Title

Maintenance in Transit: What Reliability-Centered Maintenance (RCM) Means for the Future of Transit Asset Management

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Publication Date
2018-06-01

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What Reliability-Centered Maintenance (RCM) Means for the Future of Transit Asset Management

A Comprehensive project submitted in partial satisfaction of the requirements for the degree
Master of Urban & Regional Planning

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2018

Disclaimer

This report was prepared in partial fulfillment of the requirements for the Master in Urban and Regional Planning degree in the Department of Urban Planning at the University of California, Los Angeles and of the Los Angeles County Metropolitan Transportation Authority as a planning client. The views expressed herein are those of the author and not necessarily those of the Department, the UCLA Luskin School of Public Affairs, UCLA as a whole, or the client.

Acknowledgements

I would like to thank Professor Brian Taylor and Avital Shavit for their invaluable guidance as advisors throughout this project. Thank you to all the current and former professionals at Los Angeles Metro, BART, MBTA, WMATA, and AECOM who helped inform this project and my understanding of the topic as a whole.

Thank you to my parents Jill and Martin, as well as my brother, Colin for supporting me through thick and thin. And to Ale, thank you for keeping me ever driven and hopeful.

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Executive Summary

Maintenance is a crucial aspect of transit agencies' operations. Without maintenance, system operability and reliability will fail over time. Riders depend on transit to be reliable. Systems face consequences when that reliability decreases or fails. Given this, transit agencies with aging capital stock in the United States face a challenging future. Many transit systems are not maintained at the manner or level needed to sustain or increase their reliability. Rather, for a variety of reasons, maintenance backlogs at American transit agencies have been growing. Transit managers are thus looking towards ever more efficient and effective means to maintain their systems. One commonly proposed way to increase maintenance efficiency and effectiveness is Reliability-Centered Maintenance (RCM). RCM has been widely adopted in other sectors, such as aviation and utilities, as a way to efficiently allocate time, labor, and resources in a proactive manner. Accordingly, this report examines the state of transit maintenance today, what RCM is, and the nascent experience to date with RCM in U.S. public transit.

This report examines RCM at three different transit agencies: BART in the San Francisco Bay Area, CA; MBTA in Boston, MA; and WMATA in Washington, D.C. All three of these major transit operators are at different stages of RCM implementation. I use a literature review as the foundation of these case studies and juxtapose the current body of literature to my research and interviews surrounding the three transit authorities.

I find that RCM is still relatively new in the transit world. It is difficult to conclusively determine where it has been adopted and the extent to which it has been embraced. That said, RCM has so far proven to be an effective maintenance strategy. RCM shows promise even if it is not formally adopted across a wide range of subsystems and components at a given agency. Any proactive maintenance strategy, such as RCM, involves non-trivial upfront costs due to the informational, physical, and educational infrastructure it needs to work. In the long term, however, RCM has been shown to decrease maintenance expenditures and, importantly, increase reliability and system conditions.

Transit agencies do not need to fully, or even formally, adopt RCM to realize many of its associated benefits. *Any* shift from reactive to proactive maintenance on critical systems and components will have positive outcomes. However, proactive maintenance, and RCM in particular, depends on a unified and coordinated effort among all relevant stakeholders at the transit agency. Without stakeholder buy in, as well as needed initial investments in the necessary infrastructure, RCM will be less effective. Overall, I find that RCM is an effective maintenance strategy with considerable promise in the public transit sector, provided that agencies have the commitment and resources to implement it.

Introduction

Transit infrastructure in the United States has a maintenance problem. This maintenance problem is as vast as it is complex, but one thing is for sure: transit agencies needs more and better maintenance. Transit systems, purposefully or not, have experienced a long period of neglect. One crucial issue is how transit agencies go about their maintenance strategy. For decades, many transit agencies have dealt with maintenance issues as they arise, and did not construct a long-term vision on how to optimize asset performance. Transit authorities needs a new strategies to address maintenance. Reliability-centered maintenance (RCM) is one of the proposed strategies to address current woes. What is RCM? Why is it so important? And how has it affected transit reliability to date? These are important questions I address in this study.

I seek to answer the following questions in this report:

1. What is RCM and how does it compare to other forms of maintenance?
2. What are the considerations when adopting a maintenance strategy such as RCM?
3. If transit agencies adopt RCM, what are the challenges of implementation?
4. What are the outcomes for transit agencies that adopt RCM?

Studying other systems' experiences, I want to understand how the adoption of reliability-centered maintenance (RCM) affects transit agencies that have not taken that step.

Public transit agencies often operate fleets of buses; many operate trains; and some operate ferries, cable cars, and other assorted types of modes. These fleets are often large, expensive, and must be reliably maintained. Thus, maintenance plays a crucial role in the operation of transit agencies. Current maintenance practices across the U.S. transit industry vary widely, from the informal and ad hoc to highly structured and regimented strategies. To maximize cost-effectiveness and reliability, some public transit agencies are turning to RCM in order to target scarce resources where they will deliver the most cost effective return on investment.

RCM is an innovative approach to maintenance and asset management originally developed in the 1960s (Smith, 1993). RCM has improved the effectiveness and efficiency of maintenance practices in aviation, utilities, and other fields (Marten, 2010; Moubray, 1997). In spite of this success, few transit agencies have implemented RCM. I want to know what RCM is, why so few agencies have implemented it, the process needed to implement RCM in agencies that practice it, and what the effects were on those agencies.

This applied research project examines reliability-centered maintenance (RCM), its implementation with transit agencies' asset management practices, and its effects on operations and maintenance.

Research Design & Methodology

Overview

I investigate RCM in two ways: (1) a comprehensive literature review of transit industry maintenance practices in general and RCM in particular, and (2) three case studies of large U.S. transit agencies that have either adopted or are in the process of adopting RCM. For the latter step, I investigate published reports and data on these three agencies and their maintenance practices as well as conduct interviews with maintenance professionals both within and outside those agencies.

My literature review is on research related to why maintenance is important, how transit agencies currently practice maintenance, what RCM is, its history, and how it affects maintenance in transit along with related fields. Second, I focus on three different transit agencies as case studies: BART (San Francisco Bay Area, CA), which has fully implemented RCM, MBTA (Boston, MA), which has partially implemented RCM, and WMATA (Washington, DC), which has begun to implement RCM. In each of the case studies I look at the maintenance context in each city and how RCM has affected (or might affect) operations. I chose these three cities because they are all in different phases of RCM implementation. There are other systems, such as New York MTA, that have implemented RCM. However, the three chosen cities also allow for more geographic diversity. Finally, I use interviews with asset management and maintenance professionals at my target case study cities, as well as the private sector, to corroborate, clarify, and expand upon concepts and findings from the literature review and case studies.

The literature review

This study is important to understand the current state of maintenance practices, why RCM constitutes an innovation, and why transit agencies should care. Maintenance is a vast field to cover with any semblance of totality. I want to understand one innovation (RCM) and its intersection with one sector (public transit) within the vast body of knowledge. However, it is crucial to understand where RCM fits within the context of maintenance to understand why it has certain effects. This study can tie together themes from research on RCM's ramifications on transit operations and maintenance as well as research from other fields in order to create a foundational understanding of where the current studies on RCM as well as the gaps in literature that need to be explored in the future.

I draw on existing research to answer the following questions:

1. *Why is transit maintenance important?* Transit agencies depend on maintenance to upkeep its facilities that exist to serve its city and its residents. My literature review provides a general understanding of maintenance, how RCM fits into that understanding, and why its relationship with transit is so important. If RCM has any impact on the effectiveness of maintenance, and that differential of effectiveness affects how transit operators interact with their riders, it is worth exploring how it will influence transit operations. This study seeks to show the possible ramifications of those maintenance decisions. This study looks at how asset management and maintenance, operated effectively or ineffectively, can alter regular service and how that service affects ridership and operational revenue for transit systems. I achieve this by researching what affects ridership and transit revenue then cross-examine these factors with how maintenance interacts with these factors.

2. *What is the status quo practice of transit maintenance?* I draw upon literature and my interviews to paint a general picture of how transit maintenance is currently practiced in the United States. A baseline assessment of transit maintenance practice is important to understand how to innovate current strategies.

3. *What is maintenance and asset management?* I touch upon the academic understanding on how to define maintenance and asset management, as well as to develop an overview of the different kinds of maintenance approaches. The

reader's understanding of RCM should be contextualized by an exploration of what defines maintenance.

4. *What is reliability-centered maintenance (RCM)?* RCM is the cornerstone of this project and a clear definition of RCM helps the study contextualize what I find later in the literature review as well as in the case studies and interviews. This study demonstrates how the implementation process works in order to provide a framework for how transit agencies can successfully implement RCM, if they so desire.

5. *What are the obstacles to implementing RCM?* In order to make any recommendations on RCM I must first explore the hurdles that exist with RCM and the issues that may arise from the adoption process. There are myriad challenges when organizations adopt any innovation. A cost-benefit analysis of RCM's outcomes and implementation challenges can elucidate whether or not it is worthwhile.

6. *What are the effects of adopting RCM?* This study will try to understand what ramifications could come about from RCM adoption and frame how those effects are contextualized by the challenges of implementation. I examine how RCM has shown to affect transit operations and reliability as well as the outcomes it has had in aviation and utilities, two industries similar to public transit with a broader base of literature.

Case studies

The second portion of the project is an examination of three transit agencies, their experience with RCM, and the effects of implementation. I do this through two different means: research on three different transit systems as well as conduct semi-structured interviews related to those transitions (or why there has been no transition). The systems I examine are BART, MBTA, and WMATA. These systems have all undergone some official means to recognize RCM as part of their present or future asset management strategy. BART has full RCM implementation across all lines and facilities. MBTA has an RCM pilot program on one of its rail lines. WMATA is currently studying the implications of RCM and exploring how to synergize it with its current infrastructure and maintenance practices. WMATA has not implemented RCM as of yet. These systems are all in different stages of RCM and can answer questions related to implementation and outcomes of RCM.

I examine asset management plans, capital improvement plans, and other planning documents from transit agencies that helped set the stage for RCM. I also draw upon other reports and information to show how RCM interacted with different plans/programs, its ramifications on facilities and maintenance management, and provide context for the state of maintenance and capital needs at these agencies that may have been affected by RCM. I examine metrics such as service reliability as well as less direct indicators such as capital needs to help paint a quantitative picture of the outcomes related to RCM. The data and findings from these sources are in some way related to processes that are affected by maintenance, and while not everything can be directly explained by RCM, it is important to understand how RCM fits in the larger context of asset management.

Finally, I conduct semi-structured interviews with professionals in the asset management and maintenance field. These semi-structured interviews are with professionals who have experience implementing and/or studying RCM at the transit agencies in my case studies. The interviews are with professionals are with managers who are or were directly connected to the RCM program at their respective agency or consultants who work in transit asset management. These interviews examine how agencies prepared and implemented, or are preparing to implement, RCM. I use these interviews in order to reinforce, build upon, and draw into question the information gained in the literature review and case study research

I interview current or former maintenance professionals at a managerial level from each of the case study transit authorities. I interview three maintenance professionals in the private sector to understand how consultants judge these case studies and what the implementation at other agencies would look like. I analyze these interviews by tying together central themes and concepts from their responses and how those experiences with RCM connect to findings made in the literature and case study research. Areas where there is agreement in the literature and interviews can help frame the realistic opportunities and challenges of RCM adoption. Areas of disagreement, either between interviews and literature and/or between the interviews themselves, provide me a start point on where more research needs to be done and why that is important to transit agencies.

Study limitations

It is important to consider the limitations of this research method and the issues that may arise from said limitations. The first and foremost concern is the lack of literature to confidently answer the six questions stated above. While there is a depth of research on maintenance and transit as well as the ramifications of RCM in other sectors (such as aviation), research on the intersection of RCM and the transit field is far less common. Furthermore, there is little public information about which US transit agencies have made the commitment to RCM, the framework they set forth to implement it, or how far along that implementation process they are. Finally, it may be difficult to use the interviews as an honest metric on the successes or failures other transit agencies have had in implementing RCM. The professionals I talk to about the subject may have an interest in highlighting positive or negative outcomes of implementation at the expense of an honest examination of the shortcomings of their agency's or firm's policies. This is because they are at the risk of casting doubt on their employer by speaking positively or negatively towards their professional decisions or the decisions of the peers and superiors in their professional network.

This client project describes RCM, explains opportunities for and challenges to adoption, and identifies where more research is needed.

