The Pennsylvania State University

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Department of Mechanical and Nuclear Engineering

AN ANALYSIS OF COMPLEX VEHICLE RELIABILITY: A SYSTEMATIC FAILURE RATE APPROACH

A Thesis in Mechanical Engineering by Joseph M. Yutko

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Abstract

When engineered items fail, there are often indicators of decay long before the system collapses. This thesis explores this concept applied to complex vehicles operated in public transportation, but can be extrapolated to any vehicle system. The Altoona Bus Research and Test Center and Pennsylvania Transportation Institute have operated a federally funded transit bus testing program since 1988. The testing regimen aims to simulate how the bus would perform during in-transit use, and subsequently increase the likelihood that only reliable buses are purchased for public transportation applications. This work provides an overview of the relationships between the results of testing conducted at PTI versus performance of the same model during in-transit service. Further, an analysis of vehicle subsystem component failures is conducted, where the theory of repairable reliability systems is applied to the in-transit data to determine if component failures can be detected by increases in the cumulative and subsystem level failure rates.

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"If we knew what it was we were doing, it would not be called research, would it?"

- Albert Einstein



Introduction

In this chapter, the motivation for the underlying research of this thesis is introduced, including why buses are tested, how resulting bus reports are used, and why the results of the program require verification. In the first section, the impact of the transit industry on the everyday lives of an individual, as well as relevant operating statistics are introduced. The next section details the evolution and operating procedures of the transit bus testing program at Penn State. Next, the concept of subsystem failure analysis, the basis of this thesis, is developed, as well as how this concept materialized within the underlying Federal Transit Administration (FTA) study. Finally, an outline of this thesis is presented.

1.1 The Transit Industry

Public transportation plays a vital role in the infrastructure of the United States. Patrons can ride a train into Chicago without worrying about traffic jams, parking, or fuel prices. They can ride a transit bus to and from work in downtown Los Angeles, or to take guided trolley tour of their favorite national park. They can even take a ferry between, among others, Manhattan and Staten Island. Public transportation takes many forms, but they all serve a unifying goal: to move people in an efficient manner and at an affordable cost.

The majority of Americans using public transportation choose transit bus service as their primary carrier. According to a 2002 Bureau of Transportation Statistics (BTS) study, 60% of

all public transportation is represented by transit bus ridership (Figure 1.1). Nationwide, there were more than 500 million individual transit bus trips made in January 2002 alone. According to a 2005 survey, BTS statistics show that 4.4% of working Americans use public transportation to get to work. This percentage has remained constant since 1989, even though the amount of working Americans has increased by 14% [7]. Thus, the total usage of public transit is steadily growing.



Figure 1.1. U.S. Transit Ridership by Mode [1].

Transit buses are consistently the most widely form of public transportation used due to a few key features:

- Schedule Flexibility: Transit agencies can define and redefine pick-up times to best accommodate passengers. Light rail does not have a similar capability.
- Route Flexibility: Transit agencies define and redefine routes to carry passengers to their most desired locations.
- Affordability: Transit bus fares rank near the most affordable in public transportation [8]. This trait is particularly appealing with current fuel costs reaching all-time highs.

Even though transit bus ridership represents 60% of all public transportation utilization, the American Public Transportation Association (APTA) reported that only 46.5% of public transportation revenues were generated from transit bus ridership [8]. The affordability of transit bus service makes it extremely appealing with ever-increasing fuel and automobile costs. Automobile owners are paying premium costs to operate their vehicles on a daily basis in both operating costs (Table 1.1) and total annual costs (Table 1.2). Transit bus service costs, on the other hand, totaled only 20 cents/mile in 2000, reinforcing low ticket costs [6].

 Table 1.1. Automobile Operating Costs - 2005 (gas, oil, maintenance, tires) [6]

	Sm. Car	Med. Car	Lg. Car	SUV	Bus
Operating Costs (cents/mile)	12.1	15.0	15.2	17.0	20

 Table 1.2.
 Automobile Total Annual Operating Cost (in dollars) [6]

		-	0	(
10,000 (miles/yr)	5987	6905	7574	7774
15,000 (miles/yr)	7142	8580	9509	9574
20,000 (miles/yr)	8397	10,280	11,444	11,349

1.2 PTI Bus Testing

The transit bus testing program at Penn State was formed in 1988 in response to a piece of legislation that established a transit bus testing program to examine all new bus models that would be purchased with federal funds. This section details the history of the bus testing program, including test facilities, procedures, and reporting test results.

1.2.1 Bus Testing Laws

In order to keep public transportation costs low and services reliable, vehicle maintenance must be timely and efficient. Furthermore, the buses available for purchase must be of the highest quality to ensure that maintenance costs will be low and the useful life of the bus will be extensive. In 1987, congress passed the Surface Transportation and Uniform Relocation Assistance Act (STURA) (Pub. L. No. 100-17) which was an amendment to Section 12 of the Federal Transit Administration (FTA) Act of 1964 [9]. STURA established that after September 30, 1989, no new bus models may be purchased with federal funds unless it was first tested at an approved bus testing facility.

Subsection 317(b) of STURA made funds available to the Department of Transportation (DOT) to establish a bus testing facility to test new bus models for maintainability, reliability,

safety, performance, structural integrity, fuel economy, and noise [9]. Thus, the Altoona Bus Research Testing Center (ABRTC), in conjunction with The Pennsylvania State University and the Federal Transit Administration, was established to meet the new bus testing needs. In 1991, the Intermodal Surface Transportation Efficiency Act (ISTEA) was passed to mandate that the federal government subsidize 80% of the cost of the mandated testing, and also include braking and emissions testing in the test center's program [9].

The testing is preformed by staff at the ABRTC, as well as staff at the Pennsylvania Transportation Institute (PTI) test track. The test center can accommodate up to eight buses at one time. To date, the center has tested over 300 buses and has identified more than 7,200 malfunctions [5]. The duration of the bus tests are based on estimated useful life; the procedure consists of an accelerated test regimen that approximates up to 25% of its service life [5].

1.2.2 Durability Test Center

The objective of durability tests performed at PTI are to accelerate the damage inflicted on a bus through a shorter mileage than would be experienced during in-transit usage. The durability test approximates up to 25% of the service life of a transit bus. According to Klinikowski ([10]), the PTI test track was designed to be similar to other tracks in existence. This processed developed a track that consisted of load induced road elements that would be encountered both on other tracks and during in-transit use. According to market requirements, the PTI track contains a high crown intersection, a railroad crossing, and frame twist elements in order to better approximate an urban environment ([10]). The frame twist was particularly important to fully evaluate the torsional characteristics of longer vehicles ([10]). Chuck holes, staggered bumps, chatter bumps, and chuck holes were also introduced to simulate pavement discontinuities such as pot holes and weathered roads. The testing regimen was also designed to emulate other test track programs, where the acceleration factors were verified by stress level and cumulative damage analyses.([10])

The span of the durability testing regimen varies by the expected useful life of the bus being tested. Consider the following example: A bus is brought in for a 500,000 mile test. During testing, the bus would be driven for a total of 15,000 miles: 12,500 miles on the durability track, and 2,500 miscellaneous miles. The bus would be tested under three different loading conditions:

6,250 miles driven at gross vehicle weight (GVW), 2,500 miles driven at seated load weight (SLW), and 6,250 miles at curb weight (CW) [5]. Further, all non-scheduled maintenance performed on the bus during the durability testing is recorded and listed in the final bus report.

The PTI test track (Figure 1.2), built in 1970, is a 5042 ft long oval-shaped track that is used for a variety of research at Penn State [2]. Particularly, the test track is the primary locale for durability testing for the transit bus testing program.



Figure 1.2. The PTI Test Track [2].

The track has a 1,665 ft long vehicle durability course (Figure 1.3) that contains a variety of pavement discontinuities that simulate in-transit use of buses at an accelerated rate [2].



Figure 1.3. The Durability Course at the PTI Test Track [2].

The durability track contains seven distinct events (Figure 1.4) that the buses experience during in-transit use:

• Staggered bumps

- Railroad crossing
- 1" Random chuck holes
- Chatter bumps
- 4" Chuck holes
- High crown intersection
- Frame twist



Figure 1.4. The Durability Course Profile [2].

The end product of bus testing is a report detailing the results of all the various tests performed at Penn State. The report may, at the manufacturer's request, list recommendations for possible design changes [5]. Paper copies of the reports are available for purchase or can be downloaded for free from the ABRTC website. The reports are considered confidential until the manufacturer gives permission to publish it or until the manufacturer responds to a procurement bid by an FTA-funded recipient[5]. Transit agencies use the reports to gain insight into how a particular bus has preformed at the ABRTC in order to make the best purchasing decision for their application.

1.2.3 The Transit Study

The ABRTC has been conducting tests for over 20 years encompassing over 300 different models, while producing a detailed report for each bus [5]. Thus, a significant data set of performance measures obtained in the bus testing program now exists, particularly nonscheduled maintenance occurrences. Additionally, many bus models that have been tested at PTI are currently in use in various transit agencies, which often collect similar performance and reliability data. Hence, there is a valuable opportunity to compare the performances of the same bus model at PTI and at transit agencies to determine if the results of the ABRTC program represent in-transit usage.

Consequently, the FTA contracted researchers at Penn State to conduct a reliability analysis of the transit bus testing program. The study aimed to investigate such a comparison and, in the process, achieve the following objectives:

- Help the ABRTC evaluate and review its accelerated testing program
- Guide transit agencies to better interpret PTI bus reports and use them as a resource in making fleet purchase decisions

Throughout the course of the study, a large sample of data was collected from numerous agencies throughout the continental United States. Various techniques (described later) were introduced in an effort to determine correlation between the tested and in-service buses. One particular technique plotted the cumulative rate of failure versus mileage of each bus (Figure 1.5). Interestingly, the trend of the failure rate had multiple cycles consisting of an increase, peak, and decrease. Furthermore, many of the peaks coincided with the the replacement of major components. The data was further analyzed to determine if this phenomena was purely coincidence, or if there was substance in this relationship. Thus, the crux of this thesis is the a study aimed at understanding the relationship between the peaks in failure rate plots and the corresponding replacement of major system components.



Figure 1.5. A Sample Failure Rate Subsystem Plot.

1.3 Thesis Outline

The remainder of the thesis is summarized as follows:

Chapter 2 outlines a literature review on the concepts of reliability engineering with emphasis on cases studies that represent research similar to that which has been described here.

Chapter 3 describes the extensive data collection efforts that were made on behalf of this research. This chapter includes the process of objectively ranking the buses tested at Penn State based their performance at the ABRTC, and then determining transit agencies around the United States that run these buses. Also described are the trials and tribulations of attempting to collect data from a transit agency.

Chapter 4 explains yet another extensive body of work that contributed to this thesis: preprocessing of the received data. This chapter details how the data was recategorized, arranged, and prepared for processing.

Chapter 5 explains initial comparisons made between PTI and in-transit data sets, including cumulative, major, and minor failure comparisons.

Chapter 6 delves into cumulative and subsystem failure rate analysis. The algorithms for differentiation are explained, coupled with an examination of the failure rate, and how a subsystem level analysis led to correlation between major component replacements and peaks in the cumulative failure rate. Finally, a filtered numerical derivative approach is presented which strengthens conclusions based on the obtained results.

Finally, **Chapter 7** summarizes the conclusions made from the research presented in this thesis. Further, future research topics are presented to aid the next generation of students who will take over this project in the coming years.



Literature Search

This chapter describes a survey of available literature pertaining to the reliability and failure prediction of transit buses. The literature review was conducted to determine the implications of this research, particularly how this research complements items already existing in the body of knowledge, and how it adds depth to the topic of vehicle reliability. A majority of the publications on vehicle reliability and failure prediction are focused on determining an optimum maintenance schedule to prevent any downtime associated with non-scheduled maintenance. Additional work focuses on matching past data to a Weibull distribution to develop predictive models, inferring information from accelerated testing regiments to predict high mileage vehicle reliability.

2.1 Reliability Engineering

No engineered device is or ever will be "perfect". There are inherent flaws associated with design, materials, manufacturing, construction, operational conditions (etc.) such that the useful life of the device is never infinite [11]. Thus, the field of reliability engineering has emerged to develop methods of design, analysis, and prediction such that a product could reasonably be expected to survive under normal operating conditions over a predetermined useful life.

