaxle misalignment, and rotation (see Appendix E) Of the 21 cars listed, only one matched with an L/V outlier—car 7394, which also experienced a modest frequency of IAM exceedances. NRC Canada searched for cars with several exceedances of the 99th percentile and found the same car (7934) as the only one matching an L/V outlier.

In general, the exception thresholds for all four TBOGI truck performance parameters were low compared to even the best heavy-haul railway in terms of TBOGI statistics. The exception rates for the TP-based measurements (i.e., TE and Shift) of each car were very similar between the low-speed and high-speed groups, confirming that the tracking position data are independent of speed. However, the exception rates of the AOA-based measurements (i.e., IAM and Rotation) of each truck were very dissimilar between the low-speed and high-speed groups. As expected from the IAM vs, speed scatter plot, the exception rate of the high-speed group was very high, and the exception rate for the low-speed group was relatively low. The cars that have the highest rotation exception rate in the high-speed group had no exceptions in the low-speed group, another confirmation of speed dependency of the AOA-based measurements.

AOA-based exceptions were also widespread across the population of measured NYCT cars; 60% of the unique truck IDs reported at least one AOA exception within the entire dataset. The highest rate of AOA-based exceptions was 7% for truck B of 7567 (see Appendix E) for more details. It is unlikely that the widespread occurrence of AOA exceptions across the fleet of trucks is due to a systemic issue with the trucks. Rather, the speed dependency of the AOA distributions shown in the previous section suggests that many trucks had not yet stabilized when passing by the TBOGI system after they steered out of the preceding curve. The speed dependency of the AOA distributions and high AOA σ issue could be remedied by grinding the rails to restore the rail profile in the L/V–TBOGI area, which would greatly benefit the steering and dynamic stability of the trucks.

Consequences of Truck Geometry Exceptions

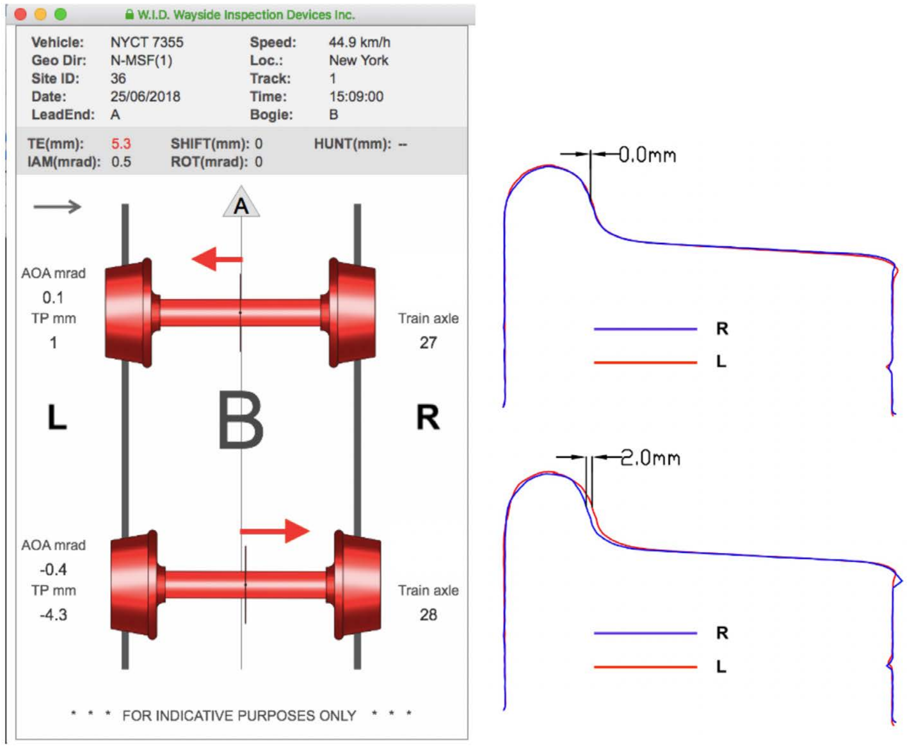
The truck with the highest rate of Tracking Error exception (TE) was 7355B. In 266 passes, the TE of this truck was greater or equal to 4.5mm on 93% of the passes. Even though the 4.5mm TE threshold represents 3σ (only 0.27% of all TE measurements for all traffic exceed 5mm), a TE of 4.5mm in freight application is negligible, even for the most stringent heavy-haul railways. Yet, on 7355B, the wheel profiles already showed evidence of asymmetric wheel wear.

Figure 5-26 is a sketch of truck 7355B produced by the Wayside Inspection Devices, Inc. (WID) database TBOGI-DB. AEI Truck B corresponds to Truck 2 in the NYCT vernacular. TE is calculated as the differential between the lead axle TP and trail axle TP. The lead axle of Truck B is +1 mm, which is negligible. The trail axle TP is 4.3 mm. The negative polarity indicates the axle moved towards to right hand side of the truck. The overlaid right and left wheel profile are shown next to each axle. With a TP of just +1, the lead axle does not show any differential wear on its wheels. However, with a TP of -4.3 mm, the trail axle already is showing a 2 mm wear of the right wheel compared to the left wheel.

The truck with the highest rate of Shift was 7547B, with a shift measurement equaling or exceeding 4 mm on 72% of its 261 passes. Truck shift is when both axles of a truck displace towards the same side of the truck. For this truck, the large shift value correlates with both right side wheels have about 2 mm flange wear compared to their respective left wheel. The differential wheel wear experienced by this truck will continue to increase over time.

Figure 5-26

Sketch of Truck B of 7355 with corresponding wheel profile



Comparison of TBOGI Values with L/V Outliers

The NRC Canada analysis of L/V data identified two train segments that, taken as a group, produced a high number of exceedances of the L/V 99% threshold—cars 7486–7490 and 7551–7555. The TBOGI parameter exceptions for those trucks are shown in Table 5-3. Cars 7488 and 7489 produced a large number of L/V exceedances within the L/V group itself and did likewise for TBOGI parameters. Other cars, such as 7487, also produced a large number of L/V exceedances but did not exceed the TBOGI 99% threshold, although the TBOGI parameter values were significantly higher.

Table 5-3 *TBOGI Parameter Exceptions for Trucks Identified as Outliers by L/V System*

High Speed	Threshold	A	B	A	B	A	B	A	B	A	B	B	A	A	B	A	B	A	B	A	B	B	A
769	4.9	0	2	1	2	1	0	0	2	0	0	0	0	3	0	0	1	1	1	0	0	0	0
50	4.4	0	0	0	0	0	27	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	1
686	6.6	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
360	4.4	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The inconsistent correlation between L/V and TBOGI is not unexpected, as the two systems are not collocated. The L/V is on a curve, and TBOGI is on a tangent 300 ft away.

Summary

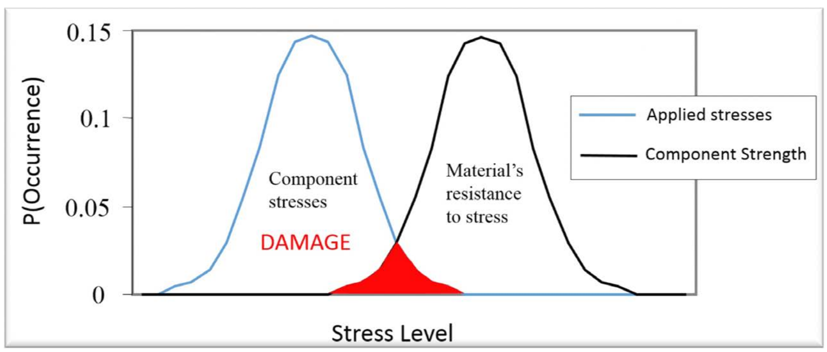
The TBOGI Tracking Position metric is useful for identifying trucks that are experiencing differential flange wear on its wheel sets, even at an early stage as shown in the previous examples. TBOGI AOA metrics are useful for identifying trucks with steering issues that will wear their wheels and other truck components unevenly and at a faster rate.

Derailment Risk

A general principal of rail/wheel failure analysis can be explained by the stress vs. strength curves (Figure 5-27). The stress applied to the track will vary depending on the truck condition, train load, and train speed, among other factors. The strength of the track is a function of its condition, particularly the fasteners. In a classic rail rollover derailment, truck and wheel-rail contact conditions (poor profiles and high friction), sometimes in combination with in-train forces, lead to high lateral forces that exceed the strength of the track at some particular location, often because of fastener failure (such as broken spikes).