Literature Review

This project explores reliability-centered maintenance (RCM) and its implications for transit. I evaluate the body of literature surrounding asset management and RCM to understand what they are and why they are important. I first discuss why maintenance is important and the effects of its investment or neglect. Second, I briefly explain how agencies carry about maintenance and the current shape of transit state of good repair. Third, I define maintenance and asset management to give context for later discussion. Forth, I examine what RCM is and how it is designed. Fifth, I discuss the obstacles of RCM implementation and why public institutions may be hesitant to adopt it. Sixth and finally, I examine the effects of implementation in both transit and other fields.

I. Maintenance in the Public Transit Industry

I need to outline why maintenance is important before I explore why RCM may or may not be a tenable maintenance strategy for transit agencies. Otherwise my study has little purpose other than to outline an innovation that seems to serves no larger purpose other than to be an innovation. So why is maintenance important to begin with? Simply put, without any maintenance systems will lose reliability and eventually break then not be brought back to an operable status. But reliability has much more nuanced implications that functional or not functional. System reliability in transit influences how users of the system perceives and interacts with it. This correlation is crucial for transit agencies to consider when it wants to change its relationship with its users.

Well maintained transit assets ensure rider safety and keeps a system moving (Hess & Lombardi, 2005). Unfortunately, capital expansion tends to captivate the public more than maintenance (Grabar, 2017). A capital bias over system asset management has often favored financial investment toward the former at the expense of the latter (Taylor & Samples, 2002). In response, transit agencies must reduce maintenance expenses and revert to more reactive maintenance strategies. When any kind of proactive maintenance is deferred, and assets are left to fail, this can have severe consequences on a system's effectiveness. This reliance on deferred maintenance presents a challenge to transit agencies: it may be cheaper to delay investing in maintenance in the short run, but it will deteriorate the system and is almost always more expensive in the long run (Hastak & Baim, 2001; Cohen, 1988). In New York City, budget cuts for transit maintenance have been a common response to fiscal constraints and problems. According to a November *New York Times* investigative article, these budget cuts have been the product of decades of shortfalls and have never been properly restored (Rosenthal et al., 2017). Transit maintenance has taken a backseat to other priorities such as poor revenues at state-operated ski areas, as evidenced by the denial of increased MTA asset management funding in lieu of a bailout for a local, state-operated ski area. This is one of many cases in which asset management funding was neglected for other statewide and municipal priorities (Rosenthal et al., 2017). These funds continue to be diverted elsewhere, which makes the MTA ever more reliant on reactive/deferred maintenance activities.

Low system reliability and inefficiencies have negative consequences on ridership (Perk et al., 2008; Taylor et al., 2003). Unreliable transit systems also make riders feel unsafe which further disincentivizes ridership (Zhang et al., 2000). Conversely, this means that increased reliability and availability increases transit ridership because people are more likely to choose it from alternative modes (Litman, 2008). Increased confidence in the system also brings more prepaid transit fares and raises revenue for the system (Perk et al., 2008). If decreased maintenance, and therefore decreased reliability, lowers the transit authority’s ability to pay for further maintenance, it is easy to see this as a potential downward spiral that would be difficult break.

It is crucial for transit authorities to maximize ridership. Effective maintenance might be one of the most cost-efficient strategy to achieve that goal. Paterson and Vautin (2015) studied the ramifications of state of good repair, the process of preserving assets (P. S. R. Council, 2014), as compared to capital expansion in terms of cost and ridership, as well as the externalities to decreased SGR investment. For the 25 largest transit systems in the Bay Area, SGR investments yield up to three times the ridership benefits per dollar spent as compared to capital expansion of the system to new locations. This comparison is calculated by the cost-effectiveness of projects potentially included in the

Regional Transportation Plan. Paterson and Vautin (2015) used a model to examine the difference between these potential capital projects and the operational changes of similar transit systems if the same amount of resources were invested in maintaining the current system. The study shows how a lack of SGR also produces negative outcomes. The relationship between SGR and ridership is yet to be thoroughly explored, but Paterson and Vautin's (2015) review of the literature strongly indicate a link between the two. Less investment in SGR means more delays and gaps of service. Systems such as New York MTA and Chicago CTA fell in disrepair in the 1970s and had profound ramifications on ridership (Deakin et al., 2012). Furthermore, a 2012 Regional Impacts Study for SF BART found that travel time and cost are the most important factors for mode choice among riders and have a much larger effect on ridership than other factors (Deakin et al., 2012). This research is reinforced by Phillips (2004) who shows that frequency, reliability, and speed of service (characteristics of service that are affected by maintenance) are critical aspects of mode choice.

II. Current Assessment of Transit Maintenance

Before I explore RCM, I need to lay out how maintenance is traditionally done at transit agencies. There is no standard model of transit maintenance. Every agency has different assets, resources, constraints, people, and a variety of factors that affect not only their stated strategy, but how crews carry out daily tasks. Therefore, it is impossible to lay out a unified prognosis of how transit maintenance was or is done before RCM. Two things are for certain: maintenance is a large aspect of any transit agency's budget and the national transit state of good repair is in trouble. A majority of transit assets at US transit agencies are below the FTA standards for "excellent" or "good" condition (Rose et al., 2012).

According to a 2010 FTA report, US and European transit agencies spend an average of approximately 27 percent of their budget on maintenance (FTA, 2010). Other studies have shown that US transit agencies can spend, on average, 20 percent of their operating budget on fleet maintenance alone (Blake et al., 2013). These numbers vary wildly across transit agencies because different agencies have different sizes, assets, and budget constraints among other things. Unfortunately, it is difficult to translate these costs across agencies because maintenance costs are allocated onto a wide array of budget line items depending on the system. For example, MBTA spreads maintenance funds across different facilities, such as the Orange Line or Blue Line (MBTA, 2016). However, BART classifies maintenance under more general facility categories, such as Maintenance Shops/Yards and Trains & Other Vehicles (BART, 2017b). While budgets are designed with much more specificity than the general examples given above, they exemplify how different systems allocate maintenance funds based on the way the budget is defined.

Reactive maintenance has been the norm for many US transit agencies. Every transit maintenance program uses run-to-failure, reactive maintenance, and scheduled maintenance for at least a part of their strategy (Blake et al., 2013). This is because it is the easiest to implement in the short term. There is little to no infrastructure needed in order to reactively maintain a system (Sillivant, 2015). However, proactive maintenance strategies are not utilized as often because of the initial investment (Blake et al., 2013). This is not to say that proactive maintenance happens at only a few agencies. Rather, most agencies have varying degrees of proactive maintenance activities (Blake et al., 2013).

Rolling stock maintenance procedures are not typically standardized (Centeno et al., 2005). This means that, often, there are few maintenance activities that have set procedures to complete. Less standardization increases the chances for inefficiencies. Floor crews will not be able to predict when they need a part and will likely need to wait an extended period of time in order to file for its acquisition, get it shipped, then install it. Facilities are only so large, and it is possible that it is difficult to retrieve the vehicle that needs the part replacement. The part that was ordered will then be shelved without a standard organizational method and will be difficult to retrieve in the future. This set of events take time and money due to its inefficiency (Centeno et al., 2005). Agencies such as BART faced these exact inefficiencies in their maintenance program (McCormick, 2018). Maintenance crews did not have unified ways to diagnose and address repairs. Work stations did not have the information or tools to quickly fix rolling stock. Because of this, rail cars would spend hours, even days in shops for tasks that could take maintenance crews less than an hour to complete (McCormick, 2018).

There are over 1,700 transit agencies within the United States alone (FTA, 2010). Even the major systems do not have unified means of maintaining their systems. As such, it is difficult to paint a complete picture of what transit maintenance looks like in the United States. I have not seen evidence of a study that looks at the current, general state of transit maintenance, the percent of systems and assets maintained reactively, proactively, etc., and how trends are changing nationally. As such, I am not be able to make any conclusive claims on how RCM will affect the average transit agency within the US because of the wide array of practices and nuances that exist within an agency's strategy.

National transit reliability performance has been increasing. One of the standard measurements of performance, mean distance between failures, has increased since 2006 (FTA, 2015). However, the state of transit assets is decreasing. In 2012, the average condition of all US transit assets was rated at 3.5/5 (FTA, 2015). As of 2015, transit agencies will invest $9.8 billion in asset preservation (FTA, 2015). This is far less than what would be needed to maintain a 3.5/5 score, let alone improve it (FTA, 2015). In 2015, the backlog of transit asset maintenance needs was $89.9 billion and by 2032, if trends remain the same, it will increase to $122.2 billion (FTA, 2015). The lack of adequate investment plays a major role in this backlog (FTA, 2015). In addition, this growing backlog is partially due to an increased awareness of transit maintenance needs, both short-cycle operating budget-funded actions and long-cycle capital program-funded actions (Baker & Peskin, 2018). It is difficult to gauge all current and future maintenance needs of transit agencies. The quality of data has been a barrier to fully assess the condition of US transit systems (Winn, 2018).

III. Defining Asset Management and Maintenance

Maintenance can be defined as "an activity carried out to retain an item in, or restore it to, any acceptable condition for use or to meet its functional standard" (Campbell & Reyes-Picknell, 2006, pg. 331). In a sense, maintenance is any process that seeks to rehabilitate an item in working condition, either by keeping it operational or restoring it to an operable status. Asset management is the bigger picture of how systems under the purview of an organizations are controlled in a larger network or structure, of which maintenance is a part (Amadi-Echendu et al., 2010; Davis, 2007; Transit Asset Management, 2006; Woodhouse, 1997). Asset management also focuses "on maximizing the impact of infrastructure investments through cost-benefit analysis of spending across the asset life cycle" (Lew, 2017, pg. 8). A sound asset management strategy provides a foundation on which to maximize the return on investment from maintenance activities. The term "asset management" is relatively new and only immerged as an operational philosophy the transit industry in the 1980s (Baker & Peskin, 2018). Important initiatives to focus investment in infrastructure began at New York MTA in 1982 and analytical approaches were developed and explored in Washington and Chicago later in the decade.

Maintenance is a crucial tenant of asset management. However, not all maintenance and approaches to maintenance are the same. A proactive maintenance action seeks to preserve system functionality before failure, while a reactive maintenance action seeks to restore system functionality after failure (Sillivant, 2015). According to Sharma, Kumar, and Kumar (2005) there are five types of maintenance strategies:

1. Breakdown Maintenance (BDM) or Frequency-Based Maintenance (FBM):

BDM/FBM is a reactive maintenance strategy intended to fix problems as they occur with no strategic vision given on how to 1) understand the patterns of such breakdowns, and 2) prevent such breakdowns in the future (Sharma, Kumar, & Kumar, 2005).

2. Preventative Maintenance (PM):

PM is a proactive maintenance strategy that bases maintenance activities on regular time intervals (Sharma, Kumar, & Kumar, 2005). Also known as age-based preventive maintenance (Van Horenbeek et al., 2013), parts are put on a schedule with regular check-ins at intervals deemed appropriate for the part. Preventative maintenance and proactive maintenance are often conflated; this study will refer to preventative maintenance as a specific strategy and proactive as any maintenance effort taken before a component has failed.

3. Conditions-Based Maintenance (CBM):

CBM is a proactive maintenance strategy that is done in conjunction with diagnostic tools such as vibration-based equipment (Marten, 2010). These diagnostic systems can detect when anomalies and faults form within the system being tracked (Sharma, Kumar, & Kumar, 2005).

4. Total Productive Maintenance (TPM):

TPM is a proactive strategy intended to permeate the culture of an organization and incentivize the reduction of loss in the six major "loss areas": downtime losses, set-up and adjustments losses, speed losses, reduced speed, defect losses, and reduced yield (Nakajima, 1988). This loss-oriented strategy integrates PM with operator expertise to help identify any signs of wear and malfunction. These checks are intended to be routine in addition to the scheduled maintenance intervals (Sharma, Kumar, & Kumar, 2005).

5. Reliability-Centered Maintenance (RCM):

RCM is a dynamic, data-driven strategy that incorporates all previous maintenance strategies to optimize and target the right type of maintenance activity towards a maintenance need (Marten, 2010). Inasmuch as this study is focused on RCM and its implementation, an expanded definition is needed.

IV. Defining Reliability-Centered Maintenance (RCM)

RCM is a maintenance strategy that deploys and optimizes an array of maintenance methods based upon best application for particular parts and prioritizes those tasks based on what will best preserve system function. RCM is intended to restore those parts to operating (but not necessarily prime) condition (Marten, 2010). Every maintenance method has an optimal way to address that activity need. This optimal maintenance method to preserve a system may be to upkeep/replace a part at regular time intervals or to monitor it then upkeep/replace it before a critical failure. RCM has been seen as a strategic means of minimizing proactive maintenance efforts (Campbell & Reyes-Picknell, 2006). However, inasmuch as RCM is intended to find the most optimal allocation of resources any means of maintenance is available. RCM operators can incorporate reactive maintenance methods where called for (Fleming, 2006).