2.1.1 Reliability Theory

No one can dispute the fact that devices need to be reliable. The origins of reliability theory started during World War II when German engineers tried to improve the reliability of their rockets. Since then, **engineers** have been studying these and other potential failure mechanisms in an effort to plan for and/or predict failures, or at least minimize their impact on the performance of the system [11, 4]. **Consumers** investigate the reliability of products before making purchasing decisions [12]. **Manufacturers** strive to generate a reliable produce in order to reduce warranty claims, maximize their profit margins, and ultimately generate return customers by achieving a well known and respected reputation [12]. Other industries such as **airlines**, **aerospace**, and the **military** require a certain degree of reliability in designs to assure the safety of those who would be exposed to their equipment [12]. Each group may have different expectations as to the reliability of a product, but all can agree that the product needs to perform when required.

Generally speaking, reliability refers to an item's ability to successfully perform an intended function throughout a predetermined life [12]. One may ask, "Why can't a design survive forever, or at least through it's preselected life?" Unfortunately, there will always exist some limiting factor that will cause the design to fail before it would be desirable. If technical knowledge is not a limiting factor in the design, manufacture, testing, materials, or engineering analysis of a product, pure practical and economical limitations will force the use of 'not-so-perfect' designs [11]. In response, the field of reliability engineering has emerged to minimize failures in engineered systems by understanding "why", "when", and "how" systems fail [11].

There are many potential reasons why a design might fail, including [12]:

- The design is inherently incapable of preforming the desired function
- The design is over-stressed (i.e. voltage, current, compressive stresses)
- The design is worn-out
- The design specifications are incorrect
- The design is not maintained properly
- The design is not used as it is intended

Reliability engineers evaluate designs in the pre-manufacture stage of development in an attempt to eliminate any of the previously mentioned causes of failure from occurring. It is for these reasons that actions such as periodic maintenance, product work instructions, design reviews, and inspections take place.

Reliability must be quantified in order to be incorporated into the design process [13]. The methods of quantifying reliability are derived from the mathematics of probability and statistics [12]. Consider the following example: a Penn State graduate student obtains a laser that he plans to use in his research. The laser manufacturer claims their product fails at an average rate of once per 2,000 hours of operation. However, neither the Penn State student nor the manufacturer can be certain that the laser will operate without failure prior to his research being completed. The manufacturer can only reach conclusions about the *probability* of the laser's performance within a specified statistical confidence interval [12].

Generally speaking, reliability has two interpretations: deterministic and probabilistic [11]. A deterministic approach to reliability involves studying the 'how' and 'why' an item failed, such as field reports, failure analysis, testing, and/or redesign. The probabilistic approach involves realizing the probability that an item will survive through its predetermined lifetime [11]. Mathematically, reliability, R(t) is defined as [11]:

$$R(t) = Pr(T \ge t) \tag{2.1}$$

where

T = time to failure of the item t = item's predetermined lifetime Pr = probability

Conversely, the probability, Pr(), that the item will fail at sometime up to time t, F(t), is defined as [11]:

$$F(t) = Pr(T \le t) \tag{2.2}$$

Thus, reliability function can be defined as [11]:

$$R(t) = 1 - F(t)$$
(2.3)

The failure rate of a system describes the frequency in which failures occur. The failure rate can be determined numerically by [11]:

$$h(t) = \lim_{\tau \to 0} \frac{1}{\tau} \left(\frac{F(t+\tau) - F(t)}{R(t)} \right)$$
(2.4)

The failure rate is a critical function when considering system reliability because it determines the changes in probability of failure over the lifetime of a part [11, 13].



Figure 2.1. The bathtub curve [3].

For non-repairable systems, if the failure rate, h(t), is plotted versus time, it generally exhibits a bathtub shape, and thus is referred to as the *bathtub curve* (Figure 2.1). The bathtub curve can be broken into three distinct periods. The first period is known as the *Infant Mortality* or *Burn-In* period [14]. This period represents the beginning of a product's life cycle, where the failure rate starts off very high, but also decreases rapidly. The next period, characterized by a somewhat constant failure rate where mostly random failures occur, is known as the *Useful Life* of the product [14]. A product spends most of its life here. The final period, characterized by an increasing failure rate, is called *Wear-Out* [14]. It is during this period that a component or system would be replaced because it has outlived its useful life.

Although the bathtub curve provides a general outline for how a product will behave over its lifetime, other statistical tools are better developed to make more bold predictions. To model reliability, engineers typically rely on the more versatile *Weibull Distribution*. The Weibull Distribution is a continuous probability distribution that is used to mimic many other statistical distributions by changing parameters in its probability density function [15, 11]. Due to its flexibility, the Weibull Distribution can also model all three regions of the bathtub curve, and can approximate a system made of one or many components [11].

Reliability engineers often generate Weibull parameters that allow the resulting distribution to approximate their data [16]. Once the distribution fits the data, it is possible to make predictions about the future life of the product within varying intervals of confidence. The main applications of Weibull Distribution in reliability modeling lie in [11]:

- Corrosion resistance studies
- Time-to-failure for electrical hardware (capacitors, transistors, etc.)
- Time-to-failure for mechanical hardware (ball bearings, motors, etc.)
- Time-to-failure of system components

For instance, Ion and Sander [17] used three months of electronic product warranty data to obtain Weibull parameters, and subsequently a Weibull distribution that was used to make early life reliability predictions. They found the Weibull distribution was a very useful tool in determining early life reliability. Fisher, Weber, and Marx [18] used the same two parameter approach to determine the lifetime of ceramic bridges that dentists install in patient's mouths. The bridge and teeth were modeled for varying stress levels with a finite element package, and the Weibull Distribution was used to evaluate the failure probability of the complex ceramic bridge under those stresses.

2.1.2 System Reliability

For simple components, the previous section provides a sufficient background on the theory behind component failures and methods of using statistical distributions to represent known data and predict future reliability. It is a well known fact, however, that very few components are designed to work alone; rather, they are designed to be installed in or contribute to the operation of systems. A system is hereafter defined as a collection of components whose coordinated operation leads to the successful functioning of the device [11]. In order to make a predictive assessment of a system, it is important to not only understand the reliability of individual components, but also to understand the relationships that the components holds in the operation of the system to realize the reliability of that system [11].

A common tool used in analyzing system reliability is called the *Reliability Block Diagram*. The reliability block diagram is a somewhat physical approach to analyzing the system in that the way the diagram is connected shows the interdependence of the actual system. For example, a dump truck with two hydraulic cylinders lifting its dump box could be represented as two mechanical systems in parallel. If one of the cylinders fails, is still possible that the dump box could be lifted if the system was designed to do so. Conversely, if a section of the drive shaft on an automobile fails, it is certain that the auto will not move because there is no way to transmit mechanical energy to the wheels. This drive shaft example represents a series system as shown in (Figure 2.2).



Figure 2.2. A Series Reliability Block Diagram [4].

In the reliability block diagram, each block represents the reliability of a component and its functional location in the system. The series block diagram (Figure 2.2) represents a system whose functional success is dependent on the the functional success of each previous component in the system. If any component of the series system fails, the entire system would fail. The reliability of Figure 2.2 is the probability that all blocks preform as expected during their predetermined

life [11]. Mathematically, the reliability of the series system is expressed as [11]:

$$R_s(t) = R_1(t) \cdot R_2(t) \dots R_n(t) = \prod_{i=1}^n R_i(t)$$
(2.5)

The parallel block diagram (Figure 2.3) represents systems in which the successful function of just one the components results in successful operation of the entire system. This type of arrangement may have multiple blocks that preform the same function in order to build redundancy into the system. Mathematically, the reliability of the parallel system is expressed as [11]:

$$R_p(t) = 1 - \prod_{i=1}^{n} (1 - R_i(t))$$
(2.6)

The Space Shuttle main avionic computer system is a great example of a system that was intentionally built in the parallel arrangement [19]. The main avionics system was designed to be quadruple redundant, meaning any of four identical computer systems could communicate with the avionics system and preform critical flight operations [19].



Figure 2.3. A Parallel Reliability Block Diagram [4].

2.2 Vehicle and Transportation Related Reliability

Reliability analysis is a critical tool in maintaining an operating a fleet and minimizing operating costs in transit systems [4]. In this section, case studies and research results are summarized that investigate transit system operation and reliability, automotive reliability, transit agency maintenance optimization, accelerated aging.

2.2.1 Vehicle Maintenance

In order to set guidelines on preventative maintenance scheduling, Guenthner and Sinha [20] analyzed the relationship between maintenance policy, reliability of the transit schedule, and performance of the system. They developed a model that predicted expected passenger wait times along a transit route by computing dependability as a function of the number of available mechanics and spare buses. Their model also considered typical maintenance statistics such as miles between failure, costs per repair, and average repair time of various subsystem repairs (i.e. brakes, drivetrain). Passenger wait times were then used to evaluate optimal maintenance policy and its effect on system performance. Their model then allowed transit agency managers to evaluate vehicle acquisitions based on operating conditions in their transit system.

Drake and Carter [21] conducted a study on transit bus maintenance manpower utilization. The goal of their study was to examine historical maintenance manpower utilization at various transit agencies about the United States, and to generate statistically significant, yet uncomplicated models that would allow maintenance managers to better plan their manpower requirements. The authors searched out manpower data from fifteen transit agencies around the United States based on the following conditions:

- Climate conditions
- Fleet size
- Terrain
- Data availability
- Fleet composition

The authors collected information such as time-to-repair estimates for certain jobs, manpower utilization, vehicle fleet information, and local policies that shaped agency operating procedures [21]. The obtained data was examined to determine the manpower distribution of hours worked based on the following categories:

• Cleaning

- Body
- Inspection
- Various subsystems

Their analysis determined the average number of man-hours for each vehicle subsystem across all agencies, as well as an associated standard deviation. The results of their modeling proved that manpower distribution requirements varied substantially among transit agencies with local operating characteristics accounting for the majority of the standard deviation [21].

2.2.2 Vehicle Reliability

In the area of vehicle reliability, Binggang and Shuijun [22] developed methods to evaluate the reliability of automotive products by categorizing failures according to degree of harmfulness and determining weighting coefficients for each failures and, subsequently, an equivalent number. They also discussed both merits and demerits of utilizing evaluation indices such as Mean Time Between Failurs (MTBF), Mean Time to First Failure (MTTFF), Mean Repair Time (MRT), and Availability. Finally, the authors described methodology for establishing a relationship between the "bench test life" of a part and it's "service life" expressing the cumulative failure number function as an exponential function of time, the Weibull distributive curve.

Singh and Kankam [23] reported their effort of creating a database for reliability of transit vehicles and their components. Their research involved collecting failure data on 500 subway cars, 400 streetcars, and 1,100 buses from the Toronto Transit commission. The authors developed their initial database filled with 28 weeks worth of data. Analysis on the available data provided some profound conclusions including:

- Accounting for all defects, the *Mean Time Between Failures* of all vehicles was approximately 100 hours,
- Reliability analysis revealed an inverse relationship between production year and reliability of subway cars,
- Reliability analysis revealed a positive relationship between production year and reliability of transit buses, and

• The Miles Between Failure follow a Weibull distribution with shape parameter less than one.

2.2.3 Accelerated Aging and High Mileage Reliability

Accelerated life testing is a method of exposing the weak links of a design by imposing operating stresses that simulate a vehicle's actual service life in a fraction of the cumulative miles [24]. In the vehicle world, accelerated testing could take the form of durability track testing, laboratory testing on a dynamometer, utilizing a driving simulator, or hardware-in-the-loop testing. In any case, the goal of the testing is to expose and remedy vulnerable components in order to bring a more reliable product to market.

Horvath and Wasiloff [25] of Ford Motor Company studied the process for extrapolating test data from the manufacturing process to predict high mileage reliability of vehicles. Their study focused on ways to determine long term product reliability in the manufacturing or design stage of product of development, rather than relying on customers identifying critical design flaws via warranty claims or complaints. Horvath and Wasiloff [25] used the Ford process of testing each transmission "as manufactured and assembled" based on a subjectively established criteria that did not consider degradation over time. The majority of Ford's feedback on the field performance of the particular transmission systems was realized from warranty claims, which expired after a certain amount of time or mileage. There was no direct link between "end-of-the-line" (EOL) test data and high mileage reliability. The authors proposed a statistical process control (SPC) model that used EOL data and preliminary warranty claim information to determine customer satisfaction versus degradation over time. Once this relationship was understood, they proposed to develop a model to predict expected high mileage performance based on understanding the degradation over time of critical performance parameters measured at the EOL.