Figure 5-27

Generic stress and strength distributions

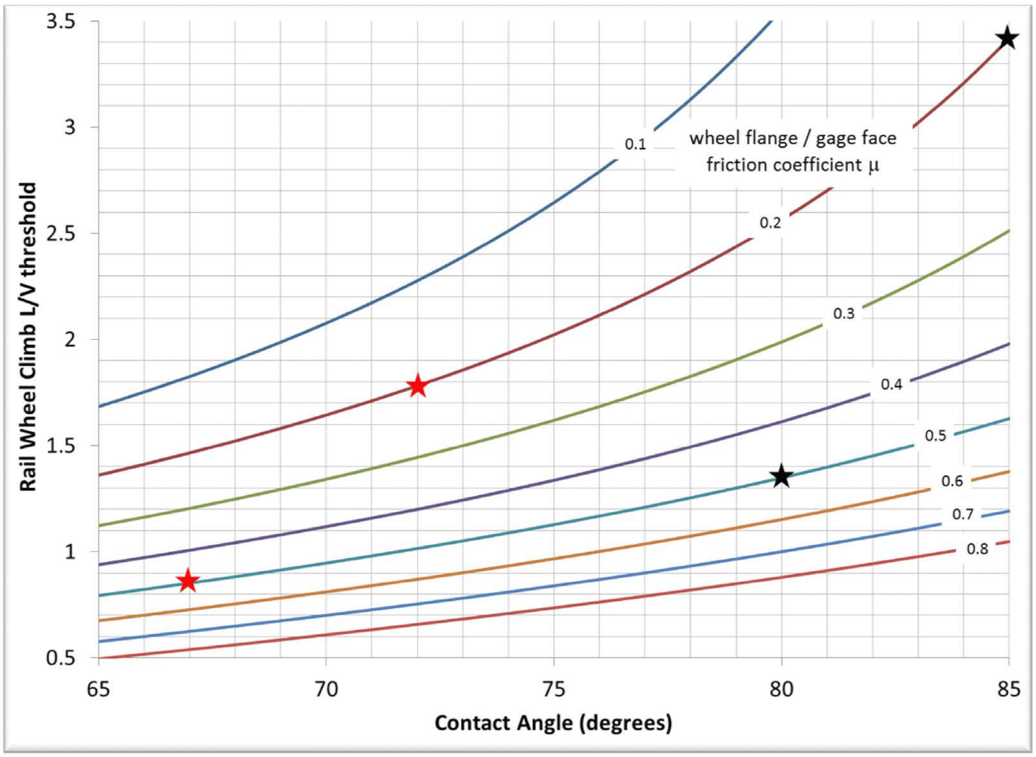


The interaction between the wheel and rail is governed by a number of inputs, including wheel and rail profiles, friction coefficients, dynamic forces associated with track geometry perturbations, and speed with respect to balanced running. In this project, the safety focus is with respect to wheel climb on unrestrained curves and restraining rail climb in sharper curves and turnouts. Other types of derailment, such as rail rollover, broken rail, or hunting, are much less common for transit agencies.

Climb of both the outside rail in curves and the restraining rail can be analyzed using the Nadal criterion, which prescribes the ratio of L/V forces that can be tolerated based on the friction coefficient and angle of contact. The current NYCT wheel, with its 67-degree wheel flange angle operating on dry rail has an L/V threshold of 0.85. Reducing friction to 0.2 through lubrication and increasing the flange angle modestly to 72 degrees increases the threshold L/V value to 1.78 (see red stars on Figure 5-28). For the restraining rail case (black stars on Figure 5 28), the base case of 80-degree contact with the restraining rail under dry (μ=0.5) conditions gives an L/V threshold of 1.35. Increasing the contact angle to 85 degrees (for example, by raising the restraining rail compared with the running rail) and lubricating more than doubles the threshold to 3.5.

$$\frac{\boldsymbol{L}}{\boldsymbol{V}} = \frac{\tan\delta - \mu}{1 + \mu\tan\delta}$$

Figure 5-28
Nadal relationship for single-axle climbing of rails



Although the Nadal analysis provides a tolerance value for a given rail/wheel pair, the IWS is an ideal tool for identifying the levels of L/V being encountered by vehicles as they traverse the system. Whereas the measured L/V values are influenced by the same friction coefficient used in establishing the threshold L/V, the IWS values are also influenced by many other factors but principally track geometry and speed. If friction conditions are more or less consistent through the property, then the IWS is, by itself, effective in identifying problematic track locations. Examples include the following:

- Turnouts north and S/O Willets Point, where values in excess of 1.5 were encountered. As noted, the highest values are encountered when the system is at or close to the as-new condition. The replacement of a restraining rail, for example, led to a tripling of the L/V value.
- Unguarded (unrestrained) curve N/O 34th St–Hudson Yards, where values of 0.65 and greater were common. In a separate project in which that curve was instrumented for L/V and data were collected from passing cars for a period of

roughly 20 hours, values as high as 0.8 were measured. For unworn wheels with a flange angle of 67 degrees on unlubricated rail, the Nadal limit is 0.82, suggesting a system that might operate at times close to the limit. Improved lubrication dramatically reduces that risk but cannot always be counted on to work. Fortunately, the shallow flange angle quickly wears to a steeper value within a few days of running, further increasing the threshold, so the high risk period is of short duration and infrequent—instances where a freshly-trued (i.e., shallow flange angle) wheel operates against dry rail. The risk of a wheel climb derailment could be diminished by modifying the new wheel shape to include a steeper wheel flange angle.

- Restrained curve S/O Queensboro Plaza, where similarly high values of L/V were measured. Detailed analysis showed that there was a strong correlation between train speed and L/V value, leading to a recommendation to operate trains at a balance speed of 14 mph.

Summary

Managing derailment risk at NYCT requires a multi-pronged approach:

- Lubrication (of rail gauge face and restraining rail contact face) significantly increases the tolerance of the system to high dynamic forces and poor wheel-rail contact conditions.
- Increasing the wheel flange angle of newly-trued or installed wheels would considerably reduce the risk of wheels climbing the outer rail of unguarded (unrestrained) curves, such as N/O 34th St–Hudson Yards.
- Increasing the contact angle with restraining rails would further reduce the risk of climb. This could be accomplished by increasing the height of the restraining rail to contact higher up the wheel back plate and instituting a process to monitor the wheel back-of-flange angle and eliminating those wheelsets with both high levels of flange wear and low back-of-flange angles.

For the Future

L/V force is readily-measured by the IWS for those two axles and by the L/V system for passing vehicles. At the outset of the project, it was a goal to bring together vehicles identified by the L/V system as outliers, with track sections identified by the IWS as being outliers. Two options have been considered:

- Data Analytics Method
  - Develop a baseline for the force (ratio) distributions based on one year of IWS data at five outlier locations.
  - Adjust distributions by considering the impact of fleet health (would not be a trivial exercise).
  - Estimate risk based on estimated fleet force (ratio) distributions.

- Stochastic Simulation Method
  - Develop vehicle and track models that match up with IWS force distributions at five locations.
  - Devise stochastic inputs for the fleet, including distributions of back-to-back wheel profiles, suspension parameters, speeds, etc.
  - Simulate to predict the distributions of forces representing the whole fleet.
  - Estimate risk based on the calculated force (ratio) distributions.

Damaging Stress

Damaging stress at the wheel-rail contact is a result of several individual and contributing factors, including the following:

- Wheel-rail profiles – poorly-matched profiles have three primary effects:
  - Instability in tangent track due to excessively conformal shapes gives rise to high dynamic forces and high wear rates.
  - Excessive contact stress that can occur if the contact is non-conformal.
  - Poor steering leading to high levels of slip between the wheel and rail and high shear forces, which contribute to both wear (and corrugation) and RCF.

    These have been discussed and demonstrated. It is not difficult to imagine in the future that these analytics being applied regularly to the entire set of measured rails for identifying "hot spots"—track locations with poorly-matched profiles that contribute disproportionately to track, rail, and wheel damage.

- Poorly-maintained or poorly-performing trucks – these are more susceptible to instability or poor curving performance. In the freight world, for example, poor interfacing between the truck and carbody can lead to excessive truck turning forces, truck warp, and high lateral forces, even in mild curves. In transit systems, the overall performance level is much better. Outlier trucks can be identified using the wayside TBOGI and L/V systems.
- High friction levels – these have a considerable effect on wheel/rail forces and, hence, damaging stress. The shakedown analysis gives an example of the effect of friction in individual wheel/rail contacts. The L/V readings from Figure 5-1 show how rain, by reducing friction, dramatically reduces dynamic lateral forces.

  Regions of high friction can be measured directly using specialized tribometers (not currently available to this project) and with the IWS when there is a single point of contact between rail and IWS, the angle of the contact is near to the track level, and there is sufficient slip between wheel and rail that the traction is "saturated."

These qualifiers on the IWS limit the length of track that can be evaluated for friction. When going through an unguarded curve, these values can be measured on the low rail. This has been done on the curve N/O 34th St–Hudson Yards, and worked well. But if the curvature is much lower, the creepage will not be saturated and the measured traction value will be lower than the friction coefficient. An on tangent track, since the IWS are unpowered and not braked, the creepage always has a low value.

- Dynamic forces can be measured directly with the IWS and indirectly through carbody accelerations. Several practical examples of high lateral, vertical and L/V force have already been discussed. The damaging stress has manifested itself through wear, corrugation and broken track spikes.

