SJSU SAN JOSÉ STATE UNIVERSITY | MTI MINETA TRANSPORTATION INSTITUTE | AECOM

Improving Rail Vehicle Reliability by Performing Component Overhauls at Los Angeles County Metropolitan Transportation Authority

Project 2253
December 2022

Aaron Disman

Introduction

This study evaluates the effectiveness of component overhauls on vehicle and component reliability by utilizing maintenance records from the Los Angeles County Metropolitan Transportation Authority (LACMTA or Metro). Rail Transportation Authority maintenance departments overhaul and perform maintenance on rail vehicle components to maintain vehicle reliability and availability. Component overhaul programs aim to maintain and improve reliability but can be more expensive and labor intensive than other maintenance approaches such as reliability-centered maintenance (RCM) or condition-based maintenance (CBM). Thus, it is important to evaluate Metro's current component overhaul programs to determine if they are effectively reducing vehicle and component failures.

Component overhauls are an example of the schedule-based maintenance approach that aims to prevent vehicle and component failures from occurring by performing maintenance at a prescribed interval. Similar to the regular, recommended maintenance service schedule for passenger vehicles, the original equipment manufacturer for rail cars recommends a schedule of when these overhauls should be performed. For the component overhaul process, components in good, working condition are refurbished to a like-new condition such that the component should operate without failure and maintain the designed reliability until the next component overhaul cycle. This work requires a time-consuming and expensive process of completely disassembling the component, cleaning, inspecting, and replacing various parts within the component, and then reassembling and testing the component.

Rail transportation authorities perform component overhauls to maintain component and vehicle reliability by reducing the risk of component failure. Component failures lead to reduced reliability, which negatively impacts transit agencies and their customers. Additionally, component failures often cause delays to revenue service as they may present a safety hazard or cause a degradation of performance. Component failures also require unscheduled maintenance that can force a rail vehicle out of service for an extended period. However, component overhauls risk raising overall maintenance costs if maintenance is performed prematurely. Parts may be replaced or maintained unnecessarily because scheduled maintenance is determined based on theory and calculations rather than performance or condition.

Rail transportation authorities must balance the need for reliability with the cost of maintenance. There is a clearly defined cost of performing maintenance and component overhauls. Metro's component overhaul programs require a total annual budget of approximately $51 million for its nearly 400 vehicle fleet.[1]

1. LA Metro Senior Director, email message to author, December 1, 2022.

Rail transportation authorities may opt to reduce expenses by limiting the scope of maintenance and component overhauls or deferring said work. Reduced reliability and unscheduled maintenance and repairs may increase costs if scheduled maintenance and component overhauls are deferred or skipped. These costs are related to failures during revenue service, performing emergency repair work, expediting parts, and extended downtime of vehicles if parts or labor are not readily available.

The methodology for this evaluation consisted of reviewing existing LA Metro rail vehicle maintenance records for two years before and after component overhauls, to determine if the rate of failures declined after the overhauls. Due to the large quantity of data associated with Metro's large fleets, two systems were selected to evaluate: the coupler system and friction brake system. These two systems were selected because they are common systems found in nearly all rail vehicles.

The remaining sections of this report are organized as follows. The next section, "About Metro's Component Overhaul Program for Rail Vehicles," provides a brief overview of Metro's rail transportation system and component overhaul programs. The third section, "Component Overhaul, Reliability, and the Impact of Component Failure," discusses component overhaul and its relation to reliability. The fourth section, "Evaluation Findings," explores the evaluation findings. The final and fifth section summarizes the findings and recommendations.

About Metro's Component Overhaul Program for Rail Vehicles

The Los Angeles County Metropolitan Transportation Authority (LACMTA or Metro) transportation system includes both heavy rail vehicles (HRV) and light rail vehicles (LRV). Metro's HRVs operate on the B and D Lines, which are underground subways. The LRVs operate on the A, C, E, and L Lines, which run both aboveground and underground. Metro currently maintains a fleet of 102 HRVs and 287 LRVs. Metro's oldest fleet began service in 1993 and its newest and largest fleet began operation in revenue service in 2016.[2]

To maintain the fleets in support of revenue service requirements, Metro performs recommended component overhauls of select components periodically throughout the life of the HRV or LRV, according to the vehicle manufacturer's recommendations. In general, component overhauls are recommended every five to six years of operation. Examples of components that Metro overhauls include the traction motors; gearboxes; friction brake systems; air compressors; heating, ventilation, and air conditioning (HVAC) systems; door systems; couplers; power converters; and pantographs or third rail current collector assemblies. Each of these components and systems are vital to the operation of the transit vehicle and undergo significant loading over the life of the vehicle.