Capitano, Anderson, and Sverzhinsky [26] wrote about accelerated aging experiences of Siemens NAMO, a manufacturer of electric motors/drives. Siemens NAMO implemented an accelerated-aging test program (simulation) to reduce durability test time without drastically increasing overhead by purchasing expensive testing equipment. The testing protocol they designed established an aging factor for the particular environment a motor would operate in, and then developed accelerated test profiles that were no longer than one-tenth of the normal product life. Siemens NAMO developed a simulation that emulated environmental conditions which would be imposed on their motors. They modeled such properties such as:

- Mass rate of change per degree C per minute
- Number of thermal cycles
- Total hours of exposure to environment
- Temperature range

Based on these results, Siemens reduced their test times significantly; for example, a system whose designed life is 2,000 hours was able to be tested in less than 170 hours with accelerated aging simulations.

Heverly [24] researched a accelerated-based correlation method to relate transit bus service life events with similar events experienced at the Pennsylvania Transportation Institute (PTI) durability test track. Heverly equipped a bus with accelerometers to measure accelerations as the bus traversed various designed obstacles at the test track. The accelerations were used to classify the relationship between each pavement discontinuity and forces (accelerations) on the bus frame. Then, based on the expected service life of a bus tested at the track, a correlation equation was used to determine the number of times each proving ground element should be traversed during testing to represent the entire service life. The research also included driving a bus equipped with accelerometers around State College, Pennsylvania and categorizing pavement discontinuities in terms of accelerations observed on the track.

Fisher [27] expanded on Heverly's work [24] by using test track and transit service data to analytically determine "compressibility factors" for various vehicle components encountered by traversing pavement discontinuities. His work focused on determining a compressibility factor for air springs by measuring the vertical displacement of the suspension system and body due to pavement discontinuities. Once the displacements were known, Fisher used a cyclical stress chart, or S-N diagram, to determine the life of the spring for displacements measured on the track and from driving around State College, Pennsylvania. Klinikowski *et al.* [10] conducted a study on the correlation of data obtained at the transit bus testing program at the Pennsylvania Transportation Institute (PTI) with in-transit bus failures. They collected in-transit failure data from two different transit agencies for three different bus models, with ten buses worth of data for each model. The in-transit data was first broken into subsystem occurrences, and then was compared to data from PTI tests on the basis of number of failures. The two data sets were then compared with a rank correlation coefficient to determine how well the transit data compared to test track data. The data correlated with r=0.944 with a 99% confidence interval, which indicated that there was a very good correlation between in-service and test track failures.

2.2.4 Shortcomings in Literature

A majority of the research on vehicle reliability is concerned with warranty claims and their effect on company profits. There is not a substantial body of work concerned with predicting vehicle reliability from proving ground analysis or accelerated subsystem level testing to predict high mileage reliability. Further, it is difficult to find research dealing specifically with transit bus reliability. Most of the work published addresses reliability of the transit scheduling system, rather than the transit bus itself. This work aims to fill that void by investigating the failure rate of various subsystems in an effort to identify vehicle component replacements, and lead future researchers down the path of developing predictive failure models to prevent failures before they occur.



Data Collection Efforts

This chapter introduces the extensive data collection efforts undertaken to complete this study. Bus testing at Penn State has been been ongoing for over 20 years, ranging over 300 different models. Consequently, a significant body of reliability data is available for analysis. Furthermore, many bus models previously tested at PTI are currently in use at various transit agencies around the United States. These agencies often collect similar reliability data (nonscheduled maintenance occurrences) at their site. Hence, there is a valuable opportunity to compare the performance of a bus model tested at PTI with that of the same model under in-transit conditions at various transit agencies nationwide.

3.1 PTI Data

This section explains the data available at PTI, how it is categorized, and how it was classified for use in this study.

3.1.1 Available PTI Data

The Surface Transportation and Uniform Relocation Assistance Act (STURAA) of 1987 established a requirement that any new model buses be tested at a federal test cite prior to purchase with federal funds [9]. This law established the Altoona Bus Research and Test Center (ABRTC) where new bus models are tested for maintainability, structural integrity, reliability, fuel econ-
omy, safety, performance (acceleration and gradeability) and noise. The tests performed at PTI are accelerated by a 10 times acceleration factor, in that the total mileage driven at PTI will be no more than 1/10 the expected life of the bus. For example, a bus with a estimated useful life of 250,000 miles would be tested up to 25,000 miles at PTI under an accelerated testing regimen. However, the test results represent anywhere from 1/10 to 1/4 of the useful life of a particular bus [5].

The end product of bus testing is a report detailing the results of all the various tests performed at Penn State. Paper copies of the reports are available for purchase or can be downloaded for free from the ABRTC website. The website (Figure 3.1) allows users to query information based on a numerous criteria including: year tested, fuel type, number of axles, and manufacturer.

[1] General Information			
- Bus Number (range)	Any	(min) and Any	(max)
- Year Tested	Any	(min) and Any	(max)
- Manufacturer	Any		
- Model	Amy		V
- Fuel Type	Any		
[2] Bus Dimension			
- Length	15	(min) and 176	(max) f
[3] Body			
- Body Structural type	Amy		
- Frame Material	Any		
- Body Material	Any		
- Number of Seats	4	(min) and 2520	(max)
[4] Engine & Transmission			
- Engine Manufacturer	Any		
- Engine Model	Any		
- Transmission Manufacturer	Any		
- Transmission Type	Any		
- Control Type	Any		
- Axle Manufacturer (Front/Mid/Rear)	Ату		
- Axle Model (Front/Mid/Rear)	Any		

Figure 3.1. The ABRTC Bus Report Search Page [5].

3.1.2 PTI Data Classification

During durability testing, any occurrence that requires maintenance outside of the manufacturer's preventative maintenance schedule would be considered a reliability issue. These instances would be recorded in the final bus report as "nonscheduled maintenance" (Figure 3.2).

DΔTE	TEST MILES	SERVICE	ΔΟΤΙΛΙΤΑ		HOURS
09-13-05	108	The piston stud of the left rear air spring is broken.	Replaced left rear air spring.	320.00	0.50
09-20-05	1,145	The rear leveling valve is leaking at the exhaust port.	Replaced rear leveling valve.	1.00	1.00
09-20-05	1,145	All the brackets are broken on the side panels on the rear CNG tank cage.	Removed side panels.	1.00	1.00
09-21-05	1,382	The Speedo is not functioning properly.	Re-secured dash cluster.	3.00	1.00
09-29-05	1,953	Coolant is leaking and a brake line has chaffed on the spring clamp on the lower radiator hose.	Replaced and relocated brake line and tightened radiator clamp.	48.00	2.50
09-30-05	2,025	The dash board is loose.	Moved an aluminum angle from the inside to the outside of the dash.	8.00	2.00
10-03-05	2,149	The dash board is loose.	Added 4" of angle and $2 - \frac{1}{2} \times 3^{\circ}$ bolts.	8.00	2.00
10-27-05	2,365	The $\ensuremath{\mathcal{U}}^{\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!}$ plates have cracked on the CNG tank cage assembly.	Removed ¼" plates and installed 3/8" plates.	288.00	2.00
11-07-05	3,329	The right rear shock is leaking oil.	Replaced right rear shock.	0.50	0.50
11-10-05	3,806	The dash board is loose.	Repositioned dash and installed new	8.00	1.00
11-10-05	3,806	The wipers are inoperative.	Replaced failed circuit breaker.	1.00	1.00

(Page 1 of 3) UNSCHEDULED MAINTENANCE

Figure 3.2. A Sample Reliability Report [5].

The nonscheduled maintenance instances are logged by PTI test professionals. Each instance is recorded along with the corresponding test mileage, date, description of the failure, the action taken by PTI mechanics, and the downtime. Test professionals also categorize each failure as a Class 1, 2, 3, or 4 so transit agencies can judge the severity of the failures experienced during testing. The ABRTC defines the failure classification system as [5]:

- *Class 1 : Physical Safety* A failure that could lead directly to passenger or driver injury and represents a severe crash situation.
- Class 2 : Road Call A failure resulting in an enroute interruption of revenue service. Service is immediately discontinued until the bus is replaced or repaired at the point of

failure.

- Class 3 : Bus Change A failure that requires removal of the bus from service during its assignments. The bus is operable to a rendezvous point with a replacement bus.
- Class 4 : Bad Order A failure that does not require removal of the bus from serviced during its assignments but does degrade coach operation.

The four class failure classification system is advantageous in that it gives a snapshot of how a bus performed during testing. However, this system does not allow a direct comparison between bus models or models tested on different regimens since all buses are not tested for the same duration. Furthermore, this system contains no objective metric to rank all buses tested at PTI based on the results of reliability testing.

To normalize the results of the four class system, a cumulative score method was employed. The cumulative score (a dimensionless number) was calculated as:

$$CS = \sum_{i=1}^{4} \frac{C_i}{C_{(i.mean)}} \tag{3.1}$$

where C_i refers to the number of "Class i" failures per 1000 miles of PTI testing. The cumulative score, as defined, would produce a score of 4 for an average bus. A score of less than 4 would be achieved by a bus performing better than average. The cumulative score allows buses to be compared to each other without regard to the duration of their test, type of power plant, configuration of bus, or any other distinguishing characteristic. Most importantly, each of the 300+ buses tested at PTI can be objectively ranked from "best performing" to "worst performing" based on their cumulative score.

3.1.3 PTI Data Reclassification

This study focuses solely on two axle diesel fueled transit buses tested at PTI prior to the start of this project. One hundred and twenty-four such buses were tested. The ten best and worst performing buses were identified from the cumulative score ranking that was described in Section 3.1.2. Then, the National Transit Database (NTD) was consulted to identify transit agencies that operated these particular bus models [28].

The NTD is the FTA's primary database for transit industry statistics including financials, fleet composition, ridership, and other pertinent information [28]. The information is available free of charge on the organization's website. Any agency receiving federal funds to operate their fleet must report the required statistics yearly to the NTD.

Agencies submitting data to the NTD are required to categorize the failures that their fleet vehicles experienced during each operating year. The NTD requires agencies categorize failures based on the following criteria [28]:

- Major Failure: A failure of some mechanical element of the revenue vehicle that prevents the vehicle from completing a scheduled revenue trip or from starting the next scheduled revenue trip because actual movement is limited or because of safety concerns. Major failures include breakdowns of air equipment, brakes, engine cooling system, steering and front axle, rear axle and suspension and torque converters.
- Minor Failure: A failure of some mechanical element of the revenue vehicle that, because of local agency policy, prevents the revenue vehicle from completing a scheduled revenue trip or from starting the next scheduled revenue trip even though the vehicle is physically able to continue in revenue service. Examples of minor mechanical failures include breakdown of fare boxes, wheelchair lifts, heating, ventilation and air conditioning (HVAC) systems and other problems not included as a major mechanical systems failure.

The requirement of classifying data as major or minor for the NTD is obviously different than the Class 1-4 system employed at PTI. Furthermore, the published NTD statistics only supply the number of major or minor failures, and not a description of the failure. Thus, to compare in-transit and PTI reliability statistics, each prospective agency would have to be contacted and asked to provide descriptions for their nonscheduled maintenance. Furthermore, the PTI data would have to be reclassified to the major/minor system for direct comparison.

In response, each PTI test report was downloaded from the web server, the reliability section was printed, and each reliability entry was reclassified as a major or minor failure. The decision was made to reclassify every bus's data in addition to the best and worst performing buses that would be studied with the possibility that this study would be extended with additional funding. Thus, each failure from every bus ever tested at PTI was reclassified, which required over 7,500 individual line item changes.

3.2 In-Service Data

This section explains the process of obtaining in-transit data by selecting transit agencies to contact, reaching the appropriate person at the agency, and obtaining the desired data in order to begin analysis.