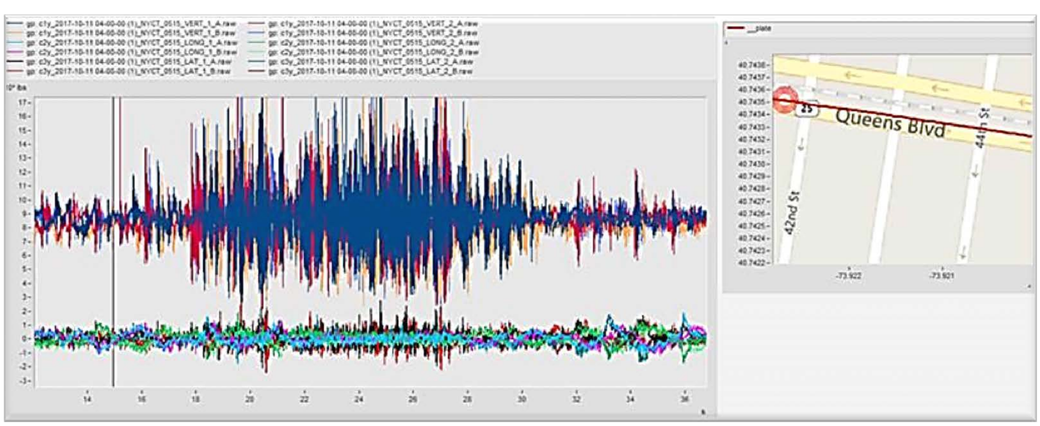
Ride Quality

Ride quality can be measured using accelerometers on the car body, and there are standardized processes for evaluating these with respect to passenger comfort [3]. The accelerometers in this project were mounted on the truck frame, which is more useful for assessing vehicle-track performance and less so for passenger ride quality or comfort.

Bad ride is always generated by high force "jerks" or oscillations. Therefore, IWS forces and accelerations can be used to identify the locations of bad ride quality and through frequency analysis, sometimes also the root cause. For example, the tangent track between the 40th/46th St stations is associated with strong vertical vibration (Figure 5-29). The 40 Hz vibration measured by the IWS corresponds to a 16-inch wavelength, which, through subsequent review of NYCT video data, coincided with a long wavelength corrugation found on the rail in that area (Figure 5-30).

Figure 5-29

Vertical vibration levels near 41st St exceeds 2g at 36 mph



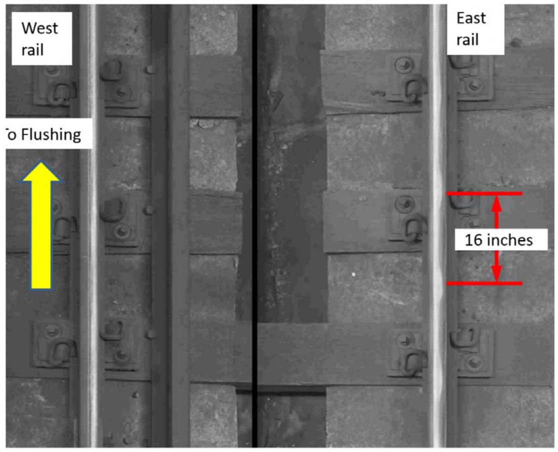


Figure 5-30
Long wavelength corrugation responsible for poor ride quality on tangent track between 40th/46th St stations

Other track problems, such as the priority vertical dip defect on the express track at Woodside station (see Appendix A) would have been ride quality concerns as well.

Wheel-Rail Noise

Wheel-rail noise is measured directly on the DCC through two external microphones. An example of the information that can be generated from these data is shown in Figure 5-31. Each plot has a y axis of frequency, and the x-axis

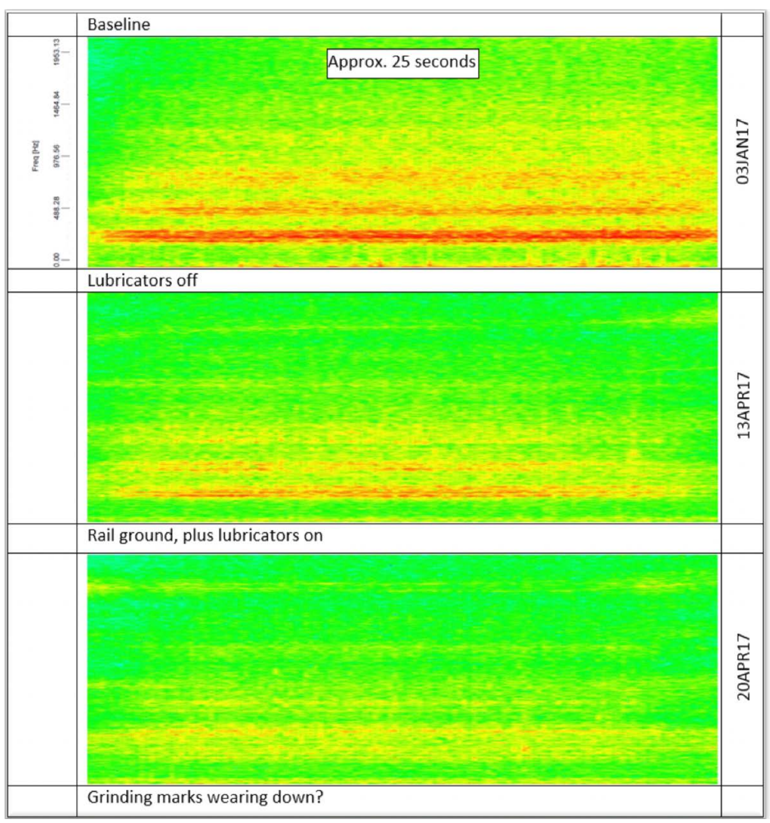


Figure 5-31
Noise plots from N/O 34th St–Hudson Yards, track CC2; upper plot—noise before rail is ground; middle plot—immediately after grinding; bottom plot—approx. one week after grinding

is time in seconds. The width of the graph spans about 25 seconds as the train travels from left to right. There are two clear frequency bands of around 280 Hz, 500 Hz, and something broader above that. Knowing the train speed, it is possible to determine the wavelength of a feature that might be associated with that frequency. At 29 mph, a 280 Hz noise has a corresponding wavelength of 1.8 inches. This corresponds to the low rail corrugation in this curve. In Figure 5-31, the top plot is before grinding where the rail corrugation has a strong influence on noise. After grinding (middle plot), the noise levels have been significantly reduced. Two weeks after grinding (bottom plot), the noise levels reduced even further, perhaps due to wearing away of the grinding roughness.

Wheel/rail noise is the result of energy exciting one or both of the components. If the microphones identify track areas that are particularly noisy, they should be targeted for treatment. Several techniques are available for minimizing this energy input and thereby reducing noise:

- Wheel/rail profiles that steer through curves reducing slip and sliding energy between the wheel and rail and can prevent wheel flanging, which is a noise problem in itself; this is limited to moderate and shallow curves, as the relatively rigid transit bogies assure high yaw angles and saturated creepage in sharper curves.
- Friction management, including lubrication of the gauge face to minimize flanging noise and top of rail with a positive friction modifier to reduce stick slip, which can reduce wheel/rail noise and, in some cases, eliminate tonal noise (such as wheel squeal) altogether. Friction management on the curve N/O 34th St–Hudson Yards has been very successful in reducing noise levels there.
- Dampers on the wheel and rail [4]; these tend to be quite expensive, however, and are sparingly applied.

Wear Monitoring and Diagnostics

Wheel Wear Monitoring

The KLD WheelScan® began collecting wheel profiles in earnest in February 2017. After being connected to an AEI system in March 2017, all data could then be associated with specific wheels. The x,y coordinates of each profile are captured and then analyzed to determine several standard parameters such as flange width, flange height, rim thickness and flange angle (see definitions in Figure 5-32).

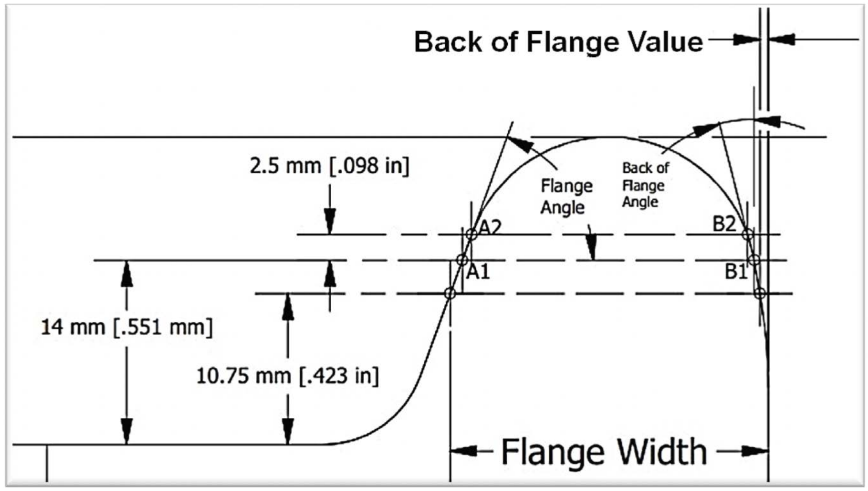


Figure 5-32

Definition for wheel parameters calculated and stored in WheelScan® database

WheelScan® data have been used many times throughout the project. For example:

- To assess whether TBOGI outliers evidenced causal or consequential wear patterns (they did).
- To assess whether there was commonality between the wheel profiles of a whole car set of L/V outliers (there was, they had all been recently renewed).
- To determine distributions of back-to-back and flange width for use in studies of effective conicities and appropriate guard rail clearances.
- To develop average worn shapes for use in designing a test wheel for implementation on Line #7.