RCM relies on a data-driven approach to optimizing all of these activities to where they are best applied to maximize the life-cycle of that inventory and to minimize the amount of system downtime. These data are often the product specifications, product function, its pattern of failure, the parts needed to sustain function, its current status, and other information needed to understand how that part interacts with the system around it. Since RCM is the data-driven exercise of prescribing the most effective maintenance method to a part, RCM takes a "best of both worlds" approach towards asset management. Rather than prescribing a condition based maintenance system where it optimizes the maintenance needs of most parts, RCM can combine those benefits with an array of the most effective methods to tackle every problem.

RCM was originally laid out as a four-step process when original studies, such as Smith (1993) examined the maintenance strategy. This process outlined the original concept and how it was executed:

1. Preserves functions;
2. Identifies failure modes that can defeat the functions;
3. Prioritizes function need (via the failure modes);
4. Selects only applicable and effective proactive maintenance tasks. (Smith, 1993; Beehler, 1996).

This is still primarily true, the four-step process evolved over time to include necessary steps to streamline and optimize RCM. Maintenance literature now defines the process of RCM through a series of seven steps to identify (Xu et al., 2014; FTA, 2013; Rausand & Vatn, 2008; Wilmeth & Usrey, 2000):

1. Isolate key systems for performance improvement;

2. Identify the functions and performance indicators of those systems;
3. Learn how those systems can fail to perform their functions;
4. Target the underlying technical issues (or failure modes) that would cause said failures;
5. Understand the consequences of those failure modes;
6. Research and test how the failure modes can be most effectively detected or prevented;
7. Optimal maintenance strategies to reflect evaluation and continue to monitor.

This cycle helps to understand, monitor, and optimize maintenance methods over time that is characteristic of an RCM strategy. While the seven-step system is mainly an expanded version of the four-step philosophy, there are exceptions. “Proactive maintenance tasks” in step four of the first iteration is different inasmuch as any method of maintenance can be implemented as long as it is shown to be the most effective and cost-effectively maintaining the life-cycle of a larger system.

As an example, suppose repairing an engine widget (a hypothetical item within the engine) every 5,000 miles of use is the most optimal way to ensure that engine, and therefore the vehicle, remains running. In this case, the transit agency would acquire maintenance data to confirm such an interval and then implement a maintenance method targeted towards that specific widget. However, the maintenance activity does not inform tasks needed to repair other inventory. RCM depends on a finely tuned strategy that directs a large array of these different maintenance activities towards the inventory and repair needs that are most suited by a specific maintenance method. Every part has a different optimal method linked to it and RCM demands a life-cycle analysis approach to testing and then prescribing the optimal means of maintenance and when or how to act on it. An organization does not need to apply RCM throughout all of its systems and components in order to see beneficial outcomes. RCM can be applied on individual subsystems and components on a case by case basis which would be derived from criticality analyses. (Palmeri, 2018).

V. Process and Challenges of RCM Implementation

How to implement RCM

I examine the process of RCM implementation to contextualize hurdles and challenges later on. Research by Backlund & Akersten (2003), who studied RCM implementation at a hydroelectric utility company, gives a rough road map for the RCM implementation process. RCM implementation is a six step process demonstrated in figure 1:

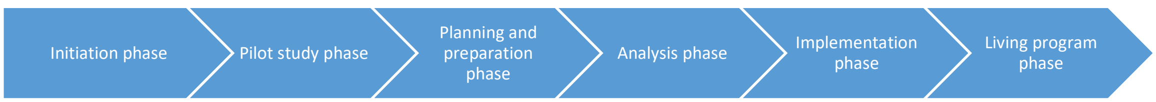

Figure 1: RCM implementation process (Backlund & Akersten, 2003)

The first phase is research and design of RCM and how it is introduced. A pilot study integrates RCM as a strategy for a subsystem or component of the overall maintenance program. Planning and preparation gives the organization integrating RCM the opportunity to adjust to unforeseen needs and issues. The analysis step studies what went right, what went wrong, how the process can be improved in the future, and what obligations need to be met before full integration. Implementation takes the lessons from the previous phase and applies those strategies to the entire maintenance program. All these culminate in the living program phase, the active operation and optimization of RCM as the pervasive strategy (Backlund & Akersten, 2003). This is the clearest breakdown in literature on an optimal iterative process to implement RCM. However, any implementation strategy that integrates the seven-step definition of the key characteristics of RCM given earlier in the literature review is all that is necessary for RCM.

Challenges can arise during any point in implementation. These obstacles can be classified in one of three different forms: technological/system implementation, organizational and communication, and political (Backlund & Akersten, 2003). Every category of obstacles will be a challenge at least to a small degree. Each challenge is experienced differently depending on the organization and the way it goes about implementing RCM.

Technological and system challenges

RCM, like any proactive or proactive-dominant maintenance strategy, requires a more significant effort to implement than reactive strategies given the large array of steps and prerequisites for proper integration (Sillivant, 2015; Marten, 2010; Backlund & Akersten, 2003). Transit agencies need to design and/or implement a maintenance management system to handle a large inventory database that allows operators to track all maintenance tasks. Transit agencies also need to account for every component within their inventory, research and/or test the life-cycle needs for each maintenance activity, then calculate cost-benefit analysis attached to the different kinds of maintenance methods that could be used (Marten, 2010). The management system should be constantly updated with latest factors driving the cost-benefit analysis. As time goes on, transit agencies use the management system to tweak and optimize the maintenance activities with each subsequent iteration.

Research by Backlund and Akersten (2003) concludes that there are numerous obstacles to RCM implementation. First is the lack of a computerized maintenance management system (CMMS). Without CMMS it is difficult to gather, analyze, and update any information and data to support RCM implementation. As mentioned before, CMMS needs to be constantly updated to optimize maintenance activates after each iteration of analysis of breakdown and repair. Second is the need of an RCM computer system (Backlund & Akersten, 2003). An organization needs time and expertise to design and develop an RCM computer system that can be utilized within a reasonable timeframe without overwhelming training and development costs. Finding such developer, if the skill set is not in house, takes time and money. At least one Eastern United States heavy rail transit operator that had implemented RCM, which was left unnamed in the study, computer skills were the primary obstacle in effectively implementing RCM and managing the requisite systems (Marten, 2010). Establishing CMMS and designing that system so it can be used by maintenance staff is difficult, it would be less expensive, and not out of the question, to buy a compatible CMMS model off another organization and integrate it into one's organizational structure (Fernihough, 1999).

The third major obstacle is a lack of plant register (in my study what we will refer to as an item master). As explained by Backlund & Akersten (2003) "(t)he (item master) should provide system structure, and information on components, equipment status and history." This means organizations need to understand what items they have in their inventory, their wear-out patterns, maintenance needs, and life-cycle costs all while creating a hierarchy of these components to grasp how they interact with each other. Organizations often have item masters already, but RCM demands detail and accuracy. RCM needs a list of parts, how many are in inventory, unit cost, and many other specifications. This information is not always available. Organizations likely need additional part information through research or an inventory audit. It is easy to lose track of which processes depend on what parts without a hierarchy. In turn, organizations will have a difficult time prioritizing tasks and responsibilities in a strategic fashion (Dekker, 1995). The fourth obstacle is the lack of documentation and/or information necessary to inform the above data/information systems. Without proper understanding of each part and process it will take additional efforts to gather said information (Backlund & Akersten, 2003). Inventory audits are unreliable without this information.

Item masters and tracking through CMMS must include a component's failure profile (how and when it is most likely to fail), and how to best address its maintenance needs. The best way of determining the optimal maintenance method for each part is examining that part's age reliability pattern (Smith, 1993). Age-reliability patterns conceptualize the likeliness a component is to fail over time and are visualized by wear-out curves (Smith, 1993; Moubray, 1997). Smith (1993) explains that only a select few age-reliability patterns are properly addressed by preventative maintenance schedules. Only age-reliability patterns that have a sharp increase in wear-out after a part ages can be addressed by preventative maintenance, since the operator will be aware of the time/mileage at which this critical failure becomes more likely. However, a vast majority of parts do not have this predictable upswing in failure likelihood. Smith (1993) explains that upwards of 89 percent of tasks cannot be addressed by "preventative" maintenance. Failures do not follow a predictable pattern. Components often need a condition based method of maintenance. While Smith studied nonstructural aircraft equipment, which does not translate perfectly to the public transit industry, confirms the above assertion: an understanding of which parts you have and how their maintenance needs are best addressed is crucial for RCM. Hopkinson, Perera, & Kiazim (2016) study the age-reliability patterns for transit road vehicles and found that documenting how to address a part's need is important to successfully carrying out RCM. Transit service do not depend on a large array of individual operations, but rather a collection of those operations in coordination and conjunction with each other. Thus the inability to progressively address certain tasks hinders their ability to address other processes dependent on that task. These parts and processes follow the same kinds of age-reliability patterns as many of their aviation counterparts, thus the need to do an audit no matter the field in which RCM is being implemented (Hopkinson et al., 2016). If a transit agency's staff understands the age-reliability patterns of its inventory, they can construct a reliable CMMS and adequately comprehend a system's needs.

Organizational and communication challenges

There are challenges to implementing RCM beyond the data challenges of inventory audits and systems management. There are numerous challenges organizations face when attempting to implement RCM related to institutional and/or labor factors (Marten, 2010; Backlund & Akersten, 2003). A prominent issue is the allocation of routines, roles, and responsibilities. An organization will face problems if decisions to implement certain maintenance methods and strategies do not include the expertise and approval of those who specialize in operations and maintenance. This muddies a clear working structure and creates challenges for allocating labor and management resources. A second obstacle is a lack of communication (Backlund & Akersten, 2003). Even if there is an adequate labor and management hierarchy a lack of communication obfuscates the needed understandings and expertise to operate a complex strategy such as RCM. Since RCM is such a demanding process as compared to reactive maintenance, there are different levels and areas of expertise that must be coordinated, and without communication such coordination is difficult.

A third obstacle for RCM implementation is the “(l)ack of overarching maintenance management strategy” (Backlund & Akersten, 2003). RCM should consider the overall big-picture of an organization when allocating resources and activities. However, this is not to say that RCM needs to be implemented on a large scale in order to be successful. RCM is just as effective when applied to individual components and subsystems (Palmeri, 2018). However, without a forward thinking asset management plan, institutions will be less effective stewards of the systems under their purview even with incremental innovation in maintenance (Baker & Peskin, 2018).

The final obstacle laid forth by Backlund and Akersten (2003) is “(i)ncomplete goal setting, and benefit identification and measurement.” As stated before, RCM needs a holistic vision in order to be fine-tuned to the organization. Without a proper understanding of what problems an organization wants to solve, the means of implementing RCM, and how to design and track performance metrics, said organizations cannot focus the effort to an optimal rate of return. These obstacles are indicative of an organization that is not properly adjusting to the demands of RCM implementation.

Political challenges

Political challenges exist beyond the obstacles laid forth in the previous chapter. Marten (2010) conducted a survey of 20 maintenance professionals, 10 management and 10 non-management maintenance professionals, on their experiences with RCM implementation at an unnamed Eastern United States heavy rail transit agency and gathered a large array of information on the internal political landscape of RCM implementation. He gathered that, while computer skills are the largest implementation challenge, unions constituted the second largest obstacle. Research suggestions that unions are particularly resistant to RCM implementation (Marten, 2010). Many unions and their members see RCM as an attempt to minimize labor costs, and therefore reduce the amount of needed labor hours. Unions would rather see these labor costs invested in workers rather than directed elsewhere. This concern is not unfounded.

A very public instance where RCM led to drastic labor changes was when the maintenance strategy was implemented at Disneyland in 1997. McKinsey & Company was hired to lead an effort to optimize ride maintenance and chose RCM as the primary strategy to cut down on labor hours and costs. Many workers were laid off and were often replaced by higher skilled technicians in an attempt to see the most cost savings from RCM (Anton & Yoshino, 2003). A survey done by de Groote (1995) recognized five primary recommended areas of focus when implementing new maintenance practices in an organization, one of which is the work-environment and union relations. Any change in practice that does not have the support of a union is likely to face resistance during implementation. Finally, a quarter of survey takers in the Marten (2010) study observed reversion to previous, non-RCM maintenance practices due to habit and/or comfort. The most likely impetus for backtracking are employees resistant to change and who believe that RCM is only a temporary measure that will be soon forgotten (Marten, 2010).