3.2.1 Agencies Contacted

Starting Monday, April 16, 2007, selected transit agencies were contacted in an effort to obtain reliability data from their maintenance departments. Agencies were chosen based on a variety of criteria including:

- Operating one of the best or worst performing models tested at PTI
- Agency size
- Agency location
- Suggestions from PTI staff

A total of fourteen agencies were contacted between April 2007 and December 2007 (Figure 3.3).

Each agency's contact information was obtained from the NTD. The process of obtaining each agency started with a phone call, usually to the general switch board. The operators were asked to put the call through to a maintenance or facility manager. Once in contact with a manager, the project was described in detail, as well as the request to obtain reliability data similar to what was submitted for the NTD. The manager would then put the call through to the individual(s) responsible for gathering reliability data and preparing the NTD statistics.

When the appropriate individual was reached, they were asked to fill out a web based survey. The survey was designed in HTML by the author of this thesis and published on a secure server with the help of the College of Engineering Network and Information Systems department. The



Figure 3.3. Summary of Contacted Agencies.

answers to the survey were stored in an Microsoft Access database on a College of Engineering server. The survey asked questions such as:

- Is the desired bus model still operated by your agency?
- What is the average speed/miles traveled/number of passengers for these buses?
- How are failures categorized?
- Is a description of each failure recorded?
- Is the data arranged in an exportable database?

The answers to these and other questions were critical in determining the course of action that would need to be taken in obtaining the appropriate data, and identifying if the agency could supply what was needed.

The process of contacting agencies seems quite trivial, but was extremely time consuming, difficult, and frustrating. First, many agencies were extremely unwilling to help during calls. Many times the initial call went well and it was mutually agreed that the agency could provide what was requested. However, more often than not, promised data was never sent, which led to lengthy sessions of "phone tag" or just having calls ignored. Some claimed they had no access to any such data, while others just ignored numerous attempts to contact them.

The data requested of each agency required three key components:

- A description of any non-scheduled maintenance performed on the bus
- An associated mileage
- An associated date (if available)

This information was necessary to determine the correlation with PTI data. The data sought was stored in many forms. Some agencies had their historical data on paper copies only, while others had just recently updated their maintenance software and, hence, only had a few years of data available. Others could provide years worth of data, while others could only provide individual work orders in raw format. This broad range of data format led to an extensive and exhausting data collection stage of the project.

The initial goal for the project was to obtain data from ten agencies from various locales throughout the continental United States. When the data collection stage of the project ended in December 2007, eight agencies had been able to supply data (Figure 3.4).



Figure 3.4. Summary of Agencies that Provided Data.

3.2.2 Obtained In-Service Data

The Port Authority of Allegheny County located in Pittsburgh, Pennsylvania was first contacted on April 16, 2007. The data collection information specialist was reached, who stated that the agency had an in-house designed data management system. Data was available from 2003 through present which, depending on the bus model being requested, encompassed 300,000+ miles. In less than one week, the Pittsburgh representative sent complete work order data for fifteen buses including both scheduled and nonscheduled maintenance, totaling over 8,000 line items.

The Manchester Transit Authority located in Manchester, New Hampshire was first contacted on April 16, 2007. The transit manager was reached and confirmed that his agency could provide data to help with the study. The data was available on a system that could not export to be emailed, but spreadsheets could be printed and mailed for manual entry into the Penn State database. The data was available from approximately 0 through 350,000 miles. After eight additional phone calls, the agency sent out data for three buses which arrived in early September 2007, totaling over 1,000 line items.

Space Coast Area Transit of Cocoa Beach, Florida was first contacted on April 16, 2007. After four phone calls and a variety of phone conversations, the Manager of Planning, responsible for gathering and submitting the NTD statistics, was reached. The data at Space Coast was printed from a non-exportable database, and mailed to Penn State. After another four phone calls, data for three buses from approximately 30,000 through 300,000 miles was sent and arrived in late July 2007. Over 1,000 line items were reported.

Delaware Transit Corporation of Dover, Delaware was first contacted on April 16, 2007. After three phone calls, the Operations Control Manager was reached. He stated that Delaware Transit could provide data in Microsoft Excel format. The data was available from approximately 0 through 100,000 miles. After two additional phone calls, data for three buses was received in early July 2007 totaling over 500 line items.

The City of Greeley Transit Services of Greeley, Colorado was first contacted on April 17, 2007. After six unsuccessful phone calls to the maintenance manager over three months, the Transit Superintendent was reached. He contacted the maintenance manager and requested that Penn State receive the data it requested. The data was only able to be sent as a Microsoft Word

document of work orders, where each page of the document was one work order. After four additional phone calls, data was received for four buses via email in late October 2007 encompassing approximately 50,000 through 250,000 miles. The data originally received encompassed both scheduled and nonscheduled work performed on the buses, totaling over 6,500 line items.

The Metropolitan Transit Authority of Nashville, Tennessee was first contacted on April 16, 2007. After nine phone calls over four months, the Planning Manager was reached, who agreed to help obtain the desired data. He stated that the Maintenance Manager and Information Technology Manager could gather the data and send it via email in text format. After seven additional phone calls, the data was received in mid December 2007 for nine buses for approximately 0 through 115,000 miles and totaling over 2,250 line items.

Long Beach Transit Authority of Long Beach, California was first contacted on August 30, 2007. After five phone calls, the Maintenance Manager agreed to send data in Microsoft Excel format via email. After four additional phone calls, data was received in early December 2007 for three buses. The data spanned approximately 280,000 through 450,000 miles and totaled over 1,100 line items.

Harford County Transportation Services of Abingdon, Maryland was first contacted on April 16, 2007. The first phone call was quite promising, in that the transit administrator was reached, and he agreed to gather what data we would need and prepare to send it via email. However, ten phone calls and five months later, the same administrator said that the data could not be emailed because it was in paper format, and that no one had worked on gathering it. On November 13, 2007, an on-site visit was made to the transit agency to manually enter the reliability data. Data was collected for six buses from approximately 80,000 through 200,000 miles. It appeared that the work orders available at the site were not complete, but it was all that was available. The work orders totaled over 500 line items.

There were seven agencies that were contacted who did not provide data.

- King County Department of Transportation in Seattle, Washington claimed they did not operate the bus model that was requested.
- Pace Suburban Bus Division of Arlington Heights, Illinois stated that their data system was too antiquated to gather any usable information.

- Hillsborough Area Regional Transit Authority declined to participate in the study citing they did not have the resources to collect any data, nor could they support an on-site visit.
- Niagra Frontier Transportation Authority of Buffalo, New York gave no response to multiple inquiries.
- The Regional Transportation Commission of Southern Nevada in Las Vegas, Nevada stated that their maintenance information was kept by a subcontracted maintenance company. Subsequent attempts to contact the maintenance subcontractor were unanswered.
- Metropolitan Transit Authority of Harris County in Houston, Texas was contacted numerous times and data was promised two times. However subsequent attempts to contact the agency were left unanswered and no data was ever received.
- Santa Fe Transit of Santa Fe New Mexico did not respond to any contact attempts.

In all, reliability data was obtained from eight agencies for forty six buses. Other pertinent statistics include:

Table 3.1. In-Transit Data Collect	ion Statistics
Agencies Contacted	15
Agencies Providing Data	8
Bus Models Represented	7
Buses Collected	46
Phone Calls Made	117
Line Item Reliability Instances	$\approx 21,000$

The obtained data now had to be processed and categorized with the major or minor failure distinction.



Preprocessing and Data

Classification

This chapter discusses the required preprocessing of the obtained transit agency data into a standardized Microsoft Excel template. The data, received in paper, electronic spreadsheet, or electronic work-order format, was entered into a Microsoft Excel database. Once entered, each item was classified as a major or minor failure in accordance with NTD definitions and specifications unique to this study.

4.1 Major and Minor Failure Distinction

This section defines the distinction between major and minor failures, an issue which must be clear both for readers of this thesis and those future researchers who will reference this work. The NTD's definitions distinguishing between the two classifications were presented in Section 3.1.3. Specifically, a major failure was defined as one that would cause the bus to diverge from its route, schedule, or that would endanger the welfare and/or safety of the passengers. However, a more stringent approach was taken when categorizing data for this work. **Any** repair corresponding to a **critical system** of the bus was classified as a major failure. This keeps the classification process focused on the easier task of determining which system exhibited a failure rather than how it failed and to what degree. This method eliminates any "judgement calls" that might arise in future reclassifications.

For instance, consider brake failures. According to the NTD's definitions, slack brakes or brake replacements would not be considered a major failure because these items could be replaced at the bus's next scheduled preventative maintenance (PM). However, for the purposes of this study, any failure relating to the brakes was classified as a major failure, as well as any other component directly on the drivetrain. Other systems that automatically received a "major failure" classification include:

- Transmission and components
- Suspension and components
- Vehicle frame
- Steering and components
- Any safety equipment

Examples of failures that were classified as major include:

- Turbo replacement
- Engine overheating or radiator issues
- No start/starter issues/glow plug replacements
- Wheelchair lift issues

Conversely, a minor failure was determined to be an issue that allows the bus to maintain its schedule, but requires repair at the next available opportunity. Minor failures may cause the passenger slight discomfort, but would not endanger the safety or wellbeing of a patron. It was recognized that some minor failures could endanger the passenger in extreme cases. For example, all heating and air conditioning failures were classified as minor failures. However, if a transit bus operating in Alaska loses heat on a rural route, the results could very well endanger patrons. This extreme case is obviously an outlier which was ignored to ease classification for this and future studies. The focus on classification was placed on what failed, not how or to what degree. Examples of minor failures encountered in data classification include:

- Heating/Air Conditioning issues
- Lamps in need of replacement
- Torn seats/ damaged passenger compartment
- Windshield wipers
- Farebox repairs

By following these guidelines, future researchers will be able to classify new data sets without having to reclassify any of the data included in this research.

4.2 In-Service Data

The reliability data sent by transit agencies was made available in a variety of forms. As stated in Section 3.2.2, three agencies sent data via electronic spreadsheet, three sent paper copies that required manual entry into the Penn State database, and one sent electronic work orders.

4.2.1 Pittsburgh Data

The Port Authority of Allegheny County in Pittsburgh, Pennsylvania emailed data in a Microsoft Excel spreadsheet with each of the fifteen buses data occupying a separate worksheet. The data was queried through Pittsburgh's internally developed maintenance software, and exported to Excel. There was, however, a problem with the format of this data: the mileage accompanying each maintenance instance was surrounded by text in the cell (Figure 4.1). The mileage needs to exist in as numerical value in its own cell, so the data could be plotted as a function of mileage.

The College of Engineering Network and Information Systems Department aided in sorting this data by compiling a Visual Basic macro used to extract the mileage and failure description data, and place it in new Excel spreadsheet. The macro was run for each of the fifteen buses, and the results were saved in fifteen separate files. Then, each instance was categorized as a major

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		1. Approved on 3/27/2007 5:13:40 AM at 304651 miles (Triggered on 2/3/2007 9:50:10 AM at 300839 miles)		1. Spring Schedule Fleet 16
55				
56	279857	Closed: 3/26/2007 6:35:07 AM	Rev Vehicle Maint-Collier	Condition Report
		1. Approved on 3/25/2007 7:13:48 PM at 304521 miles		1. Suspension:Ride Height or Leaning
57		(Triggered on 3/25/2007 7:12:28 PM at 304521 miles) Mileage		Failure Description
58	278052	Closed: 3/26/2007 6:35:07 AM	Rev Vehicle Maint-Collier	Corrective
		1. Approved on 3/24/2007 5:22:29 AM at 304394 miles (Triggered on 3/16/2007 11:20:06 AM at 304326 miles)		T. Bus Exterior Body:Body Skin/Fiberglass Repairs:Repair
59				
60	279058	Closed: 3/21/2007 6:19:40 AM	Rev Vehicle Maint-Collier	Wheelchair
		1. Approved on 3/21/2007 5:35:13 AM at 304326 miles		1. Ramp Fleet 16
		(Triggered on 3/21/2007 5:35:13 AM at 304326 miles)		
61				
62	276392	Closed: 3/9/2007 6:47:40 AM	Rev Vehicle Maint-Collier	Condition Report
		1. Approved on 3/8/2007 1:29:34 PM at 303211 miles (Triggered on 3/8/2007 1:28:48 PM at 303211 miles)		1. Suspension:Sway

Figure 4.1. Pittsburgh Data - Original Format.

or minor failure. The spreadsheet was also configured to calculate the number of cumulative, major, and minor failures throughout the duration of the available data (Figure 4.2).