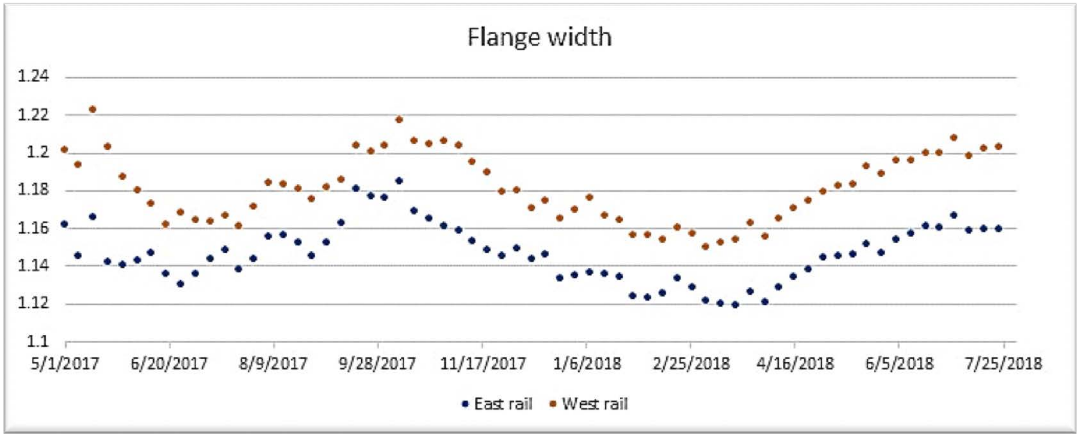
Another powerful application of the wheel data sets is to regularly review the wheel shape distributions to determine if there are any system-wide characteristics or changes of concern. Consider, for example, the plot of Figure 5-33. As shown, the average flange width varies through the year. This could be simply because there are periods of more frequent wheel retruing or replacement. More interesting is that the flange width is notably lower for those wheels that operate against the east rail. Three reasons for this have been considered:

- **Measurement error** – KLD has reviewed its system and calibrations and has confidence in the data.
- **Retruing error** – previous measurement of recently trued wheels at Corona found that there were differences between the left and right sides. A review of KLD WheelScan® measurements of eight recently-trued wheelsets found that if there were thinner flanges at all, they were on the west side of the train, not the east.

- **Flange wear** – since the trainsets are never turned, one side of the train always runs against the same rail. It was expected that if flange wear were the cause of differential wear, the thinner flanges would be those running against the high rail of the 34th St.-Hudson Yards curves. That would be the west rail, not the east.

Figure 5-33

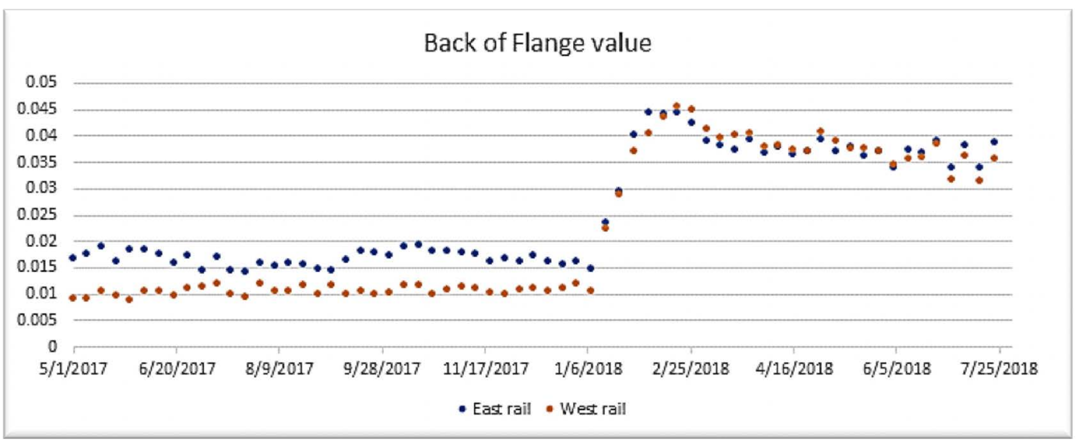
Average flange width of all wheel profiles collected in a week for duration of project



A value representing the back-of-flange wear level was devised and employed by KLD in its WheelScan® analytics. A plot of back-of flange value (Figure 5-34) shows that there was a sudden and considerable increase in back-of-flange wear in Winter 2018. This is discussed in more detail in the next section.

Figure 5-34

Weekly average value of back-of-flange value



Back-of-Flange Wear

In its early review of wheel profile data, KLD found that a noticeable fraction of the wheels exhibited a different back-of-flange shape than "normal wheels." Subsequent review of the shapes found that some has a pronounced shallower angle, with others having a very steep back-of-flange (Figure 5-35). As perhaps a shallow back-of-flange had contributed to the restraining rail climb derailments of January 2017, this back-of-flange wear observation gained immediate attention.

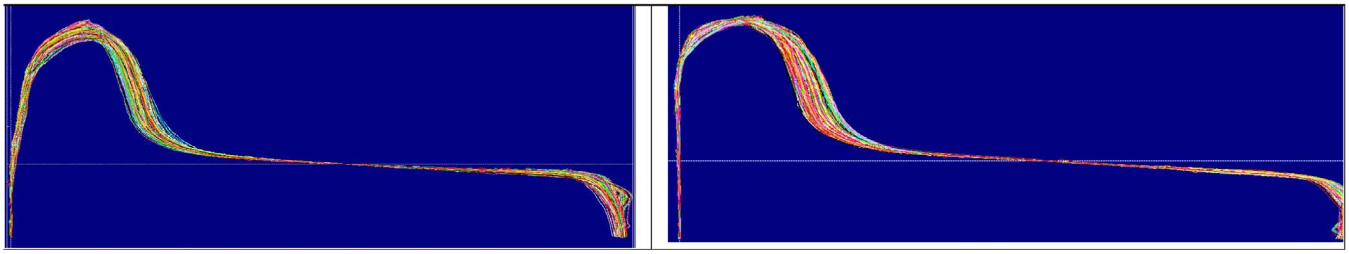


Figure 5-35 *Examples of wheels exhibiting shallow (left) and steep (right) back-of-flange angles*

Tracking both the entire population of wheels and individual wheelsets, the sudden increase in back-of-flange wear was found to have started in mid-January 2017. An example is shown in Figure 5-36 of four wheels of the two instrumented wheelsets. Clearly, something occurred that all wheels suddenly experienced a decrease in back-of-flange value. It is known that those wheelsets have not been retrued since installation, so the remaining possibility is wear against restraining rails in curves. This is probably due to cold weather and non-functioning lubrication.

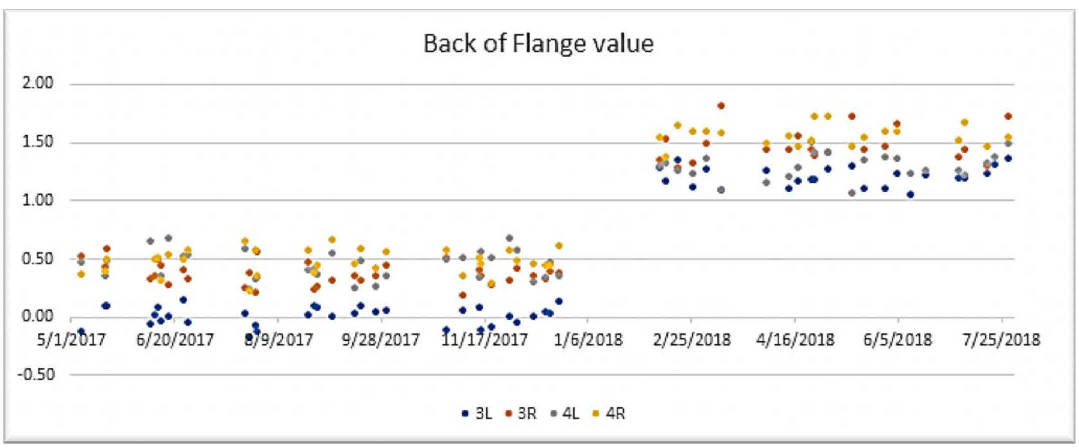


Figure 5-36 *Example of back-of-flange value for instrumented wheelsets*

Rapid Wear-in of Wheels

Looking at individual wheelsets, there are some clear and interesting wear trends. Consider, for example, the wear values shown in Figure 5-37. Those wheels had evidently been put into service as the WheelScan® data were also becoming available. It shows very rapid wear over a period of about 70 days, encountering about 6 mm of wear in that time. Those wheels were all retrued (as evidence by the wheel diameter change), and three months later all the wheelsets were replaced. The flange wear in this last year of life is more typical of what has been experienced through the bulk of the fleet—relatively rapid wear-in over the first couple of months, followed by slow, steady wear thereafter.