Unions are not universally opposed to RCM. Stakeholder dynamics change across agencies and institutions. In some cases, middle-managers are the most difficult to agree to RCM because they were promoted due to their ability to react effectively to maintenance failures (McCormick, 2018). For a lot of folks that have been in the transit industry for their entire careers, a data-driven, proactive approach to maintenance goes against their experience and expertise (Palmeri, 2018) However, educational programs can help remedy this resistance and ensure a smooth transition towards successful adoption of the RCM process (McCormick, 2018; Palmeri, 2018). Educational programs are typically necessary for employees to adapt to RCM in any industry. Small scale projects also help the transition as they allow people to see the process being implemented and deliver value in the form of increased system performance and reliability. Organizations that retain and educate current staff are best placed to see successful outcomes from their RCM initiatives as they preserve institutional knowledge and experience of the systems being reviewed (Palmeri, 2018).

Not only are managerial and organizational changes needed, but they must be reinforced by a cultural change that is open to the new tenants of RCM. This culture is difficult to harness considering the amount distrust from workplace changes such as downsizing that are bound to happen with RCM implementation (McGreevy, 2003). Without a culture shift towards RCM, however, managerial, top-down enforcement of RCM can only be so effective.

Why Few Transit Agencies Have Adopted RCM

In the previous section I examined the potential barriers that exist to implementing RCM. However, there are barriers that exist now that may prevent any efforts to adopt RCM, and may explain why so few transit agencies have implemented it. All public organizations must overcome funding and political pressures in order to implement new ways of doing things. Public agencies, including public transit providers, tend to be more risk averse than private sector organizations (Yoh, 2008). This means transit agencies need to overcome a high standard of likelihood of program success.

Funding is a common obstacle that prevents innovation in the public sector. The upfront costs of innovations are often clear, while the longer term cost-saving payoffs are uncertain, and often difficult to measure precisely. Innovations like RCM demand lots of staff and resources. Expenditures towards transit maintenance has not increased at a rate commensurate with increased costs of transit maintenance (FTA, 2015). This problem is exacerbated by the capital construction bias stated before (Taylor & Samples, 2002). As a result, many agencies report not having enough resources for increased rolling stock and cover operating costs (Taylor & Fink, 2003). A major innovation would be difficult to fund if resources are becoming sparser for maintenance and operations in lieu of capital expansion, especially since capital expansion will only add to the maintenance needs in the future.

Another major hurdle is the ability (or lack thereof) to reorient a large institution in a new direction to enable innovation adoption. RCM, for better or for worse, is an innovation in the transit asset management field. In general, there often are barriers to innovation in large public agencies. Public institutions, as opposed to private institutions, are more likely to be risk averse and limit rapid innovation (Hikichi & Beimborn, 2006). Public agencies' risk aversion can be explained by two reasons:

1. There is a high political cost of failure, and any failures limit the public body from future innovation (Wilson, 1989).
2. Public institutions are obligated to maintain a certain level of standards and provisions, any innovation runs the risk of deviating from that obligation (Gifford & Stalebrink, 2002). This is closely related to the funding shortage mentioned before.

Transit agencies are only incentivized to pursue a solution to a problem that is immediate (Yoh, 2008; Hikichi & Beimborn, 2006). This means transit agencies must identify a core issue or issues in which they seek to resolve while at the same time limiting the amount of political friction in the process.

VI. Analyses of RCM Implementation

History and effects in initial fields of implementation

RCM did not start in the transit sector (Marten, 2010). Rather, it was introduced in the aviation industry and adopted in the defense and utility industries soon after. As a result, there have been more studies of RCM in these sectors than in the transit sector. In this section I examine RCM research in the aviation and electrical utility sectors to consider its implications for public transit.

The modern version of RCM was developed in the 1960s by United Airlines as a means of coping with ever increasing maintenance costs of the Boeing 747 (Wentz, 2014). Smith (1993) examined the IMPACTS of RCM implementation on a new generation of giant, wide-body civilian aircraft, 747s, DC-10s, and L-1O11s between 1964, just prior to RCM, 1969, and then 1987 (using estimated figures). This study examined three general factors:

1. Hard-time: “process under which an item must be removed from service at or before a previously specified time.” (Smith, 1993, pg.8)
2. On-condition: process having repetitive inspections or test to determine the condition of units with regard to continued serviceability…” (Smith, 1993, pg.8)
3. Condition-monitored: “process under which data on the whole population of specified items in service…” (Smith, 1993, pg. 8)

The results are demonstrated in table 1.

	Component Distribution		
Maintenance Process	1964	1969	1987 (est.)
Hard-time units	58%	31%	9%
On-condition units	40%	37%	40%
Condition-monitored units	2%	32%	51%

Table 1: Maintenance process frequency over time (Smith, 1993).

The frequency with which of items that needed to be removed from operable service dropped significantly. Furthermore, the number of items that could be tracked sharply rose, which meant that the airline could more frequently allow failures of non-critical components, lowering the time needed to repair and increasing resource allocation efficiency (Smith, 1993). Airlines, like any institution, only have so much time and resources they can dedicate to maintenance. If maintenance crews fix non-essential components and have neglected an essential component close to failure, they have used time and resources which are zero-sum and will be less readily available for the imminent critical failure. United realized these benefits without increasing the number of repetitive inspections. This means operation and resource efficiency increased with no added time to inspections and routine maintenance.

Utilities adopting RCM have benefitted as well. In a study by Wilmeth & Usrey (2000) on RCM adoption in the utilities sector, electricity producers benefitted profoundly. Three noteworthy examples are cited: Puget Sound Power & Light, Bonneville Power Administration, and the British Columbia Hydro and Power Authority (BC Hydro). Puget Sound Power & Light adopted RCM in 1991 on numerous facilities containing transformers, substation equipment, voltage regulators, and power lines. Skog (1994) reported that the utility company was projected to have greatly extended maintenance intervals with no negative effects on liability or failure rates.

Bonneville Power Administration initiated an RCM program in 1994, switching from their original preventative maintenance-centered strategy. Bonneville Power Administration estimated a 40 percent increase in cost savings from maintenance and reported to pay back the implementation cost difference within a year (Wilmeth & Usrey, 2000). However, these cost benefits had only somewhat to do with RCM inasmuch as many maintenance personnel had already been using their own expertise to focus maintenance resources strategically, rather than maintaining a rigid preventative maintenance schedule. Maintenance personnel would keep records of items needing constant upkeep and part maintenance for items not dependent upon a preventative maintenance schedule (Sarkinen et al., 1996). While this may seem a direct success of RCM, it shows that an RCM-like system implemented from the bottom-up has pronounced effects that were then reinforced by an official strategy. Whether or not it was officially RCM, these maintenance professionals mimicked many of the dynamic tenants that make for a successful RCM strategy.

Wilmeth and Usrey (2000) also cite the BC Hydro RCM program initiated in 1995. Unlike BPA, BC Hydro did not have a *de facto* transition to RCM through grassroots means. However, BC Hydro still experienced a 20 to 50 percent savings in circuit breaker job site hours[1], as well as a 15 percent savings in transformer job site hours (Wilmeth & Usrey, 2000). RCM has proven effective in wind (Fischer et al., 2012) and nuclear (Worledge, 1993) power plant system maintenance as well.

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[1] This means time spent on this task has been reduced to 20 to 50 percent.

Effect on transit systems

In order to justify a transition to a different maintenance strategy, the benefits of RCM must outweigh the cost. Otherwise, this innovation is not worth the resources and political capital that is needed to adopt it. However, the research that exists for RCM and transit is somewhat sparse. Comprehensive studies on how RCM affects the efficacy of entire transit systems hardly exist. There is also little to no research that examines the history of RCM in transit, and who/how it was adopted over time (Marten, 2010). Rather, the studies that examine the outcomes of RCM largely cover how it affects specific processes and mechanisms.

RCM and transit have a relatively short yet obfuscated history together. RCM was first adopted in the rail transportation field by British Rail during the 1980s (Blake et al., 2013). Soon after, New York MTA began to test a CMMS system that laid the foundation of a rudimentary RCM program (Blake et al., 2013). Effective, long-term asset management strategies were almost unheard of in American transit systems before European systems such as Transport for London started adopting them, largely inspired by RCM's impact on the maritime industry (Baker & Peskin, 2018). Since RCM does not have to be formalized to be practiced (Palmeri, 2018), it is difficult to say how RCM was introduced to transit systems, especially in the United States.

Marten's 2010 study on RCM shows that the challenges in implementing RCM contrast with the benefits from implementation. In the survey of 30 maintenance professionals, 85 percent of participants reported an increase in rolling stock availability since RCM implementation. Additionally, 65 percent of professionals saw an increase in general rolling stock reliability. These numbers are peculiar, as it would be expected that the two numbers go hand-in-hand. The more reliable rolling stock the more likely it would be available for use due to less scheduled and unscheduled downtime (Sillivant, 2015). In any case, the vast majority of RCM analyses have found major benefits from implementation. Only 15 percent of those surveyed reported no change in safety or reliability, while just 10 percent saw reliability decrease with RCM. Finally, not a single respondent in this study reported a decrease in rolling stock availability (Marten, 2010).

RCM depends on a wide variety of proactive maintenance methods, so it is important to understand the difference between proactive and reactive maintenance. Reactive maintenance is usually easier and cheaper in the short-run to implement because it depends on little organizational infrastructure to manage. Simply, it is cheap and easy to set up because there is so little to set up (Sillivant, 2015). However, on average, there is more unscheduled downtime as well as increased operational costs due to unpredictability and the need for emergency parts that may not be on hand. There also tend to be increased labor costs due to unpredictable resource demands and/or labor allocation (Sillivant, 2015).

The Federal Transit Administration (FTA) recommends RCM as an effective asset management and maintenance tool for transit agencies (Blake et al., 2013). The FTA defines transit asset management best practice as "investment decisions… that consider maintenance requirements and costs." (Blake et al., 2013, pg. 5). The FTA argues that RCM is the best means to determine and distribute investment decisions for rolling stock over time. FTA states "the RCM process can benefit not just fleet performance but also the agency's overall performance" and thus fulfill FTA best practices. Some transit agencies had adopted RCM, or at the very least, were building the framework to integrate RCM into their larger state of good repair strategy before these FTA recommendations were published in 2013 (Rose et al., 2016). The FTA states that the adoption of Total Productive Maintenance is an important complementary strategy to RCM (Blake et al., 2013). TPM is "a human-focused improvement approach centered on understanding whether maintenance procedures are being performed efficiently and effectively… through continuous incremental improvements" (Blake et al., 2013, pg. 19). This means total productive maintenance is essential to understanding how well RCM is working when adopted by an agency (Blake et al., 2013). Blake et al. use Amtrak as the primary example for how RCM and total productive maintenance are necessary for each other. Amtrak adopted RCM in 2005 and saw two significant improvements: an increase from 14 to 16 available train sets by 2008 and a reduction in train annulments from eight to three per month (McGaw, 2011; Vasquez, 2008). These improvements generated additional revenue and decreased maintenance costs. As a result, locomotive availability had increased by 80 percent by 2007, just two years after implementation (Ruppert et al., 2007).

The FTA has demonstrated the benefits of reducing reactive maintenance as much as possible. However, there are limitations to the amount of proactive maintenance to which an agency can commit. Proactive maintenance takes more consistent efforts to commit to effectively; after all, it is easy to do nothing until that lack of effort causes failure. Transit agencies can see a return on investment if they commit to tracking and proactive maintenance. There is an optimal point where RCM implementation balances proactive and reactive maintenance strategies, where any more proactive effort starts to reduce the cost-benefit ratio of the program (Rose et al., 2016; Blake et al., 2013). An optimal proactive-reactive balance depends on myriad factors, such as the system needs and priorities, component functionality, and available resources. Researchers in a study of transit breaks in Korea found that agencies should formulate different RCM framework inputs to test for the optimal process (Bae et al., 2007). This means reliability is optimized by managing system and subsystem importance, complexity, cost of production, technical level, and driving cycle (Liu, 2015). The industry norm has been 70 percent proactive and 30 percent reactive (Grey, 2018). However, there is debate on whether 70 percent is too low. Ultimately these numbers depend on the agency, system, and program in question. No one ratio fits all and will constantly change as the system changes (Grey, 2018). Since that is the case, the optimal balance of maintenance functions in an RCM strategy depends not only on the system being maintained, but the way a transit agency prioritizes certain functions and calculates that optimal ratio.