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3	216210	1. Misc Items: Horn		1	1	0	1
4	216526	1. Bus Engine:Controls:Repair	1		2	1	1
5	217584	1. Brakes:Grab	1		3	2	1
6	220128	1. Misc Items:Radio/ P.A. System		1	4	2	2
7	222430	1. Bus Exterior Body:Frame:Repair	1		5	3	2
8	225982	1. Brakes:Slack Brakes	1		6	4	2
9	226955	1. Lights:Head Light		1	7	4	3
10	227479	1. Transmission:Rough Shift	1		8	5	3
11	228594	1. Bus Transmission: Assembly: Replace	1		9	6	3
12	229310	1. Suspension:Kneeler	1		10	7	3
13	229795	1. REPLACE UPPER RADIATOR HO	1		11	8	3
14	229795	1. Body:Driver's Seat/Belt		1	12	8	4
15	229795	2. Brakes:Slack Brakes	1		13	9	4
16	231665	1. Lights:Interior		1	14	9	5
17	231987	1. Brakes:Slack Brakes	1		15	10	5
18	232977	1. Brakes:Slack Brakes	1		16	11	5
19	233151	1. Lights:Head Light		1	17	11	6
20	234291	1. Heat - A/C:Defrosters		1	18	11	7
21	234291	1. Brakes:Pulls Right/Left	1		19	12	7
22	236321	1. Lights:4 Way/Turn Signal		1	20	12	8
23	238826	1. Bus Air System: Air Compressor: Repair	1		21	13	8
24	239455	1. Engine:Won't Start	1		22	14	8

Figure 4.2. Pittsburgh Data - Sorted and Categorized.

4.2.2 Manchester Data

The Manchester Transit Authority in Manchester, New Hampshire provided data (Figure 4.3) as a printout of their maintenance database. They could not export directly to Excel, nor could they export to a text program because their database was quite antiquated. The system was queried, and the results were printed for three buses. The paper copies included all the relevant information that was required for this project. Thus, upon arrival the information was manually entered into the Penn State database in the exact same template shown in Figure 4.2. The failure instances were then categorized as major or minor.



Figure 4.3. Manchester Data - Original Format.

4.2.3 Cocoa Beach Data

Space Coast Area Transit of Cocoa Beach, Florida provided data (Figure 4.4) as a printout of their maintenance database. They, like Manchester, could not export from their software to an Excel or text program because of both the age and configuration of their software. Their system was queried, and the results were printed for three buses. The information had to be manually entered and categorized in the Penn State database as previously described.

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Figure 4.4. Cocoa Beach Data - Original Format.

4.2.4 Dover Data

Delaware Transit Corporation of Dover, Delaware was able to query their maintenance software and export the required information to Excel. They were able to provide mileage, date, failure descriptions for three buses (Figure 4.5). The original data was arranged to be compatible with the Penn State template that was perviously developed, and categorized as major or minor.

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3							
4	614	0	0	20-Jan-00	R	2647	RESPOND AUX HEATER MOTOR
5	614	10385	0	22-Feb-00	R	45/3	RESPOND FAREBOX
6	614	10511	0	24-Feb-00	R	4738	RESPOND FAREBOX
7	614	13631	0	3-May-00	R	8308	RESPOND WHEELCHAIR LIFT/RA
8	614	13849	0	26-May-00	R	9493	RESPOND DOOR PAX
9	614	13900	0	7-Jun-00	R	10074	RESPOND W/C LIFT
10	614	14199	0	12-Jun-00	R	10244	RESPOND DOOR PAX
11	614	15585	0	29-Jun-00	R	11141	RESPOND DOOR PAX
12	614	18140	0	31-Jul-00	R	12570	RESPOND DOOR PAX
13	614	19521	0	14-Aug-00	R	13342	RESPOND FAN BELT
14	614	20452	0	23-Aug-00	R	13768	RESPOND TIRE FR LT
15	614	20564	0	28-Aug-00	R	13955	RESPOND WHEELCHAIR LIFT/RA
16	614	23549	0	9-Oct-00	R	16004	RESPOND HEATING
17	614	23887	0	10-Oct-00	R	16098	RESPOND BRAKING
18	614	24283	0	16-Oct-00	R	16294	RESPOND ALTERNATOR
19	614	24663	0	30-Oct-00	R	16599	RESPOND INST/WRNG
20	614	27282	0	16-Dec-00	R	17999	RESPOND ANTILOCK BRAKE SYS
21	614	29019	0	15-Mar-01	R	23925	RESPOND W/S WIPER BLADE
22	614	30252	0	2-Apr-01	R	24791	RESPOND RADIO
23	614	30932	0	13-Apr-01	R	25411	RESPOND FAREBOX SYSTEM
24	614	38375	0	29-Aug-01	R	31929	RESPOND FAREBOX

Figure 4.5. Dover Data - Original Format.

4.2.5 Greeley Data

The City of Greeley Transit Services of Greeley, Colorado emailed a complete list of work orders in Microsoft Word format. The data was queried through Greeley's maintenance software. The software did not allow a particular mileage or work order description to be exported to a text or database file. The software did allow each work order to be sent to Microsoft Word while retaining its formatting, so the document could be read as if it was still in the Greeley system (Figure 4.6). Thus, all available work orders were sent for four buses in this configuration.

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Figure 4.6. Greeley Data - Original Format.

The Greeley data presented a similar problem to Pittsburgh, in that the data had to be purged with a Visual Basic macro to extract the pertinent information and place it into a spreadsheet. The College of Engineering Network and Information Systems Department was again consulted to aid in sorting this data by modifying the existing a Visual Basic macro used to extract the mileage and failure descriptions from the Pittsburgh data, and place then in new Excel spreadsheet. Once in the spreadsheet, each instance was categorized as major or minor through the duration of the available data as previously described.

4.2.6 Nashville Data

The Metropolitan Transit Authority of Nashville, Tennessee was able to provide data for nine buses. Their maintenance software allowed the technicians to query based on bus model, and sorted all results according to vehicle subsystem. The search results, however, were sent to Penn State as a text file that could not be read into Excel and maintain the existing formatting because it was not constant throughout the document (Figure 4.7).

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001-000-000	08232004 020664	8 491780	215445 A	IR CONDITIO	N, HEAT	59.88	43.00	102.88	2.00 LP	XX	11	13
001-000-000	08132004 020610	9 490140	213810 A	IR CONDITIO	N, HEAT	257.26	64.50	321.76	3.00 LP	XX	4	13
001-000-000	08092004 020597	2 489560	213225 A	IR CONDITIO	N, HEAT	0.00	58.75	58.75	2.50 DBB	XX	11	13
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001-000-000	03032002 016339	2 376230	99892 A	IR CONDITIO	N, HEAT	0.00	86.00	86.00	4.00 MP	XX	11	13
001-000-000	01072002 016068	7 366530	90194 A	IR CONDITIO	N, HEAT	40.70	73.50	114.20	5.00 ROACH	XX	11	13
001-000-000	01072002 015990	0 366530	0 A	IR CONDITIO	N, HEAT	0.00	0.00	0.00	0.00	XX	11	1
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001-000-000	12192001 015971	7 363930	87600 A	IR CONDITIO	N, HEAT	138.57	58.80	197.37	4.00 ROACH	XX	4	X
001-000-000	10282001 015/28	9 35/350	81016 A	IR CONDITIO	N, HEAT	0.00	17.20	17.20	0.80 MP	XX	11	1
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Figure 4.7. Nashville Data - Original Format.

The files were read into excel in text delimited format. The files were manually manipulated to arrange the mileage and failure description in the appropriate manner. The failures were then categorized as major or minor for the duration of the available data.

4.2.7 Long Beach Data

Long Beach Transit Authority of Long Beach, California was able to query their maintenance software and export the required information to Excel (Figure 4.8). They were able to provide date, mileage, and failure descriptions for three buses. The original data was arranged to be compatible with the Penn State template that was perviously developed, and categorized as major or minor.

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A	B	C	D	E	F	G
1 Bus #	Work Order short description	Miles	Date			
2 9419	ENG DIED	317497	1/2/02			
3 9419	CK ENG. LIGHT.	317682	1/3/02			
4 9419	CHIME GOT A SHORT.	317709	1/4/02			
5 9419	FAREBOX BILL MODULE IS B/O	317709	1/4/02			
6 9419	REAR DOOR WORK INTERMITTENTLY.	317709	1/4/02			
7 9419	TAIL LIGHT OUT	317709	1/4/02			
8 9419	HEADSIGN B/O	317932	1/6/02			
9 9419	CK BUMPER FOR DAMAGE	318678	1/10/02			
10 9419	MISCOUNTS	318678	1/10/02			
11 9419	OVER HEATING	318799	1/11/02			
12 9419	HEADSIGN B/O	319118	1/14/02			
13 9419	PULLS LEFT	319118	1/14/02			
14 9419	HEADSIGN B/O	319305	1/16/02			
15 9419	DRIVER SEAT BACK SUPPORT AIR LEAK.	319678	1/18/02			
16 9419	REAR DOORS STICKING.	320058	1/21/02			
17 9419	LEFT HEAD LIGHT OUT	320244	1/22/02			
18 9419	COIN SLOT MISCOUNT	320618	1/24/02			
19 9419	COIN MISCOUNTS	321032	1/26/02			
20 9419	DOME LIGHT OUT	321032	1/26/02			
21 9419	HORN OUT N RITE HAND SIDE CHIME STUCK.	321118	1/27/02			
22 9419	GRAFFITI ON REAR WINDOWS.	321491	1/29/02			
23 9419	PHONE MISSING.	321491	1/29/02			
24 9419	RT. W/C SEAT BROKEN	321678	1/31/02			
25 9419	REAR WINDOW B/O	321690	2/5/02			
26 9419	REASSEMBLE RIGHT FRONT WHEELCHAIR SEATS.	321690	2/5/02			
27 9419	FAREBOX MISCOUNTS	322250	2/8/02			
28 9419	INSTALL JOHNSON MATTHEY CRT EXHAUST TRAP	322250	2/8/02			
29 9419	NO PA. BAD MICRO.	322853	2/12/02			
30 9419	COINS JAM ON TOP OF COIN MODULE.	323040	2/13/02			
31 9419	CK DEST.	323465	2/16/02			
			0.00.00			

Figure 4.8. Long Beach Data - Original Format.

4.2.8 Abingdon Data

Harford County Transportation Services of Abingdon, Maryland was not able to provide an electronic or physical copy of their maintenance data for the required bus model. The transit administrator made the invitation for an on site visit during November of 2007, which was respectfully accepted. The agency maintained numerous folders containing the work orders for each of their buses. The format of the work orders was very similar to the Greeley data (Figure 4.6). The work orders were manually entered into the Penn State database by locating the mileage and failure description on the document; the failure instances were also categorized as major or minor.

At this point in the project, all of the received data had been reclassified, and a quantitative comparison between PTI and transit data was now able to be investigated. Chapter 5

PTI vs Transit Agency Comparison

This chapter provides an overview of the comparison made between PTI and transit data. The first section presents an analysis of in-transit data failure trends observed in the received data. The following section details initial comparisons made between the PTI and in-transit data sets.

5.1 Analysis of In-Transit Data Failure Trends

After the in-transit and PTI data were reclassified into major and minor failures, a comparison could be investigated. First, the cumulative, cumulative major, and cumulative minor failures of buses at each individual transit agency were plotted against the same bus operating at the same transit agency to determine consistency in the relationships.

Consider the Delaware Transit, Space Coast Area Transit, and Manchester transit agencies. Delaware provided data for three buses of Model X, Cocoa Beach provided data for three buses of Model Y, and Manchester provided data for three buses of Model Z. By plotting the cumulative types of failures for each agency, the buses were compared against each other to determine if any one bus was failing at a greater or lesser rate than the others. This validation was significant because it confirmed that buses at the same agency generally failed at the same rate, and thus bus-to-bus variations within an agency would not skew later analysis. In essence, these plots identified "lemon" buses operating at the agency, and allowed for their exclusion from future analysis.