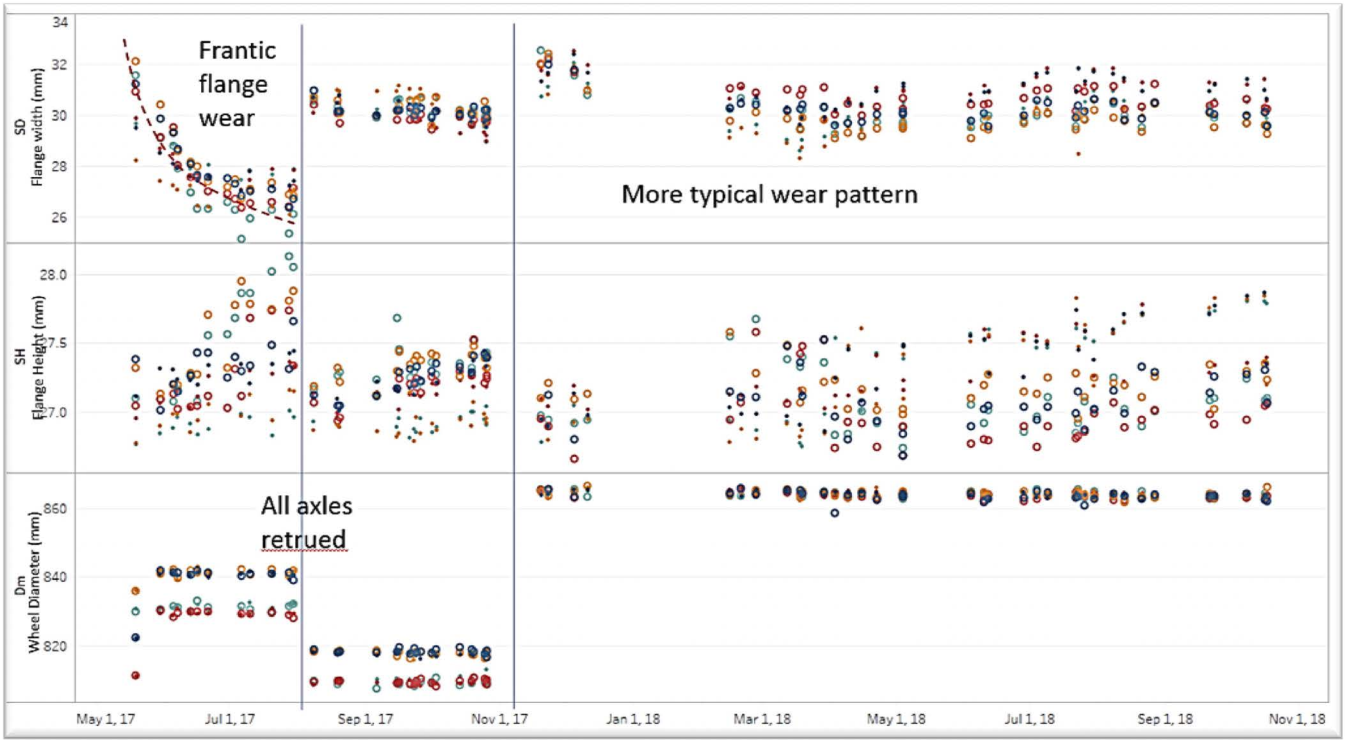


Figure 5-37 *Representative wear pattern, found on many axles, including cars 7231–7235*

The wear trends of the instrumented wheelsets, which were new upon installation on Line #7 in April 2017, reflect a widely seen wear pattern (see Figures 5-38 and 5-39). The flange width wears rapidly in the first three months of life but then steadies out. Something occurred in January 2018 to cause a noticeable increase in wheel flange wear but, unfortunately, there was a failure of the tag reader at that time. Flange angle starts at a low initial value of around 67 degrees, as measured on April 4, and by the end of May 2017 (six weeks later), it is greater than 70 degrees on all wheels. On another car (7312), the flange angle took four weeks to cross 70 degrees.

Figure 5-38

Flange wear measurements for four IWS wheels

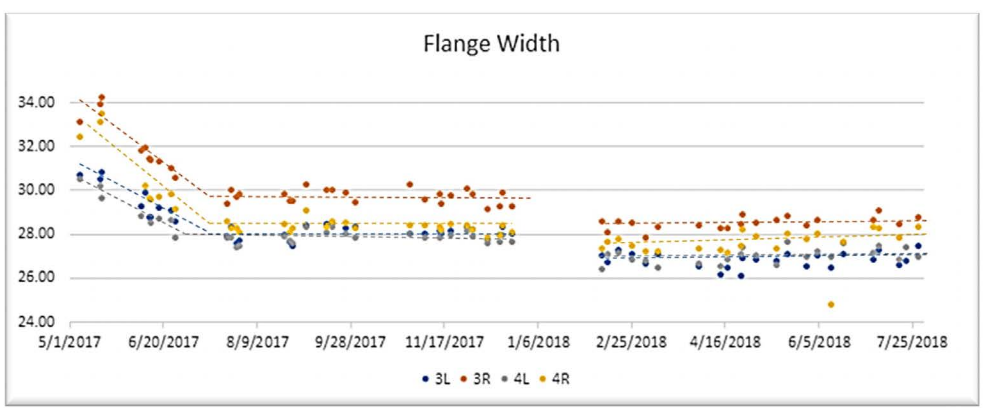
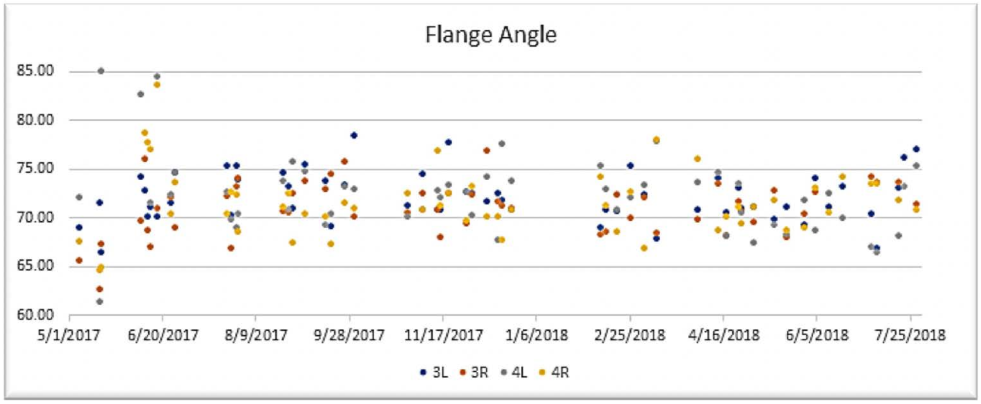


Figure 5-39

Flange angle trend for instrumented wheelsets (car 7502, axles 3 and 4, left and right sides), characteristic of other wheels in fleet



These rapid rates of wear and known poor performance of the existing unworn wheel led to the design of a new wheel profile for trial on NYCT.

SECTION 6

Evaluation Criteria

Evaluation Criteria and Original Project Demonstration Objectives

The research work completed during the extended period of performance addressed all the original project demonstration objectives and met the original evaluation criteria. See Appendix H for a list of additional research efforts reflecting a significantly expanded scope of follow-on research.

Operational Safety

Demonstration Objective: Enhance Operational Safety

- Identify and mitigate wheel/track conditions that contribute to equipment failure.
  - *Result*: Rail corrugations at curve N/O 34th St–Hudson Yards – attempted TOR friction management.
  - *Result*: Accelerated wheel flange wear after milling – testing modified wheel profile.
- Identify and correct wheel/track conditions that could lead to slow speed derailments.
  - *Result*: Data from laser wheel scanner used to discover back-of-flange issues.
  - *Result*: IWS data indicated heightened L/V forces associated with execution of track maintenance.
- Identify and correct wheel/track conditions that contribute to vehicle steering instabilities and poor ride quality.
  - *Result*: TBOGI identified cars with inter axle misalignments.
  - *Result*: Identified issue of tight gauge contributing to greater potential for instability.

Infrastructure & Equipment Resiliency

Demonstration Objective: Enhance System Resiliency

- Facilitate maintenance of current wheel/track data collection, and asset condition monitoring/documentation.
  - *Result*: Laser wheel scanner wheel profile automatic measurement, exception reporting, and data archiving.
  - *Result*: RFID asset tagging (wheel/truck/vehicle/consist identification).

  - *Result*: Physical location identification – TGC track data maps indexed by RFID tag locations (CBTC).
  - *Result*: Physical location identification – DCC vehicle performance data maps aligned with TGC maps by RFID tags.
- Accelerate post emergency documentation of wheel/track asset conditions to accelerate recovery/repair prioritization and speed a system's safe return to service.
  - *Result*: Aligned track geometry maps and vehicle performance maps now exist for the #7 Line; following any emergency, both maps might be referenced as new post incident data analyzed.

Demonstration Objective: Reduce Energy Use

- Reduce wheel/track conditions that promote hunting.
  - *Result*: Use of TBOGI data able to identify most significant "bad actors" with high inter axle misalignment issues.
  - *Result*: IWS data able to reveal track locations where hunting heightened.
  - *Result*: DCC traction energy monitoring demonstrated that rail corrugation responsible for 7% increase in energy required to mount curve.
- Reduce subway vehicle propulsion energy requirements, especially as vehicles steer through curves.
  - *Result*: DCC traction energy data acquisition indicated that in certain curves, impact of friction management able to measurably reduce energy requirements.

Increased Service Life of Assets

Demonstration Objective: Reduce Planned Capital Costs

- Facilitate extending wheel/track asset lifecycle costs:
  - Wheels – increase service life
    - *Results*: Research work contributed to wheel life extension from initial <2-year experience in 2017 to >3-year life, which effectively would eliminate one non-optimum wheel replacement event for fleet of 506 cars in #7 fleet equal to estimated $9.8 million cost avoidance.
  - Track – extend track life cycle:
    - *Result*: Efforts undertaken to reduce rail grinding at 34th St curve to extend track life in that curve; impact of TOR friction management efforts on curve N/O 34th St–Hudson Yards not quantified to permit estimate of any improvement in track life in this difficult curve.