Metro's component overhaul programs require a total annual budget of approximately $51 million, which includes vendor and Metro expenses for all rail vehicle component overhaul programs.[3] Vendor expenses include materials and labor to perform the overhaul work and shipping. Metro expenses include labor required to develop the technical documentation defining the scope; solicit competitive proposals; perform contract negotiations; remove, package, coordinate shipping of, and reinstall the equipment on the rail vehicles; and manage the component overhaul programs.

2. Los Angeles County Metropolitan Transportation Authority, Metro Rail Fleet Management Plan FY2021-FY2042 (Los Angeles: Los Angeles County Metropolitan Transportation Authority, 2021).
3. LA Metro Senior Director, email message to author, December 1, 2022.

This budget does not consider lost revenue while vehicles are out of service during the maintenance work. The component overhaul program budget includes approximately 40 full-time Metro employees ranging from technicians, supervisors, quality assurance, inventory, and project managers.[4]

Component Overhaul, Reliability, and the Impact of Component Failure

Component overhauls are an example of the scheduled maintenance approach that aims to prevent vehicle and component failures. Scheduled maintenance is the practice of performing maintenance on a pre-determined schedule. The schedule can be time-based or usage-based. For Metro, time-based schedules are frequently in terms of months or years and usage-based schedules are in terms of miles traveled or hours of operation. Manufacturers base the recommended component overhaul schedule on several factors, one of which is the expected failure of items that become consumed or worn as they are used. Hwang et al. identified three criteria often used in "determining the replacement age of a critical item for a maintained system." The three criteria are: "minimum replacement cost-rate, maximum availability, and lower-bound on mission reliability."[5] These criteria help determine what maintenance is required to meet the minimum equipment reliability at the lowest cost and requires the least amount of time to perform.

Properly performed scheduled maintenance reduces the risk of unplanned failure, and unplanned failure leads to extended downtime because the necessary resources, whether labor or materials, take time to mobilize and procure. The importance of maintenance is clarified in Zeng's *Discussion on Maintenance Strategy, Policy and Corresponding Maintenance Systems in Manufacturing* when he states that "the maintenance objective is to provide production with the long- and short-term manufacturing system availability requirements at a minimum resource cost."[6] The same principal applies to the maintenance of any machinery, including trains. The objective of maintaining a train is to ensure it is available to operate and transport passengers safely and efficiently.

Component failures that occur during revenue service may cause the train to operate at a degraded performance level and/or cause a service delay. All component failures result in unscheduled maintenance, and some may force a rail vehicle to remain out of service for an extended period due to troubleshooting or procurement of a part with a long lead-time.

The impact of a component's failure on system performance is like the impact a single station might have on a transit system. Kim et al. describe that "[a] node with low reliability can bring about a significant degradation of an entire system's reliability."[7] Depending on the component that failed, and the degree to which it failed, the failure may have a greater impact on performance and reliability. Some component failures may result from a malfunction or intermittent failure where the component remains operational but at a degraded performance level, whereas some may be a complete failure.

4. LA Metro Senior Director, email message to author, December 1, 2022
5. C. L. Hwang et al., "Optimal Scheduled-Maintenance Policy Based on Multiple-Criteria Decision-Making," IEEE Transactions on Reliability R-28, no. 5 (1979), 394.
6. Shuo Wei Zeng, "Discussion on Maintenance Strategy, Policy and Corresponding Maintenance Systems in Manufacturing," *Reliability Engineering & System Safety* 55, no. 2 (1997), 151.
7. Hyun Kim, Changjoo Kim, and Yongwan Chun, "Network Reliability and Resilience of Rapid Transit Systems," *The Professional Geographer* 68, no. 1 (2016), 53.

Evaluation Findings

This evaluation utilized existing LA Metro maintenance records to calculate the reliability of the coupler and friction brake systems of three rail fleets. The coupler and friction brake systems were selected because all three of Metro's rail fleets that have had overhaul programs have had these systems overhauled. At Metro, a Corrective Work Order (CWO) is the document used to track the repair of a failed component. The total number of CWOs were counted for each of Metro's fleet types related to the two systems being evaluated for the two years prior to overhaul and the two years following. The total miles traveled over the same time periods were calculated. The number of CWOs within a given period and number of miles traveled are used to calculate reliability. Reliability is measured in terms of Mean Miles Between Failure (MMBF). Rail vehicles and rail vehicle components are each designed to meet a given reliability that may vary for each vehicle or component.