Transit agencies provide themselves with the necessary insights to optimize maintenance resource allocation with audits of all parts and their maintenance needs. “Most equipment failure modes are not time dependent but do produce indications that failure is imminent or is occurring” (Hopkinson et al., 2016, pg. 2). Hopkinson, Perera, and Kiazim (2016) tested multiple maintenance methods on bus engine parts and found that, through testing and life-cycle analysis of an oil spray mechanism, it is possible to find the optimal method and process through which to maintain a part. In this research, Hopkinson's (2016) study of the oil spray valve mechanism optimized the way it is designed and repaired so that maintenance is more predictable and easier to track (Hopkinson et al., 2016). Bae et al. (2009) examined how RCM affects the door and door control subunit on electric motor units, the subsystem most likely to fail. This experiment used multiple optimization processes in order to explore how to most cost-effectively maintain the door to door control. The models used were based on the Army Material Systems Analysis Activity model to measure failure rate and mean time between failures. Bae et al. (2009) examined the optimization processes and used to develop an optimal process. Optimization saved approximately 23 percent of maintenance costs over the course of the study period. However, these studies only looked at one subsystem each and therefore more thorough research is necessary to understand the full landscape of age-reliability and optimization across all sub-systems and systems operated by transit agencies.

Organizations such as American Public Transportation Association (APTA) have analyzed rail transit systems operations and the reliability of 5-minute headway intervals. APTA reported that transit systems that operate on five-minute intervals and utilized RCM are more likely to be reliable and have fewer interruptions (APTA, 2012). However, the methodology used in this RCM analysis is not clear. The report calculates the likelihood of on-time performance reliability but then qualitatively argues the benefits of RCM. APTA provides no conclusive methodology as for why RCM optimizes headway intervals. Unfortunately, beyond the sources given, there is not a lot of research that examines the cost-benefit analysis of RCM implementation in transit.

Case Studies

Overview

I have chosen three transit authorities to examine RCM: BART in the San Francisco Bay Area, CA, MBTA in Boston, MA, and WMATA in Washington, D.C. Each of these transit operators have some experience with RCM. I chose these properties because they are large transit agencies and each is at different phases of RCM implementation. Organizations tackle a different array of issues at different stages of a program. I want to capture the transit agencies' outlook on RCM at different temporal swaths of program implementation. Furthermore, people look back at past experiences differently than when they lived that experience in real time (Mitchell et al., 1997). Program managers are therefore more qualified to speak on the hardships of RCM implementation in real time. BART has fully implemented RCM into all facilities management. MBTA has started a pilot program for RCM on their Blue Line. Finally, WMATA has laid the initial groundwork for RCM but has yet to formally adopt it as a policy.

All three systems operate heavy rail rapid transit (or just rapid transit). Rapid transit systems are high-capacity rail transit systems that operate on their own right of way, (usually) above or below street level, and have longer station distances than light rail or streetcars and smaller than commuter rail or national rail systems.

I also chose these three cities because of geographic diversity, clear delineation of program progress, consistency among modes (all three aim RCM efforts toward heavy rail rapid transit), and based off of the suggestion of my advisor. I chose three systems to maintain a reasonable study scope and to provide the three phases of program implementation (full, partial, no formal adoption). New York's MTA has a particularly mature RCM program for the Long Island Rail Road and Metro-North commuter rail systems that I considered for inclusion rather than BART. The inclusion of MTA would have restricted all the presented case studies to the Northeastern Corridor region of the United States and made it an inconsistent mode as compared to MBTA and WMATA. Boston and Washington are both similar in size and geography; however, these two cities were chosen because MBTA has a noticeable and clearly delineated pilot program and WMATA is a system with management that has explicitly made an effort to start RCM, but has not formalized it in any policy. I focus on heavy rail rapid transit systems because it is a consistent mode among my three case studies. Buses are a more pervasive mode across the United States but are less conducive to RCM because their parts face more rapid wear and tear. This means buses are more likely to be completely replaced far more frequently than rail rolling stock, which reduces the long-term benefits of RCM (Walsh, 2018).

It is difficult to say how many US transit agencies incorporate aspects of RCM. This is because transit agencies can adopt elements of RCM without a “ribbon cutting” moment that formalizes it as part of an asset management strategy (Palmeri, 2018). A culture and proactive tactics to increase reliability does not demand a formalized RCM strategy at an agency-wide level. BART, MBTA, NY MTA (Campbell, 2012), MARTA (Parker, 2015), Metro St. Louis (APTA, 2014), and handful of other US systems have formal RCM policies. Some are more developed than others, but they all incorporate the basic tenants of RCM. As far as I am aware from my independent research as well as interactions with other agencies, RCM is still a relatively new phenomenon amongst US transit agencies (Palmeri, 2018).

	BART	MBTA	WMATA
RCM Implementation Level	Full	Partial	Initial stages
RCM Program Start (Year)	2007	2014	N/A
Length of Heavy Rail System (miles)	112	38	117
Ridership (total annual riders)	124.2 million	352.5 million	179.7 million

Table 2: Characteristics of case study transit authorities

Bay Area Rapid Transit (BART)

San Francisco Bay Area, CA

Introduction

The Bay Area Rapid Transit (BART) is the heavy rail rapid transit system that services the San Francisco Bay Area in Northern California with stations in San Francisco and cities in Alameda, Contra Costa, and San Mateo counties. BART consists of five rapid transit lines on 109 miles of track and one automated guideway transit line on 3.2 miles of track. BART moves approximately 423,000 weekday passengers amounting to approximately 124.2 million passengers in 2017 (BART, 2017a), making BART the fifth busiest heavy rail rapid transit system in the United States. BART manages approximately 669 railcars and is currently the oldest heavy rail rapid transit fleet in the nation (BART, 2017b; Rose et al., 2016).

Map

Figure 2: BART System Map

Implementation

BART, like many transit operators, relied on a reactive, run-to-failure rolling stock maintenance strategy for many years (BART, 2017b; Rose et al., 2016; Marten, 2010). This baseline maintenance approach began to change with the introduction of the Strategic Maintenance Program. The Strategic Maintenance Program was introduced in 2006 to design a proactive maintenance program intended to increase maintenance efficiency and evolve activities over time (BART, 2007a). The Strategic Maintenance Program was implemented by the BART Rolling Stock & Shops department to increase the reliability and availability of the rolling stock within their purview. The vision of the Strategic Maintenance Program was intended "(t)o implement a continuously improving reliability-based maintenance process, which brings world-class maintenance practices to BART and its customers." (Rose et al., 2016, pg. 123). Through this vision, the foundation and practices the Strategic Maintenance Program were based around a reliability-centered maintenance (RCM) strategy and aimed towards improving the repair and condition of rolling stock.

The Strategic Maintenance Program was not designed, implemented, and finalized in 2006 in one fell swoop. Rather, the program was initiated and implemented over the course of years through steps such as full implementation in secondary repair shops by December 2009 and 50 percent implementation[2] in the primary shops by December 2010 (BART, 2008). This iterative process allowed the RCM strategy to grow and evolve before system-wide implementation. The Strategic Maintenance Program is still the guiding maintenance strategy for rolling stock and shops, and guides BART policy and planning around future resource allocation. Documents such as the most recent three iterations of the Short Range Transit Plan and Capital Improvement Program, the 2017 draft, 2014 draft, and 2008 Short Range Transit Plan and Capital Improvement Program, base their financial planning on goals and needs laid forth by the Strategic Maintenance Program (BART, 2017b; BART, 2007a). Since the implementation of the

[2] RCM does not have to be implemented unilaterally across all systems to exist within an agency. If RCM is implemented at 50 percent, that means half of the components and subsystems under the shop's purview was subject to RCM.

Strategic Maintenance Program, departments within BART that oversee other facilities such as elevator/escalator, track, and electrical/mechanical, have implemented RCM as their strategy as well (BART, 2017b; Wolfe, 2015).

Outcomes

BART rolling stock and shops saw an increase in both quantitative and qualitative improvement metrics. These improvements occurred in spite of BART's aging fleet (BART, 2017b; Rose et al., 2016). The Strategic Maintenance Program is credited for improving the effectiveness and efficiency in four key areas: processes, parts, information systems, and labor (Rose et al., 2016):

Processes

The RCM strategy implemented by the Strategic Maintenance Program changed the department's philosophy of reactive maintenance, fixing whatever was put in front of them, to a department that that depended on work plans, standardized procedures, and data-driven work cycles to establish best practices and act upon those practices (Rose et al., 2016). This methodology allowed BART to identify root causes of problems, tackle the underlying issues before critical failures, and identify ways to improve in future iterations of the task (Rose et al., 2016). This reduced time allotted to unscheduled rolling stock maintenance from over 80 to less than 40 percent (Rose et al., 2016). Within the first year alone facilities such as the electromechanical shop (a secondary repair facility) saw a 20 percent increase in productivity (BART, 2007a). By 2013, BART's fleet was 70 percent more reliable and underwent a 12 percent reduction in mechanics and technicians from the pre-Strategic Maintenance Program baseline (Allan, 2013; Blake et al., 2013). BART steadily increased its mean time between service delays (a standard indicator transit agencies utilize to track railcar reliability) between 2004 and 2016. By 2016 the mean time between service delays on BART cars had increased to 4,649 hours, up from

1,901 12 years earlier; this saved the agency $247 million, or the equivalent of 75 new cars (BART, 2017b).

Parts

The Strategic Maintenance Program implemented a supplier pre-qualification system to increase information on parts. This system expedited the acquisition of parts as well as the recourse process for part issues, and make acquisition decisions that rewarded future purchases on observed product performance. The new system improved parts stocking, distribution, and placement, as well as improved order requests by over 94 percent (Rose et al., 2016). BART standardized the way parts were ordered, stored, and moved about via work stations at maintenance facilities (McCormick, 2018). 2007 saw a 30 percent decrease in stock downtime, in some facilities, due to vehicles needing to wait for necessary parts. (BART, 2007a).

Information Systems

An effective information system, such as computer maintenance management system (CMMS), to track parts, systems, and process data is a crucial part of RCM (Marten, 2010). The Strategic Maintenance Program oversaw full CMMS integration by 2011 (Rose et al., 2016). The CMMS was reinforced by physical improvements such as wireless kiosks installed on maintenance floors that were integrated with laptop computers and allowed personnel up-to-date information on parts and processes (Rose et al., 2016). The system was further reinforced by the 2014 Strategic Asset Management Plan, which integrated new standards on how the system should be designed and integrated across the whole BART District. The system is used to catalogue and track over 200,000 assets (BART, 2017b).

People

BART maintenance management personal report a noticeable shift in workplace culture since the implementation of the Strategic Maintenance Program. According to Rose et al. (2016) there has been an increase in staff morale and a positive sense of ownership amongst personnel and a greater sense of collaboration amongst each other as well as with other departments and agencies. While middle-managers were originally opposed to RCM, BART was able to provide incentives and education to gain their support (McCormick, 2018). Furthermore, maintenance crews who worked at BART shops and facilities welcomed RCM because it empowered them more than reactive repairs (McCormick, 2018). BART has increasingly weaned itself off of outsourced maintenance activities since the Strategic Maintenance Program because in-house maintenance is now more effective and cost-efficient (Rose et al., 2016).

As discussed in the literature review, effective maintenance translates to increased reliability, and increased reliability attracts ridership and operational revenue (Marten, 2010; Perk et al., 2008). However, ridership is an elusive metric and has boundless factors that affect it. On-time performance and other performance metrics directly tied to system reliability are more productive ways to evaluate the impact of RCM.

BART's performance has a mixed record in the past decade. On-time performance was 94 percent in 2007 but has since declined to 89 percent in 2017 (BART, 2018; BART, 2007b). On face these numbers are troublesome. 2007 was the start of RCM, and therefore we might expect to see an increase. However, there are many factors at play that impact these numbers. As shown in Figure 3, BART's ridership has dramatically risen by over 20 million annual rides from 2007 to 2017 (BART, 2017a). Furthermore, BART has only just started to replace its fleet, and still operates one of the oldest fleets in the country (BART, 2014a). However, rolling stock was responsible for 30-40 percent of delays before RCM. Rolling stock is only responsible for 11 percent of delays now (McCormick, 2018). Human factors such as police activity are now far more prevalent factors that cause delays, which is contributed to by increased ridership and crowding (McCormick, 2018). Finally, on-time performance has increased in the past few years, in part due to the implementation of RCM (McCormick, 2018).