It is evident in Figure 5.4 that each Delaware bus follows the same general failure trend in cumulative, cumulative major, and cumulative minor designation. The data from Manchester (Figure 5.3) provides similar results. However, the data from Cocoa Beach (Figure 5.2) shows that bus number 9409 clearly has a greater failure rate when compared to the other buses at the agency. This bus was eliminated from any subsequent analysis of the Cocoa Beach data. This same procedure was conducted on all data obtained from each of the eight participating agencies in order to eliminate any potential outliers.



Figure 5.1. Delaware Transit Authority.





(c) Minor failures





Figure 5.3. Manchester Transit Authority.

5.2 Initial Comparison of In-Transit to PTI

Once the failure rates from each agency were verified, the data was compared to PTI-measured failure rates in the same buses. There were many variables between data sets that could be compared, particularly the number of failures, mean distance between failures, and the breakdown of major components. The first comparison made was between the cumulative number of failures.

In order to compare the cumulative number of failures, the appropriate range of transit data had to be selected to correspond with that of PTI. Recall, PTI testing begins with a production ready bus model at **0 miles** and continues for a duration determined by the useful life of the bus. Also, recall from Section 3.1.1 that tests performed at PTI are accelerated by a 10 times acceleration factor [5]. Thus, PTI mileage data was adjusted by a multiple of 10 to account for the 1/10 compressibility factor for accelerated testing. For instance, the failure data for a bus tested for 15,000 miles at PTI would be compared with 150,000 miles of transit agency data over a range beginning as close to zero miles as possible.

To illustrate how this acceleration ratio impacts data analysis, consider the plots comparing major failures incurred at PTI versus in-transit usage (Figure 5.4).

Figure 5.4. Delaware Major Failures - Scaled vs Unscaled.

After the PTI data mileage is multiplied by a factor of 10 to account for the acceleration factor, the trend matches much better in both slope and duration.

Consider again Delaware, Cocoa Beach and Manchester data compared to the respective models operated at PTI. It is quite unclear from Figure 5.5 whether any relationship exists between PTI and in-service obtained data. However, one crucial piece of information had been neglected in preparing these plots: The PTI durability test regimen consists of the bus being

(c) Manchester vs PTI

Figure 5.5. In-Transit vs. PTI Cumulative Failure Comparison.

operated on the durability track to accelerate the life of critical components such as suspension, chassis, and drivetrain (Section 1.2.2). PTI testing does not account for many usage issues that would typically cause minor failures to occur during in-transit service.

Minor failures typically occur due to excessive use of non-critical components, moderate aging (weathering effects), and in-use conditions such as fair-boxes, lifts, windows, etc. PTI's test procedures do not test in-use conditions related to these non-critical components, and thus PTI testing would underestimate the total number of minor failures. For instance, window failures that would happen in the field would not happen at PTI because the window simply wouldn't be opened a representative number of times. Furthermore, fare boxes, which would be used by every passenger on a transit bus, are not tested at PTI. Other non-critical component failures commonly found throughout in-service data include:

- Door usage
- Torn seats/ damaged passenger compartment
- Vandalism

- Bike rack repairs
- etc.

The minor failures occurring during in-service use are not reflected in the PTI data because these components are unused. If PTI and in-transit data sets are compared directly, the cumulative number of failures for the in-transit buses would contain many minor failures that would not be represented in test results from PTI. Thus, cumulative failures and cumulative minor failures were not considered a variable that could determine a relationship between the two sets.

Major failures, on the other hand, are experienced both on the track and at the agencies. All of a buses major subsystems are tested at PTI. Similarly, all of the major subsystems of the bus are utilized during in-transit service, so a comparison of cumulative major failures was the next logical step. Consider Figure 5.6:

(c) Manchester vs PTI

Figure 5.6. In-Transit vs. PTI Major Failure Comparison.

The Delaware major failure comparison matched quite well with PTI. Figure 5.6(a) illustrates that Delaware tracked well in both rate of failure occurrence and total number of major failures. However, Cocoa Beach (Figure 5.6(b)) and Manchester (Figure 5.6(c)) did not match as well.

The goodness of fit showcased by the Delaware data (Figure 5.6(a)) actually appeared "too

good." One would expect there to be a positive correlation in failure trend, or a similar match in the number of major failures experienced. However, the trend was nearly identical between PTI and Delaware, and the number of major failures was almost identical as well. Further, Manchester and Cocoa Beach failed to produce any strong correlation similar to Delaware. It was quite obvious that comparing major failures or major failure trends might not provide the evidence necessary to make any definite conclusions about the two data sets. The next step was a more thorough examination of the failure rate.

Chapter 6

Examining the Failure Rate

The preliminary results of data set comparisons presented in Chapter 5 requires a more thorough investigation of the failure rate as a means of discerning a relationship between PTI and transit agencies. This chapter examines the failure rate on both cumulative and subsystem levels. The first section looks at three separate methods used to calculate the failure rate of cumulative failures identified in the transit data including a *sliding window* algorithm to produce a moving average approximation to a derivative, a polynomial fit, and a filtered numerical derivative. Upon plotting the cumulative failure rate, the data exhibited a "resetting bathtub curve" effect, which would imply multiple component replacements. The following section examines the relationship between repeated peaks in the cumulative failure rate, and replacement of major vehicle components. The final section details the reclassification of all data at a subsystem level, and subsequent development of subsystem failure rate plots to better illustrate effects that major subsystem replacements had on the cumulative failure rate of the bus.

6.1 Cumulative Failure Rate Analysis

This section describes the methods investigated to calculate the failure rate and the results obtained from the analysis.

6.1.1 Calculating the Failure Rate

As described in Section 2.1.1, the failure rate of a system describes the frequency in which failures occur, e.g. the number of failures per unit time. In this study, the failure rate is defined as the number of failures per unit distance traveled during testing or service. In essence, the failure rate of any bus is defined as the derivative with respect to distance of the cumulative failures.

The cumulative failure data consisted of a discrete set of data points, inhibiting the calculation of the exact derivative. Numerical differentiation deals with this type of data; it is a process by which approximate derivatives are obtained from a set of discrete data points. The approximate derivative can be calculated by numerous methods, three of which are considered here:

- The discrete data can be plotted and fit with a polynomial curve. The approximate derivative can then be calculated by taking the derivative of the function that describes the curve fit.
- The discrete data can be differentiated by developing a *sliding window* of fixed interval width, summing the number of failures in the fixed interval, and repeating this process as the window is slid throughout the entire range of the data.
- The derivative can be obtained by calculating numerically with the Euler approximate derivative by calculating the failures per mile throughout the duration of the data.

The sliding window method (Figure 6.1) used intervals of fixed width w, where width was a fixed unit distance. The width chosen for this study was arbitrarily assigned as 10,000 miles. The total number of failures in the window, N, were summed. The window was then slid d units (e.g. 100 miles) and another value of N was calculated and appropriately located at the midpoint of the window in its new location. The window was repeatedly slid d units until an approximate derivative of all m miles of data had been calculated. Thus, the failure rate obtained from a sliding window approximation would be on the order of failures per 10,000 miles.

Figure 6.1. The Sliding Window Method.

A second method of determining the failure rate involves fitting the cumulative number of failures versus miles with an n^{th} degree polynomial function, and taking its derivative with respect to mileage. However, the fit was nothing more than what its name implies: *a fit*. This approach does not capture sudden changes in slope that can provide additional insight of the failure rate; it only approximates the general trend of the data. The sliding window, on the other hand, captures those local variations in the data because of the method of derivative calculation. When the two methods are compared for an arbitrary data set (a Delaware bus), the increased detail of the sliding window approach is clearly evident (Figure 6.2).

The final method of determining the failure rate involves calculating derivative using Euler's method. This method gives a failure per mile that is calculated with each failure instance, rather than a window of 10,000 miles or a polynomial fit. Euler's method for calculating the derivative of a set of data is a numeric approximation. The derivative is calculated as:

$$Failure.Rate(i) = \frac{\triangle Y}{\triangle X} = \frac{failures(i+1) - failures(i)}{miles(i+1) - miles(i)}$$
(6.1)

At this point, the derivative is filtered to smooth the curves with a Butterworth filter designed using Matlab's "butter" command. The butter command designs an N^{th} order low pass digital filter, with cutoff frequency ω , where $0 < \omega < 1.0$, with 1.0 corresponding to half the sampling

Figure 6.2. Comparison of the Polynomial Fit and Sliding Window Derivative Methods.

rate ([29]). The cutoff frequency employed in this work was arbitrarily chosen as 0.3 after running the algorithm for various other values with minimal change. Further, the derivative is filtered again to reduce the effects outliers have on the data by eliminating any derivative value such that:

$$[failure.rate(i) - mean(failure.rate)] > standard.deviation(failure.rate)$$
(6.2)

Graphically, the numerical and sliding window failure rates are plotted as Figure 6.3.

Figure 6.3. Filtered Numerical and Sliding Window Derivative Comparison.

6.1.2 Cumulative Failure Derivatives

After comparing the various measurement methods, it was determined that the sliding window approach of differentiation was preferred because of the level of precision it reflected. The goal in calculating the derivative is to compare the failure rates of PTI and transit data to determine if the PTI buses fail at a rate approximately 10x greater than transit data (due to the ten times accelerated testing factor).

Recall Section 2.1.1: when the failure rate is plotted versus time (or mileage in this case), it generally exhibits a bathtub shape, and thus is referred to as the *bathtub curve* (Figure 2.1). The bathtub curve graphically illustrates typical trends that occur during the life cycle of a product, including wear-in, useful life, and wear-out. A vehicle is no exception, as it does not boast an infinite life. However, a vehicle falls in the category of a repairable system where components that fail can be replaced to extend the overall useful life of the entire system. Consider the failure rate plot of Pittsburgh bus number 5002 (Figure 6.4):

Figure 6.4 exhibits what seems to be multiple wear-in/wear-out cycles. The failure rate appears to increase, peak quite dramatically, and subsequently drops off only to have the trend repeat itself multiple times. This type of behavior would be exhibited in a repairable system during its useful life. To verify this phenomena was not unique to this particular bus, the failure

Figure 6.4. Pittsburgh Bus 5002 - Failure Rate.

rate was plotted for numerous buses. The same results were observed again and again.

Figure 6.5. Selected Pittsburgh Failure Rate Plots.

Figure 6.6. Additional Transit Agency Failure Rate Plots.

The trend of the failure rate to increase, peak, and decrease multiple times was confirmed to exist in multiple buses from multiple agencies, thus suggesting that these trends are not an anomaly in the data. The next logical step in this failure rate analysis was to examine the cause of this failure rate behavior. Theoretically, the wear-in period occurs during the beginning of a product's life cycle and is characterized by an (initially) very high failure rate coupled with a rapid decrease towards the useful life of the product. Following the useful life, the wear-out period occurs, which is characterized by an initially low failure rate coupled which grows substantially over a short period of time.

The trends in Figure 6.4, Figure 6.5, and Figure 6.6 exhibit a repeated bathtub curve, with multiple wear-in/wear-out cycles. Multiple bathtub curves exhibited by a single system reflect component replacements that contribute to the cumulative failure count of the system. In order to determine if the repeated peaks are in fact repeated birth/death cycles, the associated mileage is inspected in the work order data to locate any major component replacements.

6.1.3 Analysis of Failure Rate Peaks

The repeated peaks observed in the failure rate were examined to determine if they corresponded with any major component replacements. If this relationship is verified, then the peaks may be considered as repeated bathtub effects, and not an anomaly in the data. Consider Figures 6.7 through 6.14 and the corresponding replacements discovered in the received data. It was quite clear that many of the peaks in failure rate corresponded with a major component replacement. The next step in this analysis is to determine how subsystem failure rates match up with the peaks exhibited in these figures.

Figure 6.7. Pittsburgh Bus 5001 - Component Replacements.

Mileage	Description
228,594	Replace Generator
283,816	Replace Transmission
313,566	Replace Engine Assembly
339,122	Repair Transmission

 Table 6.1. Pittsburgh 5001 Component Replacements

Figure 6.8. Pittsburgh Bus 5003 - Component Replacements.

Mileage	Description
250,272	Replace Suspension
281,512	Replace Engine/Turbo
308,200	Replace Generator/Engine Component
347,398	Replace Water Pump
371,246	Replace Air System Controls

 Table 6.2. Pittsburgh 5003 Component Replacements


Figure 6.9. Pittsburgh Bus 5086 - Component Replacements.