Not all CWOs carry the same level of importance. When evaluating the failure's impact to the riding public, Metro places a higher priority on incidents with a delay of five minutes or more. An incident is a failure that causes the train to stop during revenue service and cause a delay in service. Incidents with a longer delay have a greater impact on the customer because they often result in transferring passengers to a different train. Incidents may be a result of a failed component or other external factors such as loss of power or collision with an automobile.

The evaluation findings do not clearly indicate that overhaul had a positive impact on reliability. Instead, component overhaul impact on reliability is dependent on how the data is interpreted. There are multiple angles to view the data and multiple variables that affect reliability. Some variables that affect reliability may include COVID-19, delays in beginning an overhaul cycle, time to complete an overhaul cycle, and complexity of the component being overhauled. In addition, the data may be interpreted as a whole or by fleet type.

For this report, component reliability was first calculated and evaluated on an individual basis per component and per fleet type and then, on average, per component. Six component overhaul scenarios were evaluated: P2550 friction brake, P2550 coupler, P2000 friction brake, P2000 coupler, A650 friction brake, and A650 coupler. The average reliability across all three fleets improved 72% and 7% for the friction brakes and coupler, respectively. However, individually, only three of the six overhaul programs resulted in improved reliability.

Coupler Reliability Following Overhaul

Viewing the data on average shows that coupler reliability improved by 7% following overhaul, as indicated in Table 1. Reliability improved following overhaul of the P2550 and A650 couplers, but P2000 coupler reliability declined after overhaul. It is also noted that vehicle miles traveled decreased across all three fleet types after overhaul. Reduced vehicle miles traveled during the two-year period following overhaul may lead to improved reliability because the equipment is not used as much as it was during the two-year period before overhaul. However, while vehicle miles traveled decreased for all three fleet types, reliability only improved for the A650 and P2550 couplers.

Viewing the data by individual fleet provides a different perspective because reliability on each fleet varied greatly. As shown in Table 1, the P2550 coupler reliability following overhaul increased by 85% from 87,544 mean miles between failure (MMBF) to 161,521 MMBF. For the P2000, coupler reliability decreased 42% from 233,581 MMBF to 136,435 MMBF. Reliability increased 94% from 50,844 MMBF to 98,870 MMBF for the A650. The time to complete the coupler overhaul programs for the P2550 fleet was approximately three and a half years, five years for the A650, and seven and a half years for the P2000. The variations in component overhaul program length are due to delays or pauses in the program, not the time required to perform the individual coupler overhaul work. Delays or pauses in the programs were due to administrative factors such as budgeting and labor availability. The time to completion may have impacted the perceived reliability.

The number of CWOs was the primary driver of coupler reliability with the change in miles traveled being secondary. The P2000 was the only fleet to experience an increase in CWOs and the only fleet with a decrease in reliability. The quantity of CWOs were reduced by approximately half for the A650 and P2550. The P2000 and P2550 fleets both had a similar decrease in miles traveled of about 35%, while the A650 mileage was nearly the same. The reduction in miles traveled did not correlate to reduced reliability. Alternatively, the increase in CWOs for the P2000 versus a large decrease in CWOs for both the A650 and P2550 appeared to be the primary driver of decreased reliability.

Another factor affecting reliability could be the reliability prior to performing the component overhaul. The P2000 had high reliability and the A650 and P2550 had low reliability prior to overhaul. This could indicate that reliability was just reverting to the mean, as the reliability for each was much closer following overhaul than prior to overhaul. Not surprisingly, no coupler incidents were reported on any fleet during the evaluated period. Couplers commonly do not have failures because there are few moving parts and they have a somewhat simple circuitry.

Table 1. Coupler Reliability Summary

Type of Rail Vehicle	Number of Corrective Work Orders			Total Fleet Miles Traveled			Reliability (Mean Miles between Failure)		
	Before Overhaul	After Overhaul	% Change	Before Overhaul	After Overhaul	% Change	Before Overhaul	After Overhaul	% Change
P2550	50	18	-64%	4,377,187	2,907,372	-34%	87,544	161,521	85%
P2000	31	34	10%	7,241,023	4,638,790	-36%	233,581	136,435	-42%
A650	140	71	-49%	7,118,147	7,019,775	-1%	50,844	98,870	94%
All Rail Vehicles	221	123	-44%	18,736,357	14,565,937	-22%	371,969	396,826	7%

Note: Data covers the two-year period prior to a vehicle's component overhaul and the two-year period following.