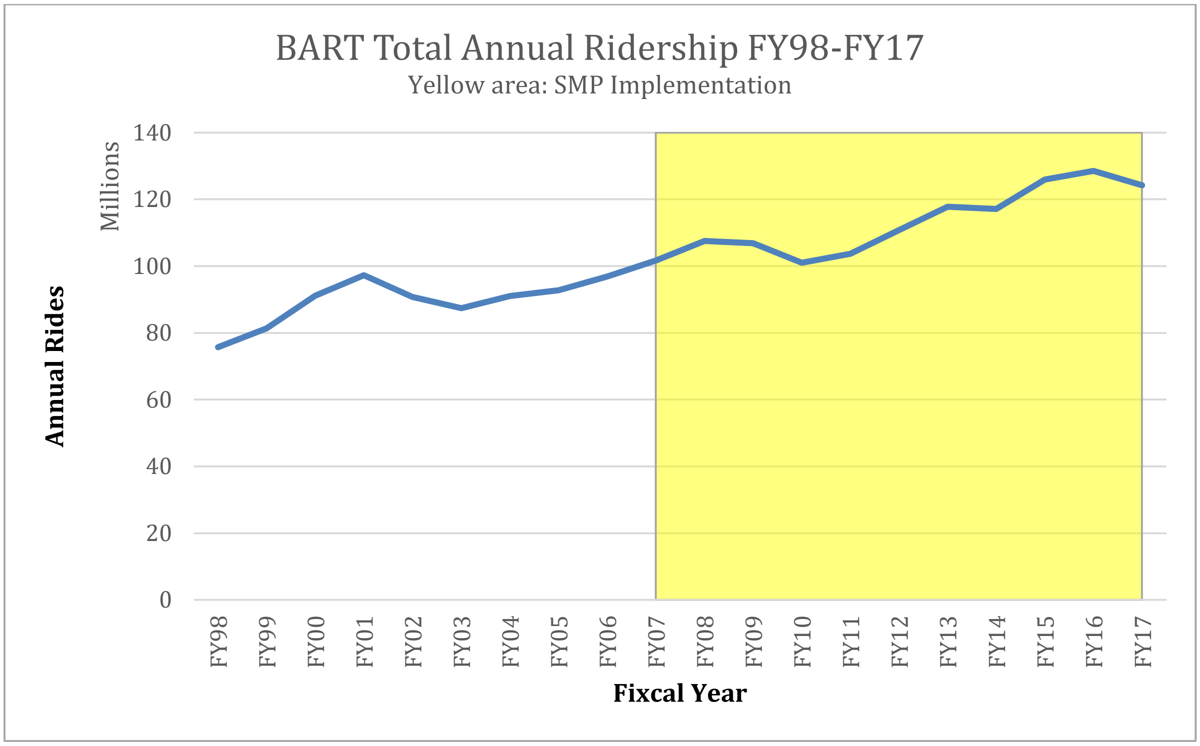


Figure 3: BART Total Annual Ridership FY98-FY17 (BART, 2017a)

Another important factor when assessing the effects of RCM is examining BART's capital needs. Capital needs outline the amount of money the agency needs in order to complete the projects it has planned. The BART Short Range Transit Plan and Capital Improvement Program forecasts the agency's capital needs. The 2008 Short Range Transit Plan and Capital Improvement Program identified capital needs amounting to $11.5 billion by fiscal year (FY) 2032 with only $5.6 billion in reasonably secured funds, leaving roughly 51 percent of its capital needs unsecured (BART, 2007a). The 2014 Draft Short Range Transit Plan and Capital Improvement Program draft identified a $9.6 billion capital need by FY 2024, with $4.8 in funds secured, again leaving roughly 50 percent of its capital needs unsecured (BART, 2014b). The 2017 Draft Short Range Transit Plan and Capital Improvement Program draft identified a $17.1 billion capital need by FY 2031, with $11.8 in funds secured, leaving roughly 31 percent of its capital needs unsecured (BART, 2017b). These figures show an increase in average annual capital need from the 2008 plan from $479 million/year in 2008 to $960 million/year in 2014, and then to $1.2 billion/year in 2017. This signals a rapid growth in capital needs for infrastructure reinvestment and operations (BART, 2017b).

These numbers can be deceptive. The SRTP/CIT does not always accurately account for every possible need. Maintenance crews, staff, managers, and planners are needed to develop a list of every capital need. This necessary human element introduces errors in two ways: 1) not every need is always known and/or given attention, and 2) staff who develop the cost estimates for the Short Range Transit Plan and Capital Improvement Program may not always know the true costs associated with that need (McCormick, 2018). The above numbers seem to show that BART's costs have skyrocketed, but only because the agency has become more thorough and effective at capital needs identification as well as cost evaluation (McCormick, 2018). BART's investments in capital expansion in conjunction with labor costs (for both current and retired workers) have also increased costs, but to a lesser degree (BART, 2014b; BART, 2017b; McCormick, 2018).

Massachusetts Bay Transportation Authority (MBTA)

Boston, MA

Introduction

The Massachusetts Bay Transportation Authority (MBTA) operates many transit modes in the Metropolitan Boston Area. This includes a commuter rail system, heavy rail rapid transit, light rail, motor buses, and ferries. The MBTA heavy rail rapid transit system has the fourth highest ridership of any system of its kind in the United States (APTA, 2016).

Map

Figure 4: MBTA System Map

Implementation

The MBTA has implemented an RCM pilot program for their Blue Line. The Blue Line is one of the three heavy rail rapid transit lines in the MBTA system, and is operated with the youngest heavy rail rapid-transit fleet of the three systems I examine (procured in 2008) (MBTA, 2017a). This pilot program was initiated with the adoption of the 2014 MBTA Transit Asset Management Plan (AMP). The Blue Line was selected to be a test to inform best practices for the future Orange and Red Line car fleet (MBTA, 2014a). The AMP initiated RCM implementation alongside a 24-month long study period in which identified best practices, cost-benefits analysis, and modifications towards optimization as the pilot program developed. Insights from the research in conjunction with the pilot program laid the foundation for how RCM would be implemented into future lines if the program was deemed successful and viable.

One of the primary concerns with RCM noted by the MBTA is how to govern the implementation, and then operation of the AMP (MBTA, 2014a). The MBTA set up a four-stage hierarchy of command in order to anticipate and address organizational problems. This chain of command was intended to oversee the implementation of every aspect of the AMP, not just RCM (MBTA, 2014a). A Leadership Team develops clear direction for policy, changes in management, and organizational structure of the AMP as well as any revisions to the AMP. Four Asset Management Executive Sponsors work below the Leadership Team (MBTA, 2014a). The sponsors are the Chief Financial Officer, Chief Information and Technology Officer, Chief of Strategic Business Initiatives and Innovation, and Chief Operating Officer. They act as conduits of information and direction for the specific division they oversee. A Program Manager for AMP Implementation acts as a coordinator between the efforts of each division and assists with day-to-day issues (MBTA, 2014a). The Program Manager ensures there is a successful progression and communication among the divisions, gives quarterly updates on the plan to the Leadership Team, and chairs the Asset Management Working Group. The Asset Management Working Group is the final rung on the organizational ladder in charge of AMP implementation and is a group composed of professionals from many different teams within each team. They provide professional expertise on how to implement AMP within their area. The representative from Engineering & Maintenance is the one in charge of implementing RCM for the Blue Line (MBTA, 2014a).

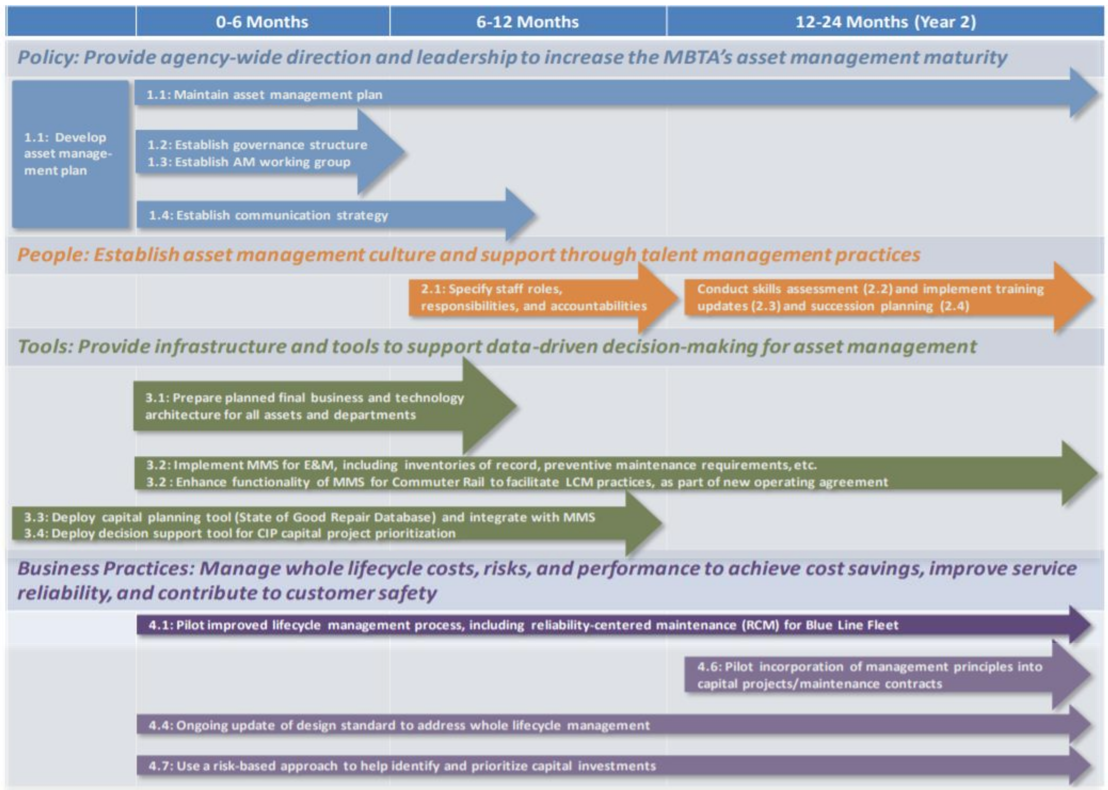


Figure 5: Asset Management Plan Implementation Roadmap (0-24 Months) (MBTA, 2014a)

The MBTA established a roadmap of RCM expansion after the 24-month study period (MBTA, 2014a). The roadmap outlined three individual system needs in order to move forward with RCM if the study period produced positive results. First, maintenance crew coordination with the groups in charge of business and technology to form a maintenance management system team. This team enhanced the existing maintenance management system data collection, functionality hierarchies, and administer efforts to optimize this system over time (MBTA, 2014a). Second, maintenance management system professionals looked at how to transfer the experiences of the Blue Line Pilot Program to other lines if the program is deemed successful (MBTA, 2014a). Finally, maintenance crews needed “to support asset lifecycle management planning, identify capital investment needs, develop system architectures and investment plans, and lead performance improvement efforts" coordinated by specialized maintenance engineers (MBTA, 2014a) The MBTA continues to use their maintenance management system to implement the above three-prong strategy and it will be updated in late 2018-early 2019 (Hicks, 2018).

RCM implementation did not happen all at once. Most of the system infrastructure was initiated at the beginning of the AMP in late 2014 and 2015, but many steps followed within 6 or 12 months. However, the entirety of the Blue Line RCM pilot is on a five-year long implementation schedule. The program initially targeted specific components of rolling stock such as air compression heads and HVAC equipment. The MBTA introduced new components and subsystems as time went on (Hicks, 2018).