Table 6	.3. Pittsburg	gh 5086 Component Repl	acements
	Mileage	Description	
	207,145	Replace Shocks	
	237,316	Replace Differential	
	240,764	Replace Engine	

Figure 6.10. Pittsburgh Bus5087 - Component Replacements.

Mileage	Description
233,021	Replace Brake Controls
$266,\!638$	Replace Generator/Shocks
279,093	Replace Turbo

 Table 6.4. Pittsburgh 5087 Component Replacements



Figure 6.11. Long Beach 9410 - Component Replacements.

Table 6.5. Long Beach 9410 Component	t Replacements	;
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Mileage	Description
292,000	Engine Issues (No Description of Action Taken)
309,350	Transmission Won't Go Into Gear
337,097	No Start (No Description of Action Taken)
361,516	Engine Tune-Up



Figure 6.12. Long Beach 9414 - Component Replacements.

Mileage	Description
261,718	Repair/Replace Generator
333,658	Replace R/F Leveling Valves
350,320	Multiple Engine Shutdowns (No Description of Action)
355,616	Transmission Slips/Slams (No Description of Action)
382,026	Overheating Engine Repairs (No Description of Action)

 Table 6.6.
 Long Beach 9414 Component Replacements





 Table 6.7.
 Long Beach 9419 Component Replacements

Mileage	Description
384,184	New Transmission
393,328	Rebuild Differential
465,158	No Start (No Description of Action Taken)



Figure 6.14. Delaware Transit 613 - Component Replacements.

 Table 6.8. Delaware Transit 613 Component Replacements

Mileage	Description					
42,260	Replace Engine Assembly					

The figures presented in this section illustrate the notion that peaks in the cumulative failure rate can be attributed to major component replacement/repairs. There were instances, however, where peaks existed that could not be attributed to any major repair. Thus, the next step was to compare the sliding window results with the Euler derivative to determine if some of the peaks exhibited in the cumulative failure rate actually existed, or if they could be attributed to bad data.

Plotting the filtered numerical derivative and sliding window derivative on the same plot gave insight into the validity of the peaks generated by the sliding window approach. The resulting plots are presented as Figures 6.15 through 6.26.



Figure 6.15. Long Beach 9414 Filtered Numerical vs Sliding Window Derivatives.



Figure 6.16. Long Beach 9419 Filtered Numerical vs Sliding Window Derivatives.



Figure 6.17. Pittsburgh 5003 Filtered Numerical vs Sliding Window Derivatives.



Figure 6.18. Pittsburgh 5086 Filtered Numerical vs Sliding Window Derivatives.



Figure 6.19. Pittsburgh 5087 Filtered Numerical vs Sliding Window Derivatives.



Figure 6.20. Pittsburgh 5092 Filtered Numerical vs Sliding Window Derivatives.



Figure 6.21. Pittsburgh 5120 Filtered Numerical vs Sliding Window Derivatives.



Figure 6.22. Pittsburgh 5122 Filtered Numerical vs Sliding Window Derivatives.



Figure 6.23. Pittsburgh 5123 Filtered Numerical vs Sliding Window Derivatives.



Figure 6.24. Pittsburgh 5133 Filtered Numerical vs Sliding Window Derivatives.



Figure 6.25. Pittsburgh 5134 Filtered Numerical vs Sliding Window Derivatives.



Figure 6.26. Pittsburgh 5135 Filtered Numerical vs Sliding Window Derivatives.

The trends exhibited by the filtered Euler numerical derivatives match well with the trends in sliding window derivatives. The peaks produced by the sliding window method also match with peaks in the Euler derivative. Thus, two independent methods of calculating failure rate produce the same results, meaning the sliding window method is an appropriate method for calculating failure rate, and the peaks generated by it are not erroneous. The peaks are indeed characteristics of the failure rate, many of which correspond with major component replacements.

The sliding window validation is particularly favorable for transit operators. For instance, if a transit operator wanted to determine failure rate of buses at an agency, it would be reasonable to expect a typical transit operator would be more apt to understand failures per 10,000 miles verses understanding a numerical derivative. Likewise, it would be difficult for them to relate to a polynomial fit. From a research standpoint, the polynomial fit technique requires too much effort to get a good result, including finding such a high order polynomial to approximate the cumulative failures. The Euler numerical derivative approach also requires a great deal of effort including developing an appropriate filter, and adjusting for outliers which skew the data.

Now that the sliding window method has been verified as an effective method of calculating the failure rate, the next step in this analysis is to determine if peaks in the cumulative failure rate corresponding to major component failures are exhibited on a subsystem level.

6.2 Subsystem Failure Rate Analysis

The next step in this research seeks to involve the following question: If a major component replacement corresponds with a peak in the cumulative failure rate, as seen in Section 6.1.3, would the failure rate corresponding to that component's subsystem also peak at the same mileage? For example, if an engine replacement corresponds with a peak in the cumulative failure rate, would the failure rate of engine-only failures exhibit a peak near the same mileage? To produce plots that might answer this question, all of the in-transit data was reclassified per subsystem.

6.2.1 In-Transit Data Reclassification

Section 4.2 explains the process for initially classifying the in-transit data failures as major or minor, and how the Excel database was arranged. In order to look at the failure rate of individual

subsystems, each of the forty-six bus files was sorted into ten separate work sheets as:

- Cumulative: All failures encountered
- Drivetrain: Any component associated with the engine, cooling system, and brakes.
- AC/Heat: Any component associated with air conditioning or heating
- Suspension: Any shocks, leaf or air springs, and/or air system repairs.
- Transmission: Any component associated with the transmission, drive shafts, differentials, and axles
- Steering: Any component associated with steering
- Frame and Mounting: Any repairs or replacements on the frame or structural mounting
- Wheels and Tires: Any flat tires, bent rims, or replacements
- Controls: Any electrical repairs that are responsible for control of some component
- Not Tested: Any component failure not tested for at PTI including windows, fareboxes, wheel chair lifts, and horns.

The work sheets retain the original formatting described in Section 4.2, except each sheet contains repairs for only those described subsystems (Figure 6.27). The multiple work sheets listed across the bottom of the excel file for this Pittsburgh bus correspond to each of the individual subsystems mentioned above.

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2		-		Major	Minor	Cumulative Failures	Cumulative Major	Cumulative Min
3								
4	253887	Closed:	1(6. Bus Suspension:Front Shocks:Replace	1		1	1	0
5	253887	Closed:	114. Bus Air System:Controls:Repair	1		2	2	0
6	253887	Closed:	118. Bus Air System:Concept Valve:Repair	1		3	3	0
7	253887	Closed:	19. Bus Air System: Air Dryer: Replace	1		4	4	0
8	270080	Closed:	1, 1. Bus Air System: Air Compressor: Replace	1		5	5	0
9	270569	Closed:	1, 1. Bus Air System: Air Compressor: Replace	1		6	6	0
10	277209	Closed:	3 1. Suspension:Ride Height or Leaning	1		7	7	0
11	281703	Closed:	3.4. Bus Suspension:Left Front Leveling Valve:Repair	1		8	8	0
12	281703	Closed:	3 5. Bus Air System: Air Dryer: Replace	1		9	9	0
13	289403	Closed:	5/1. Suspension:Ride Height or Leaning	1		10	10	0
14	290287	Closed:	5/1. Suspension:Air Leak	1		11	11	0
15	290287	Closed:	5/2. Suspension:Ride Height or Leaning	1		12	12	0
16	292299	Closed:	6.1. Bus Air System:Undefined:Repair	1		13	13	0
17	298809	Closed:	8.2. Suspension:Ride Height or Leaning	1		14	14	0
18	298895	Closed:	8 2. Suspension:Ride Height or Leaning	1		15	15	0
19	301534	Closed:	8.2. Suspension:Ride Height or Leaning	1		16	16	0
20	304868	Closed:	9.4. Bus Air System: Air Dryer: Replace	1		17	17	0
21	330105	Closed:	3/2. Bus Suspension:Drive Shocks:Replace	1		18	18	0
22	348647	Closed:	8/4. Bus Suspension:Left Rear Leveling Valve:Replace	1		19	19	0
23	356599	Closed:	1.1. Bus Air System:Undefined:Repair	1		20	20	0
24	361766	Closed:	2 3. Bus Air System: Air Dryer: Rebuild	1		21	21	0
25	361766	Closed:	2.5. Bus Air System:Undefined:Repair	1		22	22	0
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Figure 6.27. A Sample of the Subsystem Classification Template.

6.2.2 Sliding Window Subsystem Analysis

The sliding window derivative method explained in Section 6.1.1 is applied to the new in-transit data files to conduct a subsystem level failure rate analysis. The objective of this procedure is to determine if peaks in the cumulative failure rate are also apparent on a subsystem level.

Consider subsystem level plots corresponding to the cumulative failure rate plots outlined in Section 6.1.3. Keep in mind that only subsystem failure rates corresponding to known component failures are plotted to eliminate the clutter that would exist by plotting up to eleven functions on one figure.

Figure 6.28 illustrates the subsystem level analog to Figure 6.7. The failure rates of systems directly associated with peaks in the cumulative failure rate are plotted on the same graph. The generator replacement at mile 228,594 that corresponds with a peak in the cumulative failure also showed up as a peak in the drivetrain subsystem. Generator failures are categorized with drivetrain failures because of their close association with the engine. The transmission replacement at 283,816 miles corresponds to a rise in both drivetrain and transmission failure rates. The engine replacement at 313,566 miles is also characterized by a rise in the drivetrain failure rate around this particular mileage. Finally, the transmission repair at 339,122 miles is characterized by an increase in both drivetrain and transmission subsystem failure rates.



Figure 6.28. Pittsburgh 5001 Subsystem Failure Rates.



Figure 6.29. Pittsburgh 5003 Subsystem Failure Rates.

Figure 6.29 showed the failure rates corresponding to Pittsburgh bus 5003. The suspension failure at 250,272 miles is not matched very strongly by the suspension failure rate. However the drivetrain rate does rise along with suspension, and peaks at about the same time as the suspension replacement. At 281,512, the engine/turbo replacement is matched exactly with a very distinct peak in drivetrain failure rate at the same mileage. The generator and engine component replacements at 308,200 is also characterized by a rise in drivetrain failure rate. The increase and peak in drivetrain failure rate corresponds with the water pump replacement at 347,398 miles.

Finally, there is a noticeable correlation between the air system controls replacement and the suspension failure rate.

The items not tested at PTI were plotted here due to the large spike around 310,000 miles. The items not tested contributed significantly to the large magnitude in failure rate at this mileage.



Figure 6.30. Pittsburgh 5086 Subsystem Failure Rates.

Figure 6.30 highlights an increase and peak in the suspension failure rate corresponding to a replacement of the shocks. The differential replacement at 237,316 miles was characterized with a very evident spike in both drivetrain and suspension failure rate, highlighting both their relationship with the differential, but also the interdependence vehicle subsystems have on each other. Interestingly, the engine replacement did not induce an increase in the drivetrain failure rate. The rate did, however, remain elevated until the engine was replaced.

Figure 6.31 highlights the drivetrain failure rate since most of the notable failures were all associated with this subsystem. The increase in drivetrain failure rate at 223,021 miles corresponds to a brake controls replacement. The increase in both drivetrain and suspension failure rate near 266,638 matches well with the generator and shocks replacements. Finally the turbo replacement at 279,093 miles is accompanied by a steady failure rate from the drivetrain system which subsequently decreased after the new turbo was installed.

Figure 6.32 depicts drivetrain, suspension, and transmission subsystem failure rates, and their



Figure 6.31. Pittsburgh 5087 Subsystem Failure Rates.



Figure 6.32. Long Beach 9410 Subsystem Failure Rates.

relation to the cumulative failure rate. The peak in cumulative failure rate around 292,000 miles due to engine issues shows up clearly in the drivetrain failure rate. However, the transmission issues experienced at 309,350 are not depicted well by the transmission failure rate. The bus did not start at 337,097 miles, which was a culmination of increasing drivetrain failure rates leading up to that mileage. Both the cumulative and drivetrain failure rates peak at the same time and drop off significantly after the engine tune-up at 361,516 miles. The last peak in the cumulative failure rate occurrs at approximately 420,000 miles. The data shows no major component replacements near this mileage. However, the transmission failure rate was clearly a contributing factor to this peak in the cumulative rate. Upon further investigation, the transmission experienced numerous issues around this time, including not going into gear, not shifting once in gear, and not moving the bus when in gear. The agency never provided information saying the transmission or any critical drive-line components were replaced, but one can surmise that some major repair may have had taken place, and yet was not reported.