Friction Brake Reliability Following Overhaul

Viewing the data on average shows that friction brake reliability improved by 72% following overhaul, as indicated in Table 2. Reliability decreased modestly for the P2550 and A650 friction brakes, but reliability increased dramatically for the P2000 friction brakes. It is also noted that vehicle miles traveled decreased across all three fleet types. Similar to the coupler, even though vehicle miles traveled decreased for all three fleet types, reliability did not improve for all fleet types. Reliability only improved for the P2000 friction brake system.

Viewing the data by individual fleet shows that reliability on each fleet varied greatly. As shown in Table 2, P2550 friction brake reliability following overhaul decreased 17% from 38,483 MMBF to 32,054 MMBF. A650 friction brake reliability decreased 12% from 26,302 MMBF to 23,134 MMBF. However, reliability increased a tremendous 297% for the P2000 from 24,933 MMBF to 99,101 MMBF. The time to complete the friction brake overhaul program for the P2550 fleet was approximately three and a half years, approximately three years for the A650, and nearly nine years for the P2000. Like the P2000 coupler overhaul program, the P2000 friction brake overhaul program also began the earliest and had the longest total period for the two years following each overhaul, at approximately seven years. The period for the A650 was approximately two and a half years, and the period for the P2550 was just over one year.

In contrast to the coupler, both the quantity of CWOs and change in miles appear to have impacted reliability somewhat equally. Interestingly, all three fleets experienced a decrease in CWOs, although the P2000 was the most drastic, with a 77% decline from 254 to 59. The miles traveled for each fleet decreased, with the A650 decreasing nearly twice as much as the P2000 and the P2550 more than four times that of the P2000.

In stark contrast to the coupler, there were incidents reported both prior to overhaul and following overhaul. There were two incidents reported for the P2000 prior to overhaul and 14 reported incidents following overhaul. The number of incidents increased from zero to three for the P2550. There were no incidents reported for the A650 friction brake system before or after overhaul. Review of the incident notes did indicate that the friction brakes were the proximate cause of the incident, but, from Metro's experience, the ultimate point of failure is often determined to be some other system. Further evaluation of the P2000 and P2550 CWOs and incidents is warranted to determine if the results were anomalous. However, it is possible that while there may have been fewer P2550 and P2000 friction brake failures, those failures may have been more impactful on reliability.

Table 2. Friction Brake Reliability Summary

Type of Rail Vehicle	Number of Corrective Work Orders			Total Fleet Miles Traveled			Reliability (Mean Miles between Failure)		
	Before Overhaul	After Overhaul	% Change	Before Overhaul	After Overhaul	% Change	Before Overhaul	After Overhaul	% Change
P2550	104	80	-23%	4,002,244	2,564,284	-36%	38,483	32,054	-17%
P2000	254	59	-77%	6,332,949	5,846,947	-8%	24,933	99,101	297%
A650	169	164	-3%	4,444,988	3,794,036	-15%	26,302	23,134	-12%
All Rail Vehicles	527	303	-43%	14,780,181	12,205,267	-17%	89,718	154,289	72%

Note: Data covers the two-year period prior to a vehicle's component overhaul and the two-year period following.

Conclusion – Summary of Findings and Recommendations

The evaluation found that component overhauls improved reliability by some metrics but unexpectedly reduced reliability in other cases, as shown in Table 3. The impact component overhaul had on reliability is dependent on how the data is interpreted as summarized in Table 3. When the data is evaluated on a fleet-by-fleet basis, the results indicate that component overhaul activities had a net-zero impact on reliability. Half of the component overhaul programs resulted in improved reliability while the other half resulted in a decline in reliability. However, when evaluating the data for all vehicles combined, the result was a net improvement in reliability. With either method of evaluating the data, reliability on average did not decrease because of component overhaul.

Table 3. Change in Reliability by Type of Rail Vehicle

Type of Rail Vehicle	Change in Mean Miles between Failures	
	Coupler	Friction Brake
P2550	85%	-17%
P2000	-42%	297%
A650	94%	-12%
All Rail Vehicles	7%	72%

The Impact of Component Overhaul on Reliability

As indicated previously, the impact of component overhaul on reliability is not clearly positive. On average across all three fleets, reliability improved as indicated by the 72% and 7% improvement in reliability for the friction brake and coupler systems, respectively. However, when viewed individually, only three of the six overhaul programs resulted in improved reliability. The P2550 coupler, A650 coupler, and P2000 friction brake overhauls resulted in an 85%, 94%, and 297% improvement in reliability, respectively. The P2000 coupler, P2550 friction brake, and A650 friction brake overhauls resulted in a 42%, 17%, and 12% decrease in reliability, respectively. It is important to note that reliability is never expected to decrease following component overhaul. At worse, it might remain the same if the overhaul occurred prior to reliability starting to decline.