Equipment Condition Monitoring & Condition-Based Maintenance

Demonstration Objective: Reduce Cost of Asset Ownership

- Facilitate maintenance of wheel/rail asset condition monitoring/ documentation.
  - *Result*: Use of RFID identification tags for vehicle and track location indication facilitated automated documentation of wheel measurements and vehicle component pairings and locations.
  - *Result*: Wheel wear data trending allows for maintenance forecasting and condition-based shop scheduling.
  - *Result*: Wear trending identified period of "run-in" that contributes to significant reduction in wheel life (prompting design and testing of "worn wheel" profile).
- Enable coordinated condition-based maintenance of wheels, track and truck components (create the best value proposition).
  - *Result*: Automatic wheel wear trending can facilitate condition-based maintenance and scheduling of wheel service and replacements.

Demonstration Objective: Improve Customer Service and Customer Experience

- Reduce wheel/rail noise.
  - *Results*: Higher noise areas identified by external microphones.
  - *Result*: Noise levels may be monitored and addressed when certain levels reached (for example, corrugated rail on curve N/O 34th St–Hudson Yards).
- Improve vehicle safety / operational continuity.
  - *Result*: Instrumented wheelset data used to identify areas of excessive forces and greatest risk.
  - *Result*: Improved knowledge of track and vehicle performance and conditions on daily basis permits proactive decisions if safety issues seen developing.
- Improve vehicle ride characteristics (wheels, track, and trucks).
  - *Result*: Excessive noise, truck hunting, and vertical vibration may be identified and reduced to improve ride characteristics.

Project Effectiveness

The research team effectively installed and established a suite of data acquisition technologies at NYCT where wheel/rail data characteristics of daily operations were routinely collected while equipment was in revenue service. The interest shown by other transit agencies in the work being undertaken is evidence of the effectiveness of the research project overall.

An area in which the project could have been improved was invoice payments being delayed due to accounting procedures within NYCT's system, which is fundamentally structured for capital projects, not research expenses.

Project Innovation

Employing combinations of technologies and their installation on vehicles on the wayside and in-track configurations is not really innovative. The collaborative team structure and the truly collaborative approach to the research at an operating transit agency-hosted site embodies the project innovation. Careful selection of team members who are willing to collaborate (without enjoying a profit for their resource commitment) allowed all to work efficiently and effectively to advance their technology's performance and provided a unique, perhaps innovative, opportunity to demonstrate how potential combinations of their technologies and services (collaboratively leveraged with others) could provide an agency with significantly more benefits than single technologies operating alone.

National Applicability

There is strong evidence of national applicability of the wheel/rail research work employing daily revenue service rolling stock equipped with data acquisition equipment in combination with wayside and in-track data acquisition equipment. Research presentation requests by industry groups and the participation of other US transit agencies, commuter rail, and Federal Railroad Administration (FRA) representatives in research team open team WebEx meetings is evidence of national transit industry interest and applicability.

Commercialization or Dissemination Plan

The technologies employed in the research collaboration are all commercially available, and the research team sought to provide evidence that additional analytical strengths might result from the combined use of these technologies. The use of a revenue vehicle in daily operation as a system-wide data collection device in conjunction with way-side and in-track data collection equipment collecting vehicle fleet data can be replicated at many transit, commuter, and Class 1 rail operations.

The research team sought to share and inform the industry of its work by participating in numerous industry group presentations:

- May 2016, WRI Integrated Wheel/Rail Characterization through Advanced Monitoring and Analytics

- January 2017, TRB Rail profile design for curve N/O 34th St on NYCT–MTA's #7 (Flushing) Line
- June 2017, WRI Integrated Wheel/Rail Characterization through Advanced Monitoring and Analytics
- August 2017, ICRI Case Study, Investigating and Testing Accelerated Wheel/ Flange Wear
- October 2017, APTA/AREMA Wheel/Rail Interface Group, presentation at NYCT's Corona Car Shop
- April 2018, WRI FTA Research, Project NY-26-7113 Wheel/Rail Characterization, Monitoring and Analytics
- June 2018, APTA NYCT Maintenance Innovation Using Research
- July 2018, CUTR Standards Working Group Meeting, Philadelphia
- March 2019, APTA N&V presentation of FTA Wheel/Rail Research effort
- October 2019 (planned), World Congress on Railway Research presentation, Monitoring and Managing Wheel/Rail Forces by Using Instrumented Wheelset Technology

Recapture of Investment (Value Proposition)

A condition of this collaboration was that no research team members were permitted to incorporate any profits into their budgeted efforts. To evaluate a Return on Investment (ROI) for the suite of data acquisition equipment incorporated in this project, team members provided estimates of what their technology and services might cost agencies at competitive commercial costs. Table 6-1 shows these cost estimates to be $3.1–$4.3 million installed, with technical support and data processing.

To simplify the development of a value proposition supported by the above suite of data acquisition technologies and analytics associated with the research on the #7 Line, "hard" and "soft" savings are described. This approach allows this report to document the investment recapture for the installation and operation of the equipment based on easily-measurable savings that can be quickly calculated. Readers can consider any additional value or benefits that might be ascribed to the continued application of the data acquisition equipment for operational improvements as well as avoidance or mitigation of other events.

Since this effort was targeted to impact safety and resiliency in transit, the potential impact the use of such instruments and data analysis might have on the #7 Line in NYCT are discussed. Many of these examples can be replicated in other transit environments.

Estimation of Investment Recapture

As noted, an agency replicating the data acquisition suite and analytics from the research effort would face an installed expense of similar technologies on the order of $3.1–$4.3 million. An assessment of the recapture of the initial investment can be made by employing the hard savings that are estimated from improving the service life of the vehicle wheels and avoidance of manual wheel inspections. The savings identified associated with these two items alone amount to approximately $10 million within the first two years following the installation of the equipment at NYCT's #7 Line. The initial investment at NYCT can be recaptured in less than one year.

Extended Wheel Life and Impact of Reduced Wheel Replacements

At the start of this research, the average wheel life on the #7 Line was, on average, <2 years. A standard SMS cycle for the #7 Line is currently on a seven-year cycle, which means that the wheels on the #7 Line were experiencing non-optimum wheel replacements twice between regular SMS cycles. During the research period, the wheel life reached an average wheel life of >3 years. The estimated avoided costs associated with the elimination of one non-optimum wheel replacement across the #7 Line Fleet is $9.8 million, as shown in Table 6-2.

It would be a goal of NYCT to further reduce wheel wear to improve the wheel service life to allow return to a seven-year SMS cycle or even a condition-based maintenance approach, thereby avoiding all non-optimum wheel replacement costs. The ongoing effort to improve friction management and extend wheel life with an experimental wheel profile evaluation are the two efforts that NYCT hopes will lengthen wheel life to reach the seven-year SMS target.

Result: Extended wheel life to eliminate one non-optimum wheel replacement across the #7 Line Fleet – Avoiding $ 9.8 million in premature wheel replacement costs.

Table 6-1 *Estimated Cost of Commercially Priced Data Acquisition Equipment*

Team Member	Research Equipment Description	Location	Estimated Costs					
			Installed Equipment		*Optional Equipment*		*Optional Services*	
			Low End	High End	Low End	High End	Low End ($/yr)	High End ($/yr)
KLD Labs	KLD Laser Scanner System	In-Track - Exterior	$800,000	$950,000				
	Options: Data Processing and Custom Analysis				$300,000	$700,000	$50,000	$150,000
	Total Estimated Cost – Laser Wheel Scanner		**$800,000**	**$950,000**	**$300,000**	**$700,000**	**$50,000**	**$150,000**
NRC Canada	Instrumented Wheel Sets	Onboard DCC	$580,911	$604,147				
	Options: Data Processing and Custom Analysis						$309,819	$348,547
	Total Estimated Cost – Instrumented Wheel Set (2)		**$580,911**	**$604,147**			**$309,819**	**$348,547**
Dayton T Brown	Data Collection Car Equipment	Onboard DCC	$225,000	$325,000				
	Options: RFID Reader, Mounting Fixture, Software and Integration				$150,000	$200,000		
	Options: Data Processing and Custom Analysis						$135,000	$250,000
	Total Estimated Cost – Consist Data Collection Suite		**$225,000**	**$325,000**	**$150,000**	**$200,000**	**$135,000**	**$250,000**
WID	TBOGI	In-Track	$225,000	$275,000				
	Options: Data Processing and Custom Analysis – Custom Reporting							$36,000
	Options: Post warranty service agreement per system						$9,600	$19,200
	Options: Upgrade TBOGI to add Hunting Detection capability				$230,000	$270,000		
	Options: Spare Parts					$90,000		
	Total Estimated Cost – TBOGI System		**$225,000**	**$275,000**	**$230,000**	**$360,000**	**$9,600**	**$55,200**
ISI	L/V	In-Track	$100,000	$120,000				
	Total Estimated Cost – In-Track L/V System		**$100,000**	**$120,000**				
TOTALS for Equipment Suite in Research Project			**$1,930,911**	**$2,274,147**	**$680,000**	**$1,260,000**	**$504,419**	**$803,747**
LOW	**$3,115,330**		**$1,930,911**		**$680,000**		**$504,419**	
HIGH	**$4,337,894**			**$2,274,147**		**$1,260,000**		**$803,747**

Note: All costs in US$ (0.774548 USD = 1 CAD).