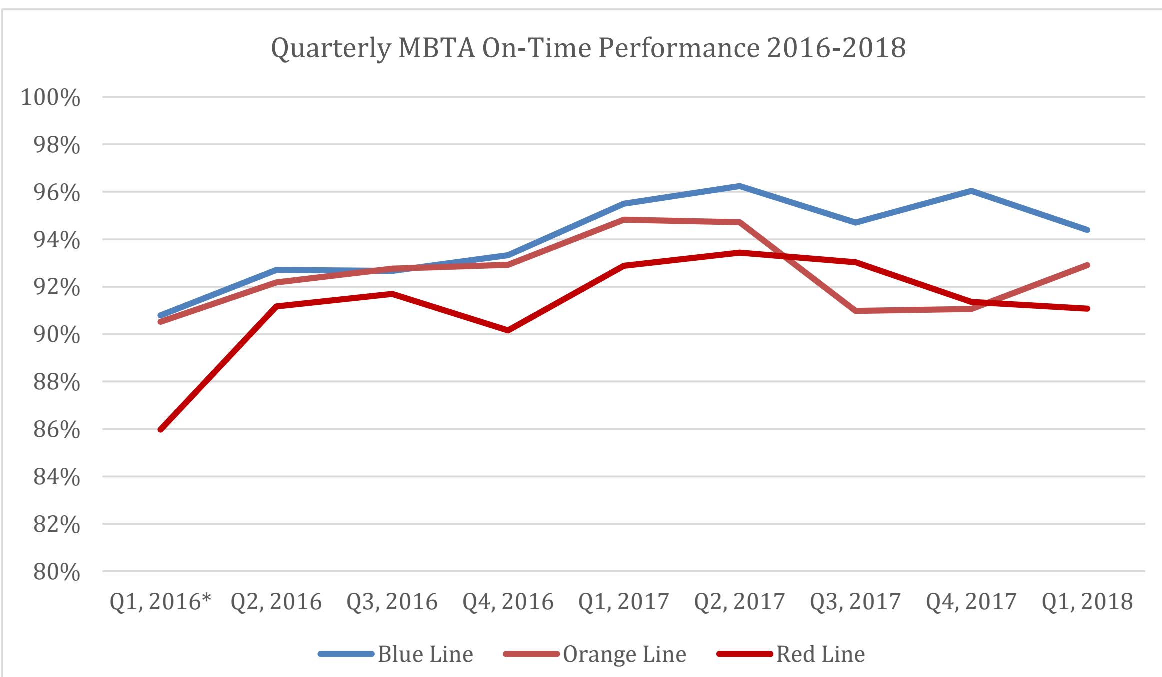
The foundation for the Blue Line RCM Pilot Program was an improved lifecycle management process complemented by inventories, part maintenance requirements, and the development of a coherent communication/management hierarchy as well as the identification of priority investments (MBTA, 2014a). Staff roles and responsibilities were studied starting at the six-month mark, and by 12 months of the AMP there needed to be a skills assessment, implement updated training, and plan for succession. The MBTA incorporated lifecycle management principles into capital projects and maintenance contracts (Hicks, 2018; MBTA, 2014a).

While progress has been made on all fronts, efforts to optimize the current system and prepare if for expansion are ongoing (MBTA, 2017). MBTA initiated a 2018 AMP update in order to comply with new federal rules introduced in 2016 with the TAM Final Rule 49 USC 625, which expanded the requirements set forth by MAP-21. These rules require additional performance measure in four main categories: rolling stock, equipment, infrastructure, and facilities. The update will include a continuation of RCM (MBTA, 2018a).

Outcomes

The MBTA has already seen a response to reliability since the program's implementation in 2014. However, not many metrics exist to show a conclusive effect of RCM. As a result of RCM, the Blue Line has increased its carrying capacity by 24 percent. This capacity increase is due to an ability to run six-car trains rather than four-car trains since RCM implementation (MBTA, 2017a). Capacity increased because more rolling stock was readily available for use due to an increase in mean distance between service incidents (Walsh, 2018). Furthermore, according to the MBTA, RCM has increased reliability through predictive part replacement that the agency will be able to forego mid-life overhaul of rolling stock (MBTA, 2017a).

In 2016, the MBTA launched a data portal that provided daily information on reliability, ridership, and other metrics. This portal can be used to look at the on-time performance trends of MBTA transit lines. It is useful to see how Blue Line performance has changed over the past few years as compared to other heavy rail rapid transit lines (Figure 6). This trend appears to show that the Blue Line's reliability has increased in comparison to the Orange and Red lines.



*Data only available for the month of March

Figure 6: Quarterly MBTA On-Time Performance 2016-2018 (MBTA, 2018b)

The two year timeline does not paint a long-term picture. This is because the data portal only has data going as far back as March 2016. Furthermore, the trend-lines display some variation in the rate of on-time performance. However, the Blue Line increase in reliability over time, as compared to the lines where RCM has not been implemented, is telling; in the literature review, I discussed research that showed benefits to RCM do not always manifest immediately. RCM has been introduced to the Blue Line over time, and therefore the outcomes would not happen immediately after the 2014 AMP. Past data points show that the Blue Line now has the same on-time performance as it had in past years. In 2011, the Blue Line regularly achieved a 95 to 96 percent on-time performance (MassDOT, 2013). This was a time where Blue Line trains were new enough to not see many maintenance issues and had overcome the high number of problems during the first year or two of implementation (Hicks, 2018). The Blue Line's performance declined a year after as most months saw around 93 to 95 percent on-time reliability (MassDOT, 2013). Blue Line on-time performance did not go above 95 percent once between 2012 and 2016, and only reached 95 percent in one quarter (MBTA, 2018b; MassDOT, 2015; MassDOT, 2014). The increase in reliability shown in Figure 5 is noticeable because of the gradual increase to consistently meet or break the 95 percent threshold. MBTA maintenance officials confirm that this upward progression in performance coincides with RCM (Hicks, 2018; Walsh, 2018).

The Blue Line's progression is important, but it is also important to understand how it compares to the Orange and Red Lines. In 2011-2012, the Red Line was consistently as reliable, if not more reliable, as the Blue Line. The Orange Line was less reliable (MassDOT, 2013). This changed, and between 2013-2015 the Red and Orange Lines had become less reliable with the Red Line around 86 percent and the Orange Line around 82 percent between those years. While the Blue Line has increased its reliability, and is currently the most reliable heavy rail rapid transit line, the Orange and Red Lines have seen much higher rates of on-time performance improvement since 2015 (MassDOT, 2014; MassDOT, 2015).

A key discrepancy lies in how much the MBTA is spending on maintenance for the Orange and Red Lines as compared to the Blue Line (MBTA, 2017b). In 2017, the Orange Line had a maintenance budget of $14.9 million, an increase of 9 percent since 2015 (MBTA, 2017b). The Red Line had a 2017 maintenance budget of $25.4 million, an increase of 8 percent since 2015 (MBTA, 2017b). These budgets dwarf the $7.6 million budget of the Blue Line (MBTA, 2017b). However, these discrepancies can largely be explained by the length of each line. The cost per mile looks different, and shows that the Red Line, per mile, is the least expensive line to maintain. The Orange Line is more expensive per mile than the Blue Line, but only by $0.20 (MBTA, 2017b).

The cost difference stated above might appear to cast some doubt on the effectiveness of the Blue Line maintenance program, but there are two factors that still show the Blue Line as positively influenced by recent maintenance trends. First, the above costs to maintain each line do not reflect overhaul costs. Red and Orange Lines will need overhauls due to their age, while the MBTA reports that the Blue Line will not need any overhauls in the near-term, due to the implementation of RCM (Hicks, 2018; Walsh, 2018; MBTA, 2017b). These overhauls are not directly factored into the maintenance budget since they are capital costs, but would greatly expand the costs to the agency. Electronic overhauls will still be necessary, but they are much less costly than mechanical overhauls (Walsh, 2018). Second, Blue Line maintenance costs have decreased by -3 percent since 2015 (MBTA, 2017b). This is in direct contrast to Red and Orange Line costs per year that have, on average, risen in past years. Finally, as stated in the BART section, expenditures on maintenance do not correlate exactly with need. Rather, agencies budget resources towards capital needs that have been identified. Not all needs are easily and exactly identified, but RCM helps with that identification process as well as the accuracy of information (McCormick, 2018). This means RCM on the Blue Line may show an increase in capital needs in the first years of implementation.

There a variety of factors that influence the reliability of a system's fleet. To designate RCM as the whole reasoning behind this gradual increase in with liability does not take into account the full picture of MBTA’s maintenance strategies. This is especially true considering the increase in the reliability of other lines within the system, despite the fact that they never had RCM. But RCM has only begun to affect the Blue Line's performance considering the slow implementation process.

As I discussed in the literature review, the costs for doing RCM goes down over time. MBTA has predicted the same trend with Blue Line maintenance (MBTA, 2017b), which means even though there are discrepancies in the amount spent on maintenance across the lines, the Orange and Red Lines will see an increase in their per-mile maintenance costs, while the Blue Line will see a decrease. The MBTA has had enough success in their pilot program that RCM will be implemented when they overhaul their fleet Orange and Red Lines (Hicks, 2018; MBTA, 2017c). The fleet replacement for these lines will start in December 2018. The MBTA will phase in four cars per month until the order is fulfilled (Hicks, 2018). RCM will be immediately phased into each new car.

Washington Metropolitan Area Transportation Authority (WMATA)

Washington, D.C.

Introduction

WMATA operates the Metrorail, also known as the DC Metro, a six lined heavy rail rapid transit system. It has the third highest rapid transit ridership of any system in the United States with 179.6 million riders per year (WMATA, 2017a; APTA, 2016). WMATA operates other transit modes, but for the sake of this study I focus on the DC Metro because it is where RCM is starting to be applied and is consistent with the other two case studies.

Map

Figure 6: WMATA System Map

Implementation

The Washington Metro heavy rail rapid transit system serves Washington, D.C. as well as the surrounding suburban areas in Maryland and Virginia. Unlike BART and MBTA, WMATA is still in the process of implementing its RCM strategy. This case study thus allows me to focus on the motivations to make the change to RCM, and the challenges to realizing its implementation in real time. I set a foundation of what metrics are useful throughout adoption and understand the challenges that WMATA experienced that made RCM an option only in recent years.

WMATA has suffered a series of public incidents where the Metrorail has experienced critical-failure incidents in operations. These incidents have accelerated WMATA's need for more thorough and innovative maintenance methods. Such incidents include fires which led to smoke filled stations and cars, days-long unscheduled emergency shutdowns, and train-on-train collisions (Mccartney & Duggan, 2016; NTSB, 2009). While some incidents can be explained through human error in transit vehicle operation, many of these issues come from mechanical issues. Not only has this lowered the reliability of Metrorail service, but has endangered the safety of its riders (WMATA, 2017b). WMATA has initiated multiple strategies to address these issues, including RCM (WMATA, 2017b). Activities such as SafeTrack have been initiated to work on maintenance activities beyond rolling stock. SafeTrack was an intensive overhaul program that rapidly replaced rail track through a series of accelerated work schedules, reduced operation hours, and reduced track closures to give maintenance crews more time to work (WMATA, 2018a).

WMATA's RCM activity is intended to improve systems performance and reliability by improving maintenance practices and applying one time changes (redesign, training, procedures) where appropriate (Palmeri, 2018; WMATA, 2018f). RCM initiatives within WMATA are being focused on the needs of its rapid transit rolling stock, similar to BART and MBTA, as well as the supporting infrastructure for rolling stock which the track, traction power and signaling systems (WMATA, 2017b). RCM initiatives will target the subsystems and components that are most crucial for the system as a whole and those that show a priority need for improvement (Palmeri, 2018).

Currently, WMATA depends primarily on reactive maintenance in order to fix failures as they arise. As of 2017, approximately 70 percent of WMATA maintenance activities on railcars and railcar supporting infrastructure were reactive, and only 30 percent were proactive (WMATA, 2017c; Grey, 2018). As I discussed in the Literature Review, reactive maintenance is typically less efficient and more expensive than proactive maintenance. WMATA managers have had this in mind in shifting to RCM, hoping to reverse those numbers and rely on reactive methods for only 30 percent of their maintenance activities (Grey, 2018; WMATA, 2017c). RCM is being slowly phased in across WMATA on a case by case basis. A lot of training is being conducted to educate people on the RCM process and to dispel any myths of what RCM "is" and "is not." WMATA uses a variety of data sources available to inform the RCM process and improve maintenance effectiveness as well as improve system performance and reliability (Palmeri, 2018).

WMATA's RCM efforts are led by Reliability Centered Maintenance Planning, a team under the Capital Planning & Program Management. The RCMP supports the Office of Rail Services to implement RCM in a way that every asset under the office's purview is properly maintained. The larger effort to update the Metrorail system is supported by the Office of Materials and Inventory Planning, established in May of 2016. The Office of Materials and Inventory Planning services a myriad of different teams, including the Reliability Centered Maintenance Planning team, to unify procurement and asset logistics (WMATA, 2018).

Some crucial fixtures to an RCM strategy already exist at WMATA. The agency has already invested in a CMMS to collect, organize, and evaluate asset inventory within the transit system and has so since 2010 (Archer, 2010). This step will not only allow for more seamless transition to RCM, but can streamline the Office of Materials and Inventory Planning's attempts to unify the material needs and assessment of the agency.

These stepping-stones can accelerate the experienced outcomes of RCM through less time spent on information architecture.