In addition to the impact component overhaul has on reliability of the component, failure of the component may affect the reliability of the rail vehicle. As indicated by the findings, this relationship between component reliability and rail vehicle reliability is not always fully understood or monitored. Dinmohammadi et al. share that “there has been a great deal of interest in the study and analysis of failure mechanisms for railway infrastructure assets,” but “few attempts have been made by researchers to develop failure criticality assessment models for rolling stock components.”[8] The reliability of components and the rail vehicle are related and yet independent. As such, both must be monitored and evaluated to determine the impact component reliability has on vehicle reliability.

The data did not indicate that the decline in reliability of the P2000 coupler, P2550 friction brake, and A650 friction brake resulted in an increase in incidents or rail vehicle failures. However, the

8. Fateme Dinmohammadi et al., “Risk Evaluation of Railway Rolling Stock Failures using FMECA Technique: A Case Study of Passenger Door System,” *Urban Rail Transit* 2, no. 3-4 (2016), 128.

relationship between component reliability and rail vehicle reliability must continue to be monitored and evaluated because reduced reliability negatively impacts transit agencies and their customers, who depend on reliable transportation. Lierop and El-Geneidy's studies illustrate the impact of reduced reliability on transit agencies and their customers as they found that "reliability is more influential than frequency in predicting users' overall satisfaction with the service quality."[9] It is much easier for a customer to make travel plans when they can depend on the transportation system to get them to their destination on time. Component overhaul not only impacts component reliability, but also impacts rail vehicle reliability and, potentially, customer experience.

Alternative to or Improvement of Component Overhaul

Despite the lack of clarity from the evaluation findings, improvements can be made to the component overhaul process to improve its impact on reliability. The first improvement is to ensure component overhauls are performed on time and in a timely manner. However, as indicated by the evaluation findings, there was not a clear relationship between time to complete the overhaul program and reliability. Both CBM and RCM are practices that could be implemented either instead of or in coordination with scheduled component overhauls.

Reliability-centered maintenance could compliment standard scheduled maintenance by providing a signal to begin a component overhaul ahead of schedule if components are beginning to fail prematurely. Condition-based maintenance could also compliment scheduled maintenance by providing insight into the condition of components so that overhaul can be performed in advance of the proposed schedule. Additionally, both RCM and CBM can help by identifying new or different parts that need to be replaced, repaired, or upgraded. This information will allow for a change in scope to improve the effectiveness of the component overhaul while in progress or for future overhaul cycles.

Component overhaul is never expected to cause a decline in reliability. This expectation is supported by Corman et al.'s explanation that "perfect [preventive maintenance (PM)] actions restore the system to an optimal state, that is, the reliability of the system is increased to the 'As Good As New' (AGAN) level."[10] The performance of post-overhaul monitoring of reliability is important to identify shortcomings of the overhaul and to verify reliability has returned to when components were in as-new condition. Without monitoring, the process won't be improved, and expenses may be wasted. Part of the added benefit to implementing RCM and CBM is that maintenance is only performed when it is needed rather than based on time, mileage, or other theoretical determinations. Alstom explains that "CBM saves money and increases efficiency by reducing life-cycle costs and improving performance."

In addition, CBM can save money because "less unscheduled corrective maintenance is required, and fewer unexpected failures occur," which means maintenance departments can prepare and plan for maintenance activities.[11]

9. Dea van Lierop and Ahmed El-Geneidy, "Enjoying Loyalty: The Relationship between Service Quality, Customer Satisfaction, and Behavioral Intentions in Public Transit," Research in Transportation Economics 59 (2016), 50.
10. F. Corman et al., "Optimizing Preventive Maintenance Policy: A Data-Driven Application for a Light Rail Braking System," *Proceedings of the Institution of Mechanical Engineers.Part O, Journal of Risk and Reliability; Proc Inst Mech Eng O J Risk Reliab* 231, no. 5 (2017), 534.
11. "Alstom Proves Value of Condition-Based Maintenance: A New Approach to Maintenance is Proving Successful for

Recommendations for Further Evaluation

The benefit of component overhauls as a tool for Rail Transportation Authorities (RTA) to improve reliability may be better understood by performing additional evaluations. It would be beneficial to perform similar evaluations of other components and of other RTAs. Other components to evaluate are the traction motor, door system, HVAC, and auxiliary power supply. These systems would be useful to study because they have a great impact on vehicle reliability and availability. In addition, evaluating multiple component overhaul cycles would provide more clarity, since this would provide a larger set of data over a longer period.