Table 6-2

Cost Estimations of Non-Optimum Wheel Change Off SMS Cycle

Labor Estimate	
797	Man hours for truck work in SMS cycle/car
$35.00	Hourly wage estimate
$27,895	Total labor cost/car for truck SMS
506	# cars in #7 Line fleet
$14,114,870	Total SMS cost for labor on truck work
50%	Estimate of labor (% SMS truck labor) for non-optimum wheel change
$7,057,435	
Material Estimate	
$55,413	Material cost/car for truck SMS work
506	# cars in #7 Line fleet
$28,038,978	Total materials cost for truck work in SMS cycle
10.00%	Estimate of wheel and axle costs in SMS cycle material
$2,803,898	
Estimated cost avoidance of one wheel change between SMS Cycle: $9,861,333	
Avoids one non-optimum wheel change by end of Year 2 of six-year SMS cycle	
Avoidance of 30-day mid-cycle manual inspections of entire #7 line fleet required by Office of System Safety after 2017 derailments	
Saving from elimination of extra 30-day cycle of manual wheel inspections: $240,000 per year in shop labor costs	

Avoidance of 30-Day Mid-Cycle Manual Wheel Measurements

Following the two January 2017 slow-speed derailments at Willets Point, the Office of System Safety mandated 30-day manual wheel measurements for the entire #7 fleet. The normal frequency of manual wheel measurements historically was around every 72 days; with the installation of the automated wheel scanner, it was recommended that the manual wheel measurements every 30 days be discontinued.

Result: Elimination of the 30-day manual wheel measurement mandate avoids approximately $240,000 per year in labor costs at the Corona Shop.

Monitoring Wheel Flange Measurements to Delay Truing

The NYCT Division of Car Equipment Wheel Truing Standard for Rail Car Wheels, Document SUB 703.14 revision H dated 7/17/2018, states that a wheel with a flange reading of “6” or greater in the Overhaul Shop must be reported for truing. That same specification states that if a flange reading of “8” or greater is seen in the Maintenance Shop (Corona Shop), it must be reported for truing. Following the two January 2017 derailments, the Corona Shop was very conservative and did not release anything from the Maintenance Shop that might result in reaching an “8” flange width classification while in service.

As the research work progressed, the team was notified that the IWS was in need of truing because the flange width had reached a “5” reading. As the truing of the IWS would require recalibration by NRC Canada, the team requested not to true the IWS at a “5” classification but rather to monitor the IWS wear rates to avoid reaching an “8” while in service. This approach led to an additional nine months of IWS operation while maintaining a “5” classification. The use of the wheel scan on a high frequency inspection basis can potentially permit the Corona Shop to begin an elevated monitoring approach once a wheel reaches a”5” rating to extend the wheel’s accumulated mileage between truing events so as to plan truing after the reading is seen at a “7” or some higher reading made possible by the higher frequency measurement reporting by the wheel scan device. In addition, the ability of the Corona Shop to monitor the variances in wheel measurements (diameter differences) between wheelsets within a truck is enhanced by the laser wheel scanner to proactively manage truing events that might be driven by these wheelset-to-wheelset variances growing out of acceptable ranges.

Additional Value Elements from Daily Use of Data Acquisition Equipment

Although wheel-wear improvements might be the easiest to value, the use of the suite of data acquisition equipment associated with this research effort can also contribute the following value elements to the total value proposition. Each agency should assess how these elements might be valued by their operations, engineering, and maintenance groups. The total value propositions will vary from agency to agency.

Proactive decisionmaking is strengthened by monitoring data trends:

- Mitigate risks associated with potentially unsafe operations or failures while in service (derailment risk mitigation).
- Identify data that indicate abnormal or inefficient equipment performance or design.
- Enable condition-based maintenance of equipment and track.
- Conduct diagnostics and analysis to enable fuel improvements.
- Identify locations of damaging stress.
- Conduct diagnostics of ride quality (noise and vibration) and vehicle/track performance.

Note: See Table 4-2 for a summary by the Third-Party Independent Evaluator of both safety and maintenance (resiliency) strengths of the research instrument suite.

SECTION 7

Third-Party Review of Integrated Wheel/Rail Characterization and Safety Project[1]

Summary

The University of Delaware's Railroad Engineering and Safety program conducted an independent third-party review of NYCT's Integrated Wheel/Rail Characterization and Safety through Advanced Monitoring and Analytics Project. The main objective was to monitor and review the activities performed by NYCT and its team members in implementing its research efforts and addressing key transit performance areas such as enhanced operational safety and strengthened resiliency of transit rail systems. This includes review and assessment of various performance metrics in the areas of subway system safety improvement, subway system resiliency, subway system effectiveness, and financial measures. Although there has been insufficient time available to fully evaluate the effectiveness of the measurement systems (a longer timeframe is required to act on the data and realize the improvements and to see the actual results in the data), it is still possible to assess whether the program shows progress in addressing these objectives and setting the stage for further evaluation and implementation.

Overall, the University of Delaware (UD) believes that the project was a success and clearly illustrated the potential that these new systems offer to transit systems. The activity showed a successful implementation of the measurement systems. Integration of a wide variety of connected systems carries a unique set of challenges; the team was able to overcome these challenges and provide a large stream of inspection data and start the process of interrelating the data.

This study demonstrated the ability to collect very large quantities of data and use basic threshold level analysis to obtain useful information and improve safety. It also demonstrated the ability to use engineering knowledge, experience, and judgment in conjunction with the data to obtain valuable and meaningful insights from both safety and maintenance points of view. However, it also showed the need for a higher order level of analysis of the data, to include:

- Trend and forecasting analysis
- Correlation of different measurement systems to extend the basic analyses and perform root cause investigations

[1] This section was prepared by the Railroad Engineering and Safety Program at the University of Delaware, dramz@udel.edu.

- Identification of non-obvious relationships between different measurement streams and safety and/or maintenance issues
- Optimization of maintenance and associated asset management
- Conversion of data into information

Table 7-1 provides a summary of the metrics defined for evaluation as part of this third-party review. The table includes original metrics, a synopsis of goals achieved, and recommendations for future work to further refine the metrics.

Findings

The opportunity for broader data analysis is illustrated in Appendix I, "Third-Party Independent Evaluation," which presented supplemental analysis of the wheel wear data, should be a focus of any follow-up activity. Thus, there is significant opportunity to apply improved data analysis techniques, e.g., data analytics or "big data" techniques, to further use these data to better understand the interrelationships between the measured parameters, component degradation, maintenance, and safety.

In addition, UD believes that this research effort can directly lead to the implementation of new and improved safety and maintenance standards. Whereas many of these parameters have the potential for use as safety standards, nearly all of the direct and indirect measurements have the potential for new maintenance standards. For example, the measurements associated with the WheelScan® wheel profile measurement system can be used both as safety standards and maintenance standards and offer a real opportunity for optimization of the current wheel truing and replacement practices. Further measurements, such as IWS forces, L/V ratios, track geometry, and angle of attack, give insight on equipment and component condition and could be used to create thresholds at which a component must be serviced or replaced. Table 7-2 illustrates the potential for setting safety and/or maintenance standards from the data acquired by these different measuring systems.

Table 7-1 *Metric-Based Research Project Evaluation Summary*

Subway System Safety Improvement					
Incident Type	**Phase II (As-Is) 12 mo**	**Phase III (After)**	**R&D Result**	**Instrument or Method Used**	**Recommendations**
Accidents or Incidents	Historical Record	Extrapolation of Examples Evidence Reduction	NYCTA reported reduction in wheel climb derailments as result of available data from research activity	NYCT Incident Reports	Continue to monitor accidents and related incidents, including driver feedback; create database and link to maintenance activities
Red Conditions	Historical Record	Extrapolation of Examples Evidence Reduction	Data not available to assess all red conditions and not enough elapsed time since implementation allowed for in-depth analysis	Analytics, TGC, IWS, TBOGIE, L/V	Evaluate rate of change of Red and Yellow instances; in particular, define dates when actions implemented or changes in policy undertaken
Risk Mitigation	Historical Measures	Measured Risk Reduction	Using data acquired through system implementation allows for reduced risk, as demonstrated by identifying several potential new safety parameters	Analytics, TGC, IWS, wheel scan, TBOGIE, L/V	Implement addition risk mitigation thresholds based on additional higher order analytics; include maintenance actions undertaken for reference; monitor trends and rate changes in defining data variables
Subway System Resiliency					
Element	**Phase II (As-Is) 12 mo**	**Phase III (After)**	**R&D Result**	**Instrument or Method Used**	**Recommendations**
Wheel Rail Noise	DB Before	DB After	Grinding implementation on corrugated curve reduced noise and noise reduction able to be quantified	Microphones and accelerometers, DCC Suite	Strongly recommended to analyze noise data on production basis, particularly changes over time; correlate data with maintenance actions such as grinding, rail replacement, and friction management
Energy Use	Historical	Energy Use After	Energy data acquired but not analyzed to date; heuristically, noted that energy somewhat reduced but cause could not be attributed to any specification.	Instrumented traction motors, DCC Suite	Strongly recommended to analyze energy data on production basis, particularly changes over time; correlate data with maintenance actions such as friction managing and rail grinding
Maintenance events (pre and post)	Historical	Maintenance Records After	Due to limited time from implementation to action, metric not evaluated	Analytics, NYCT data	Recommended to evaluate levels of annual maintenance (normalized with tonnage or use levels), correlate with any maintenance philosophy changes and implementation
Component Life Cycles	Historical	Re-estimated Component Life Predictions	Data available to evaluate potential extensions in life cycle for wheels and rails; data supported changes in maintenance approaches that showed significant increases in life cycle	Calculations and estimations	Continue to monitor rates of degradation and resulting life cycles for wheel, rail, and other track/ vehicle components; correlate to maintenance actions