Potential Outcomes

Complications and failures currently faced by WMATA are largely due to its worn and aging infrastructure it operates. This is a very similar to BART's problems, and why BART's capital needs are also so onerous. WMATA's RCM program strategy is intended to emulate BART in that the pilot program does not focus on a single line, but rather the entire transit fleet and fleet-dependent infrastructure (WMATA, 2017b). While BART initially implemented RCM on secondary facilities then primary facilities, WMATA does not have a formal implementation sequence or timeline. Rather, RCM is slowly phased in incrementally. Frank Palmeri, the Director of Reliability-Centered Maintenance at WMATA states that there is no easy way to chart how to phase in RCM. WMATA uses data available to guide the most important areas to improve maintenance efficiency (Palmeri, 2018).

WMATA has already seen a large increase in on-time performance reliability in Metrorail service over the past year amidst its recent push on maintenance, but this is a new trend. In 2013, Metrorail had a strong on-time performance rating and delivered passengers on-time between 91 and 93 percent of trips (WMATA, 2015). However, this performance started to rapidly and continuously decline (WMATA, 2015; 2016; 2017e). By early 2017, on-time performance had declined to approximately 69 percent (WMATA, 2017e). This trend changed in 2018, when a year after the 69 percent evaluation shot back up to 88 percent on-time performance (WMATA, 2018b). WMATA credits this improvement to a few distinct efforts. First, WMATA retired 378 of their oldest railcars with the worst on-time performance, and initiated a replacement program with 56 new cars (WMATA, 2018b). Second, the aggressive SafeTrack program provided rapid improvements to rail safety and reliability. Finally, WMATA recognized law enforcement, customer relations, and operator based efficiency improvements since the prior year that improved timeliness (WMATA, 2018b). However, it is yet to be seen if this improvement lasts, and is not just an outlier.

RCM is intended to decrease Metrorail delays by 50 percent and prevent future emergency overhauls such as SafeTrack. This effort is seen in concert with the "Get Well" program already initiated and intended to replace the aging railcar stock and decrease delays by 25 percent (WMATA, 2017f). The Get Well program has already contributed, albeit to an unknown degree, to an increase in on-time performance (WMATA, 2017e).

While performance is improving, WMATA has seen an increase in fire and smoke events on their system (WMATA, 2018b). As of 2016, WMATA has had the second highest rate of major failures of any heavy rail system in the United States (FTA, 2016a). New York MTA has had the most. At the same time, WMATA's operating expense for every vehicle revenue mile has increased nearly $3/mile in the past 10 years (FTA, 2016b). Maintenance improvements are a priority for WMATA because of the ramifications recent events have had on ridership. Since the rapid decline in on-time performance, ridership has also dropped. This ridership decline is directly caused, at least in part, by the lower reliability (WMATA, 2017g).

WMATA's goal of 30 percent activity towards reactive maintenance is noteworthy. As I mentioned in the literature review, a 70/30 percent balance is often considered the industry standard for an optimal ratio to maximize resources, but there are many different factors that affect such a ratio (Grey, 2018). There are myriad different system parts and processes that demand different maintenance functions. Maintenance optimization depends on this allocation of functions as well as an optimal balance between proactive and reactive maintenance (Rose et al., 2016; Blake et al., 2013). WMATA has not formalized their RCM program yet. As a result, the will likely not know what the optimal balance of proactive and reactive maintenance is until RCM is more widespread.

Findings

1. Maintenance is crucial for transit agencies, and the smarter the maintenance strategy, the better

Maintenance is necessary, not only because it makes the difference between function and failure, but that it can increase the reliability of systems over time. Transit agencies need their systems, whether they are railcars, railway infrastructure, the utility grid, etc., to function properly and provide a base level of service. The more reliable and safe a transit system, the more likely that system is going to be trusted by its users. This has ramifications on ridership, operating revenues, and public perception of safety (Perk et al., 2008; Taylor et al., 2003; Zhang et al., 2000). Systems such as NYC MTA and Chicago CTA have suffered major ridership and revenue losses in past decades because of disrepair and lack of public confidence in the system (Deakin et al., 2012).

Operators ought to seek out the most effective means to carry out maintenance activities since maintenance is crucial for the ability for transit agencies to function successfully. RCM is among an array of different strategies to tackle maintenance issues, and whether or not it is unequivocally the most effective is not clear, what is most important is transit agencies of any size can take steps towards smarter and more cost-effective maintenance practices. RCM is a strategy that can be applied as widely or narrowly as an agency chooses. As Sillivant (2015) explained, proactive maintenance efforts quickly out-pace reactive efforts in terms of cost-effectiveness on a large array of issues. A strict regimen of RCM is not necessary to see cost-effective measures put in place.

2. RCM works, but needs to part of a larger strategy to address asset management

RCM has shown positive results over several performance metrics at both BART and MBTA, as well as in other sectors. Again, whether it is conclusively the most effective strategy is unclear, but it does have comparative advantages over a reactive-based maintenance method as part of an agency's asset management strategy. However, RCM should not be framed as a panacea for all asset management woes. As vehicle assets and systems age they become less reliable. The findings from BART's implementation program show that RCM almost certainly affected reliability and rolling stock downtime. However, these outcomes were seen where RCM was used in concert with other programs, such as rolling stock replacement. RCM may have staved off the harmful ramifications of infrastructure age and wear and strategically manage component replacements.

Ridership and operating revenues, as mentioned before, are affected by reliability. However, RCM cannot be the only mechanism relied on to increase reliability. Quick degradation of transit reliability has a pronounced effects on ridership, as evidenced by the MTA and CTA ridership plunges in the 1970s and the ridership numbers from WMATA in the midst of current public maintenance incidents and low reliability (Deakin et al., 2012; WMATA, 2017g; Freed, 2017). Whether or not a sharp increase in reliability will create an equally noticeable rebound is unclear. It is more important to gauge maintenance effectiveness through metrics such as mean time/distance between service interruptions.

This study demonstrates that different kinds of maintenance activities demand different kinds of solutions and a one-size-fits-all would be a blunt instrument for a more nuanced problem. A balance between 70 percent proactive and 30 percent reactive maintenance has been the industry standard, but such a norm is in question (Grey, 2018). The balance between proactive and reactive maintenance depends on numerous factors. An audit of different subsystems and components along with finding optimal maintenance mode for each is crucial to strike this balance.

3. RCM can only happen effectively if all stakeholders are committed

Transit agencies have many different actors and stakeholders with different interests. RCM does not align perfectly with everyone's interest because it can have different ramifications on different people and teams from across management and non-management (Marten, 2010). Without backing from these different groups, successful RCM implementation will be difficult. Decision makers in management positions need to communicate and work with implementation teams and groups who would actually carry out RCM in order to prevent a disjointed effort. Managers from BART, MBTA, and WMATA confirm that every stakeholder, from those who work the maintenance floor to executive officers need to commit to RCM to make it effective (McCormick, 2018; Grey, 2018; Walsh, 2018).

Unions can be cautious around RCM because of the potential labor force implications (Marten, 2010; de Groote 1995). In some instances, middle managers are more vocal against RCM because they were promoted due to their ability to react quickly to system failure and "put out fires" (McCormick, 2018). Even still, training and incentives have been effective mechanisms to inspire change within the organization towards RCM (McCormick, 2018). The transition from a reactive maintenance culture to a proactive approach using RCM does not lead to people being laid off. Rather, agencies can use the transition to retrain the existing labor-force and leverage their knowledge and experience to improve system performance (Palmeri, 2018). RCM is most effective when it is supported by the institutional knowledge of existing personnel (Palmeri, 2018). Communication, education, and consistent improvement efforts are necessary to prevent old habits from immerging that degrade the effectiveness of RCM (McGreevy, 2003).

4. Transit agencies should start with a pilot program with clearly defined performance metrics

RCM is a complicated, multi-variable, and data-driven maintenance strategy that takes an immense foundation to operate successfully. An RCM program should not be implemented in one fell swoop. A full RCM program needs a gargantuan amount of data, changes in process, and expertise. RCM is phased in slowly into individual subsystems and components over time. MBTA for example, implemented RCM on select assets on rolling stock, and implemented on 20 percent of rolling stock each year over the course of five years (Hicks, 2018). RCM should be eased in wherever it is most dire and easiest to implement. Subsystems and assets that have the most data, are the least resource intensive to track, and are crucial to the functionality of the system are prime candidates for RCM. It is crucial to get quick and easy victories that demonstrate the value of RCM (Grey, 2018).

Agencies such as BART and MBTA, have chosen to implement RCM through a pilot program. These pilot programs allowed the agencies to test the efficacy and feasibility of a larger-scale RCM strategy. In both instances, RCM was introduced slowly, a few pieces at a time and grew over the course of years. This allowed these agencies to understand optimal maintenance strategies, stress test the technological systems set in place, and minimize political resistance to the program.

Without the technological infrastructure, such as CMMS, transit agencies are not likely to have the information needed to effectively track, upkeep, and eventually replace parts and systems to maintain functionality. This infrastructure will be developed over time, often on the back of existing systems. From there, program expansion and regular audits of inventory to update specifications, status, and optimal maintenance prescriptions help agencies make a more effective RCM strategy over time.

5. More study on the intersection of RCM and Transit Asset Management is needed in order to understand how it affects transit operations

This study shows that RCM has real potential to benefit a transit agency’s asset management practices. However, while both BART and MBTA have shown beneficial outcomes, as other agencies have with RCM implementation, these examples have shown that these efforts typically exist in concert with other strategies to improve reliability. This means that the benefits seen by these agencies could very well be influenced by RCM. On the other hand, perhaps RCM adoption has less pronounced effects on the system’s reliability, and rather supports the more effective measures taken. It is unlikely that RCM is actively harmful or outcome neutral. These agencies have attributed much of their progress to RCM (McCormick, 2018; Grey, 2018). But the extent to which RCM alone influences these positive results is hard to infer.

My study only focuses on three heavy rail rapid transit systems in major US cities. Only a few American transit agencies operate a heavy rail rapid transit system. While I have identified a series of outcomes that could apply to other heavy rail rapid transit systems in the US, this does not mean they are easily translatable to other modes such as light rail, commuter rail, trams, buses, etc. Buses, for example, have a different calculus because they are more prone to wear and tear therefore more likely to have vehicles be replaced outright (Walsh, 2018). This means RCM will likely not have the same kind of calculus for buses, and may not have the same long-term cost effective trends as seen on heavy rail. The transit maintenance field would benefit from further study on how RCM impacts different modes differently.

Studies on how RCM interacts with specific processes show that there are definitive positive outcomes to the strategy. Fuel nozzles and EMU sub-units can be effectively maintained with decreased repair activity and downtime through RCM (Hopkinson, 2016; Bae et al., 2009). However, Marten (2010), a study based on 20 surveys at one transit agency, is the only large scale study I could find. While small, the survey does give a useful overview of the issues and benefits of RCM. Studies such as Marten’s may be more useful in the future.

A census of transit agencies’ maintenance strategies and extent of reactive/proactive practices will benefit RCM and transit literature. RCM can be utilized whether it takes the form of a formalized agency wide program, or a smaller more focused analysis on a particular system (Palmeri, 2018). We cannot determine the impact that RCM will have on the American transit agencies if we do not know what the starting point would be. As with any comparative analysis, you must first establish a baseline from which you will measure any future change, albeit positive or negative. Furthermore, large-scale studies that examine how RCM directly influences transit asset management, and more specifically how it affects the operations and reliability of transit service can bridge the gap between the specific studies and general surveys that have been down.

Without a connection between the ultra-specific examples and the larger survey-based study, I am left to draw intermediate conclusions from literature and case studies that cannot isolate the true impact of RCM on transit operations.

Conclusion

This study outlines the problems with current transit maintenance practices and how RCM fits into that larger picture. RCM is not a panacea through which the current maintenance problems will be solved. Rather, RCM and the proactive tactics that shape it have proven to be effective ways to increase the efficiency and effectiveness of maintenance programs both in transit and in other industries. Despite its potential merits, transit agencies cannot adopt RCM agency-wide in one large effort. Maintenance crews adopt RCM slowly, a few components and subsystems at a time, and use those successes to grow the program. These quick victories help gather momentum for the agency to expand RCM. These benefits can only be realized if every potential stakeholder helps incubate a culture of proactive maintenance and RCM. RCM shows promise for more widespread adoption in public transit, but there must be more study to gauge the level of success these transit programs truly have. Maintenance programs exist as part of larger asset management strategies. Since other maintenance efforts often exist in concert with RCM, further study should isolate the unique impacts RCM has on a transit operator. Furthermore, my study does not examine how RCM can be applied to modes beyond heavy rail rapid transit.

Transit is new to RCM. More study will be possible as transit agencies update their maintenance strategies. Until then, this study can be used as an overview of the opportunities and challenges of RCM and why it poses a promising future for transit.

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