Alstom in Improving Rolling Stock Usage, but Makes New Demands of Maintainers." *International Railway Journal and Rapid Transit Review* 45, no. 8 (2005), 26.

Bibliography

"Alstom Proves Value of Condition-Based Maintenance: A New Approach to Maintenance is Proving Successful for Alstom in Improving Rolling Stock Usage, but Makes New Demands of Maintainers." *International Railway Journal and Rapid Transit Review* 45, no. 8 (2005): 26.

Corman, F., S. Kraijema, M. Godjevac, and G. Lodewijks. "Optimizing Preventive Maintenance Policy: A Data-Driven Application for a Light Rail Braking System." *Proceedings of the Institution of Mechanical Engineers.Part O, Journal of Risk lInd Reliability; Proc Inst Mech Eng O J Risk Reliab* 231, no. 5 (2017): 534-45.

Dinmohammadi, Fateme, Babakalli Alkali, Mahmood Shafiee, Christophe Bérenguer, and Ashraf Labib. "Risk Evaluation of Railway Rolling Stock Failures using FMECA Technique: A Case Study of Passenger Door System." *Urban Rail Transit* 2, no. 3-4 (2016): 128-45.

Hwang, C. L., F. A. Tillman, W. K. Wei, and C. H. Lie. "Optimal Scheduled-Maintenance Policy Based on Multiple-Criteria Decision-Making." *IEEE Transactions on Reliability* R-28, no. 5 (1979): 394-9.

Kim, Hyun, Changjoo Kim, and Yongwan Chun. "Network Reliability and Resilience of Rapid Transit Systems." *The Professional Geographer* 68, no. 1 (2016): 53-65.

Los Angeles County Metropolitan Transportation Authority. *Metro Rail Fleet Management Plan FY2021-FY2042*. Los Angeles: Los Angeles County Metropolitan Transportation Authority, 2021.

Van Lierop, Dea and Ahmed El-Geneidy. "Enjoying Loyalty: The Relationship between Service Quality, Customer Satisfaction, and Behavioral Intentions in Public Transit." *Research in Transportation Economics* 59 (2016): 50-9.

Zeng, Shuo Wei. "Discussion on Maintenance Strategy, Policy and Corresponding Maintenance Systems in Manufacturing." Reliability Engineering & System Safety 55, no. 2 (1997): 151-62.

Acknowledgement

I would like to thank my wife, Lauren, and children, Eliana and Ethan, for supporting me throughout the development of this project and helping me stay focused through all the late nights. Without their support, the project would not have been possible.

I would also like to thank my Deputy Executive Officer, Nick Madanat, and colleagues, Juan Ruvalcaba and Greg Athas, for providing guidance, support, and mentoring as I researched maintenance records and studied reliability. Without their support, I would not have the breadth of knowledge nor the ability to collect and evaluate the maintenance records for this project.

Finally, I would like to thank Lisa Rose, for editorial services, as well as MTI staff, including Executive Director Karen Philbrick, PhD; Deputy Executive Director Hilary Nixon, Education Director Asha Weinstein Agrawal, PhD; Public Programs Coordinator Alverina Eka Weinardy; and Graphic Design Assistant Minhvy Tran.

About the Author

Aaron Disman is Senior Manager of LA Metro's Transit Vehicle Engineering department. He received his B.S. in Mechanical Engineering from UC Santa Barbara in 2002, MS in Transportation Management from San José State University in 2022, and is a licensed Professional Engineer. Aaron's professional experience spans transportation, environmental engineering, and manufacturing. His work at Metro primarily focuses on providing engineering support to the rail vehicle and bus maintenance departments. Aaron's work on this project received the AECOM award for an Outstanding Capstone on Transportation Operations Management.

This report can be accessed at
transweb.sjsu.edu/research/2253

MTI is a University Transportation Center sponsored by the U.S. Department of Transportation's Office of the Assistant Secretary for Research and Technology and by Caltrans. The Institute is located within San José State University's Lucas Graduate School of Business.