Subway System Effectiveness					
Element	**Phase II (As-Is) 12 mo**	**Phase III (After)**	**R&D Result**	**Instrument or Method Used**	**Recommendations**
Equipment and car condition			Data collected clearly provides ability to assess equipment component and overall condition; to date, no actions taken on this data; potential safety and maintenance thresholds on data identified	Analytics, IWS, wheel scan, TBOGIE, L/V	Analyze various data sources and use higher-order data analytics to define car/equipment condition indices that are function of measured data to monitor car/equipment condition seamlessly and continuously
Ride Quality			Ride quality addressed through combined data inputs from several measurement systems; no direct measure of ride quality exists at carbody and should be investigated; metrics can be developed from available data to assess ride quality and act accordingly	Analytics, IWS, TBOGIE, L/V	Use higher-order analytics to develop ride quality metric for available data sources that can be monitored continuously and autonomously and alerts provided when thresholds exceeded
Acceptance by NYCT operating units		Adoption in Procedures	NYCT operating units reviewing resulting data and potential maintenance and safety thresholds for further implementation	Analytics, NYCT data	Develop justification for all recommended changes in philosophy and training materials for NYCT departments
Financial Measures and Other Benefits					
Element	**Goal**		**R&D Result**	**Instrument or Method Used**	**Recommendations**
Reduced life cycle costs (wheels)	10% increase wheel life		Analyses showed extension in wheel life can be directly attributed to data and analysis resulting from research effort, with potential annual savings of $7,500,000	Wheel scan, Analytics	Refine life cycle cost calculations based on analytic results of degradation rates and refined costs; expand to include secondary and tertiary benefits
Lower life cycle costs (rail)	10% increase rail life		Not all rail analyzed; data subset analysis showed $160,000+ can be saved annually for rail	Analytics, TGC	Refine life cycle cost calculations based on analytic results of degradation rates and refined costs; expand to include secondary and tertiary benefits
Lower cost of asset ownership			Total cost of asset ownership not evaluated; time to implementation too short to capture reduced life cycle costs; analyses for wheel and rail support significant reduction in cost of asset ownership	Analytics	Perform total cost of asset ownership study based on results of further analytics

Table 7-2

Establishment of Maintenance and Safety Standards from Measured Parameters

Instrumentation	Parameter	Maintenance	Safety
***NYCT* Track Geometry Car**	Track geometry parameters	Yes	Yes
	Track quality index	Yes	No
	Rail profile	Yes	No*
	Rail wear rate	Yes	No
	Rail life prediction	Yes	Yes
	Rail corrugation	Yes	No
	Video recording	Yes	No
***KLD* Automatic WheelScan®**	Wheel wear parameters	Yes	Yes
	Wear rate (flange thickness)	Yes	No
	Wheel maintenance prediction	Yes	Yes
	Wheel replacement prediction	Yes	No
	Wheel climb risk (wheel flange angle)	Yes	Yes
	Effective conicity	Yes	No
***NRC Canada* Instrumented Wheelset**	Forces (lateral, vertical, longitudinal)	Yes	Yes
	L/V ratio (wheel climb risk)	Yes	Yes
	Dynamic impact loads	Yes	No
***WID* TBOGI**	Angle of attack	Yes	No
	Inter axle misalignment	Yes	No
	Rotation	Yes	No
	Misaligned/skewed trucks	Yes	No
	Tracking position	Yes	No
	Tracking error	Yes	No
	Shift	Yes	No
***ISI* L/V System**	L/V ratio (wheel climb risk)	Yes	Yes
***DTB* Microphones**	Noise levels	Yes	No
	Wheel/rail noise	Yes	No
***DTB* Energy Monitors**	Propulsion energy usage	No	No
	Traction motor current	No	No
***DTB* Accelerometers**	Acceleration	Yes	No**
	Ride quality	Yes	No

Green highlights are direct measurements supported by the instrument suite. The Yellow highlights are analytical results/information that can be supported by the data collected from the instrument suite.
**Rail gage face angle, which can be measured as part of rail profile, has potential for safety monitoring.*
***In some high speed rail application, truck acceleration used as safety factor, but not commonly used for metros or transit systems.*

Recommendations

Based on the results of the NYCT project and the conclusions presented in the full UD review, the following recommendations are made on how to best move forward with this research effort. Although the program was a very successful demonstration of the implementation and potential use of the suite of instrumentation and measurement systems, there was insufficient time and resources for a more comprehensive assessment of the data and its potential impact on safety, operations, and maintenance. As such, UD recommends follow-up focusing on analysis of the data, both individually and in an integrated fashion, to develop key implementation functions such as:

- Safety parameters and thresholds as directly measured by the systems
- Maintenance parameters and thresholds as directly measured by the systems
- Ridership performance parameters and thresholds
- Component degradation relationships
- Relationships between energy use, noise, vibrations, accelerations and other parameters
- Other intra-measurement relationships that can enhance safety and operations, to include derived parameters

In general, there are two overall approaches that can be taken in a next phase analysis:

- Engineering-based analysis in which the data are combined with an existing understanding of railway performance and engineering behavior to identify methods of improving performance. This was the approach taken in this initial activity by NYCT and its team. Integrating the new measurement data with existing engineering knowledge allowed the team to identify problems and solutions as presented in its report.
- Higher-order data analytics-based analysis approach that looks at the data through the lens of data science and allows for a "broader" assessment of the data and the information contained within it. Based on the results of this study, there is a clear opportunity for further, more aggressive analyses using higher-order data analytics. "Big data" analytics use complex mathematical and stochastic processes to examine very large data sets and the interrelationships between the different data sets. This approach allows users to uncover information such as behavioral trends and relationships between data sets, which are often not obvious using the more traditional approaches; it allows for the railway to "learn" from the data as more and more data are collected.

When used in parallel with, but separate from, a more traditional engineering-based analysis, this approach allows for a more comprehensive assessment of the data and how best to convert that data to information. Thus, it is recommended that a second analysis phase be performed as follow-up to include parallel analyses using engineering-based and data science ("big data") analysis approaches. The focus of this follow-up study should be the development of the implementation functions noted above and in Table 7-2 that can be used not only by NYCT but by other US transit and rail systems. The goal of such an activity would be to identify appropriate techniques and standards.

Appendices

All appendices are available at https://wp.me/pjbUY-G.

A: "Practical Examples of Performance Issues Identified on Line #7"

B: "Techniques for Assessing Wheel-Rail Profile Compatibility"

C: "NRC Instrumentation Approach"

D: "July 2018 Review of Curve N/O 34st St–Hudson Yards Top-of-Rail Friction Management Units on CC1 and CC2 Tracks"

E: "WID Report"

F: "Analysis of DTB Acceleration Data"

G: "Friction Management Studies on Curve N/O 34th St–Hudson Yards"

H: "Research Team's Proposed Follow-on Research Considerations"

I: "Third-Party Independent Evaluation" – University of Delaware

Glossary

Back-of-flange value – Measure of the amount of back-of-flange wear on a wheel profile.

Conformality – Wheel-rail parameter that evaluates whether contact between a wheel and rail pair in curving presents a single- or multi-point contact and whether that contact is conformal (close in shape) or non-conformal (the shapes diverge significantly).

DCC (Data Collection Consist) – Revenue trainset on NYCT's Line #7 that has been outfitted with several different sets of instrumentation to evaluate vehicle-track interaction and energy consumption.

Effective conicity – Wheel-rail profile analytic that includes also the effect of track gauge; represents magnitude of steering forces that arise with lateral shifting of wheelset on rail and is applied most often to stability predictions in tangent track.

Friction management – Process of controlling friction level between wheel and rail to values that are sufficient for safe operation but which limit undesirable high forces.

IAM (interaxle misalignment) – Yaw between two wheelsets of one truck, calculated by taking difference between angles of attack measured for each of axles.

Mrad (milliradian, 1/1000th of a radian) – Measure of yaw or angle of attack, referring to angular rotation of wheelset with respect to rail; 1 milliradian is equal to 0.0573 degrees, and 1 degree is roughly 17.5 mrad.

RCF (rolling contact fatigue) – Cracking and related defects that develop, typically in running band, as result of progressive plastic flow whenever contact and shear stresses exceed yield point of wheel or rail steel.

Rolling radius – Radial distance from center of wheel/rail contact patch to centerline of axle.

Rolling radius difference/differential – Difference in rolling radius for two wheels on an axle.

Saturated creepage (or slip) – Level of relative displacement between wheel and rail so that all points within contact patch are in slip; coincident with this condition is usually a level of greatest friction force.

Tracking error – Lateral displacement of truck from central running position, calculated as average of lateral tracking position of two wheelsets of that truck.

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1200 New Jersey Avenue, SE
Washington, DC 20590
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