Figure 6.33. Long Beach 9414 Subsystem Failure Rates.

Figure 6.33 shows an increase in drivetrain failure rate corresponding with a generator replacement at 261,718 miles. There is also an increase in the suspension system failure rate near 333,658 miles, when the front and rear leveling valves were replaced. The drivetrain and transmission failure rates were elevated during the issues these subsystems experienced around 350,000 miles. Finally, after an overhaul at 382,026, the engine and cumulative failure rates decreased substantially.

Figure 6.34 illustrates an increased transmission failure rate corresponding with a transmission replacement around 385,000 miles. The rebuild of the differential at 393,328, however, was not represented by an increase in drivetrain or transmission failure rate. This would be indicative of a one-time differential failure that required the component be rebuilt, or of scheduled preventative maintenance on the drive-line. The no start issues near 465,158 miles are also characterized by an increased drive-train failure rate, which decreased after the issue was resolved.



Figure 6.34. Long Beach 9419 Subsystem Failure Rates.



Figure 6.35. Dover 613 Subsystem Failure Rates.

Figure 6.35 clearly exhibited an increased drivetrain failure rate corresponding to an engine replacement at 42,260 miles. The rate rises, peaks, and falls in direct correlation with this occurrence.

l Chapter

Conclusions and Future Work

This chapter summarizes the results of this thesis and suggests potential future work.

7.1 Conclusions

Contributions of this thesis are concluded in this section as follows:

- The sliding window moving average approximation to a derivative is a quick and easy way transit operators can determine the failure rate of a bus without employing advanced mathematical techniques to calculate a polynomial fit or filtered Euler numerical derivative.
- The failure rate corresponding to complex vehicles exhibits multiple peaks and valleys which imply repeated bathtub curve effects
- Major component replacements can be identified by analyzing these peaks in the failure rate
- Subsystem failure rates also exhibit peaks corresponding to major component failures

7.1.1 Bus Testing Program Validation

This thesis presented preliminary research that attempted to correlate reliability data from PTI and various transit agencies throughout the continental United States. In Section 5.2, plots were presented that compared cumulative and cumulative major failures of buses from PTI and transit agencies. It was determined that major failure count and trend was a more logical choice for a comparison metric since minor failures represent items not typically tested at PTI, and were skewing the cumulative failure results. The analysis of the PTI testing program ended here in the thesis, but continued on through other research efforts. Without going into detail which is outside the scope of this thesis, the PTI versus transit data comparison was furthered with numerous advanced statistical modeling and nonlinear trend analysis techniques. The ultimate result was that no conclusion could be drawn because the data received carried too many internal variations. At a recent Federal Transit Administration (FTA) project presentation, the FTA expressed their approval of the testing methods employed in this thesis and in other research on the bus testing project, and stated that they would like to fund this project into the future so more advanced research could take place.

7.1.2 Subsystem Analysis

After the major failure comparisons between PTI and transit agencies were complete, the failure rate was generated with a sliding window approximated derivative. The sliding window exhibited repeated bathtub curve effects that are typical of repairable systems. The failure rate was also calculated with a numerical derivative technique coupled with a low pass digital filter to smooth the results. The numerical derivative was then plotted along with the sliding window results to compare the two methods and determine if the sliding window gave an appropriate representation of the derivative. Many of the peaks in failure rate corresponded with major component replacements or system repairs. Numerous examples were presented which listed replacements and corresponding mileage. A subsystem level analysis was then conducted which resulted in many peaks from subsystem derivatives corresponding with peaks in the cumulative failure rate. This result proved that system failures may be identified on a subsystem level. The future work presented in the following section explains methods for advancing this research.

7.2 Future Work

This thesis laid the groundwork for future work in a breadth of complex vehicle system reliability and test track validation problems. A few of those are summarized in this section.

7.2.1 Weibull Analysis of the Sliding Window Approach

The sliding window approach of analysis presented in this thesis formulated a way for using the failure rate to identify major component replacements as they occurred during the useful life of the vehicle. Ideally, an transit manager would like to have a way of predicting these major break-downs before they occur to minimize downtime and costs of repair. Using the Weibull probability density function, it may be possible to predict when these peaks in failure rate, and subsequently the major failures, would occur. The curves could be fit to past data to develop an algorithm that would identify the peaks within a given mileage variance. The algorithm could be implemented in a pseudo-realtime environment, where new data could be processed without plotting the failure rates to determine if major component failures could be predicted, and ultimately prevented.

7.2.2 Economics of Reliability and Preventative Maintenance

A continuation of Section 7.2.1, this problem would analyze economic implications of determining when to replace a component based on a Weibull model. The Weibull algorithm would not be able to predict to the exact mile when the component would fail. It would, however, provide an estimate with a variance of, say, twenty thousand miles. The question of when to replace the component ("reset the bathtub curve") so you gather the maximum utility from the nearly depleted component, while replacing it before the vehicle experiences unnecessary downtime or its failure causes additional components to break.

Further, the economic study could delve into determining the break even point of profit versus outlay over the lifetime of the bus. This research would look to determine not only when the most efficient time to replace components would be, but would also suggest the optimal time to retire the bus.

7.2.3 Large Agency - Multiple Model Comparison

It was made very clear during the analysis phase of this project that agencies report and categorize fleet failures differently. The instances used in this research almost certainly originated at the shop floor level, with maintenance personnel entering work order information into a database. Some of the agencies had two times as many failures over one hundred thousand miles, which could be due to route differences, ridership, preventative maintenance schedule, or maintenance personnel simply neglecting to input data into the system. In order to remedy this issue, data could be collected from large agencies who could supply data for no less than ten buses of three different models. The goal here would be to collect as many repeat models from as many different agencies as possible, so the results obtained would be more complete.

7.2.4 Agency to Agency Comparison

Building on the data set described in Section 7.2.3, an agency to agency comparison could be made based on replacement and preventative maintenance schedules. For instance, if two agencies operate the same bus model, but observe different replacement or PM schedules, a researcher could discern which agency "out-performs" the other based on quantitative measurements such as failure count and failure rate. This study would, in essence, determine optimal maintenance scheduling.

7.2.5 In-Vehicle Ride Quality

Another way to compare PTI to transit agencies is to compare in-vehicle ride quality at both. This potential research would entail traveling to agencies that are willing to provide reliability data and physically sitting on their buses on various routes with an internal measurement unit (IMU) and recording dynamic characteristics of the ride. These roll, pitch, yaw, and vibration measurements could used to determine a "ride quality" and compared to PTI and other agencies. Thus, if a bus model performs better at Agency A than Agency B, the ride quality would be another means of discerning why the model performed better, and would help PTI account for factors occurring during in-transit usage that might not be represented in the present test regimen.

7.2.6 Manufacturing Variations

All buses tested at PTI are supposed to be **production ready**. This research topic would answer the question: If a model performs well at PTI and receives a good rating and is subsequently put into production, what metrics can be used to determine that the buses rolling out the factory door are the same as what was tested at PTI? After speaking with numerous transit operators through the course of this research, it was made clear that manufacturing variations are quite evident at agencies who run multiple buses of the same model. The federal government spends millions of dollars each year subsidizing bus test at PTI, so manufacturers need to be held responsible for producing what was tested in the first place. By analyzing multiple buses of the same model at the same agency, a researcher may be able to determine manufacturing variations in the product, and offer metrics or means of improving production. This research would ensure transit agencies receive the same quality bus that was tested at PTI, on which their purchasing decision was based.

7.2.7 Identifying False Positives

This research would investigate the existence of false positives presented as peaks in the failure rate data. In Chapter 6, peaks in failure rate plots were analyzed to determine any relationships between peaks and major component replacements or repairs. Some peaks existed, but could not be attributed to any specific component failure. This research topic would look to present a methodology to identify these false positives. For example, the plots generated for this research consist of only nonscheduled work performed on the bus. If a component failed about the same time as a scheduled preventative maintenance session, the failure would be hidden as a repair during the PM. Thus, the failure rate would exhibit a peak that could not be attributed to any failure instance provided as nonscheduled maintenance. By obtaining and plotting the preventative maintenance work performed on the bus along with the nonscheduled maintenance, all peaks in the failure rate data could be identified.

7.2.8 Periodicity in the Failure Rate

Some of the failure rate plots generated for this thesis exhibit what appears to be periodicity between the peaks. Consider Figure 7.1:



Figure 7.1. Pittsburgh Bus 5003 - Failure Rate.

The peaks in the failure rate for this bus seem to occur approximately every 3,000 miles. This could be due to many repairs being delayed until the next scheduled maintenance downtime. Thus, this future work would investigate if maintenance scheduling causes periodicity in the failure rate. By plotting all work performed on the bus, the researcher could determine if the frequency of preventative maintenance relates to the frequency of nonscheduled maintenance instances.

7.2.9 Seasonal Effects

The final future research concept would examine seasonal effects on the failure rate of the bus. By plotting failure rate as a function of time, a researcher could determine how winter months affect the performance of a bus model in a northern state, versus the same bus being operated in a southwestern area. Then, a more robust preventative maintenance schedule could be developed for agencies and bus models depending on the time of the year, adjusting the schedule when the bus is more or less prone to failure.



Transit Agency Data

The following is a sample data file (Pittsburgh 5001) that was received from The Port Authority of Allegheny County in Pittsburgh, Pennsylvania. Due to the large size of the file database, one file is presented here for illustration purposes. The rest of the files are stored on Dr. Sean N. Brennan's file server at the following location:

 $Publications \Rightarrow Academics \Rightarrow 2008 \Rightarrow 2008YutkoMSThesis$

The descriptions of each column are as follows:

- Ma : A major failure is indicated by an integer 1
- Mi : A minor failure is indicated by an integer 1
- Cum : The cumulative count of both major and minor failures
- C Ma : The cumulative count of major failures only
- C Mi : The cumulative count of minor failures only

Miles	Description	Ma	Mi	Cum	C Ma	C Mi
216210	Misc Items:Horn		1	1	0	1
216526	Bus Engine:Controls:Repair	1		2	1	1
217584	Brakes:Grab	1		3	2	1
220128	Misc Items:Radio/ P.A. System		1	4	2	2
222430	Bus Exterior Body:Frame:Repair	1		5	3	2
225982	Brakes:Slack Brakes	1		6	4	2
226955	Lights:Head Light		1	7	4	3
227479	Transmission:Rough Shift	1		8	5	3
228594	Bus Transmission:Assembly:Replace	1		9	6	3
229310	Suspension:Kneeler	1		10	7	3
229795	REPLACE UPPER RADIATOR HO	1		11	8	3
229795	Body:Driver's Seat/Belt		1	12	8	4
229795	Brakes:Slack Brakes	1		13	9	4
231665	Lights:Interior		1	14	9	5
231987	Brakes:Slack Brakes	1		15	10	5
232977	Brakes:Slack Brakes	1		16	11	5
233151	Lights:Head Light		1	17	11	6
234291	Heat - A/C:Defrosters		1	18	11	7
234291	Brakes:Pulls Right/Left	1		19	12	7
236321	Lights:4 Way/Turn Signal		1	20	12	8
238826	Air System:Compressor:Repair	1		21	13	8
239455	Engine:Won't Start	1		22	14	8
239455	Indicators:Generator Light		1	23	14	9
240247	Engine:Won't Start	1		24	15	9
241100	Bus Wheels and Hubs:Tires:Repair		1	25	15	10
241554	Lights:Head Light		1	26	15	11
244454	Heat - A/C:Too Warm		1	27	15	12
245242	Heat - A/C:Too Warm		1	28	15	13

Miles	Description	Ma	Mi	Cum	C Ma	C Mi
247629	Lights:Head Light		1	29	15	14
247629	Engine:Lack of Power	1		30	16	14
248597	Suspension:Air Leak	1		31	17	14
248959	Suspension:Air Leak	1		32	18	14
249646	Doors:Won't Close	1		33	19	14
250911	Brakes:Slack Brakes	1		34	20	14
250911	Lights:Interior		1	35	20	15
252386	Lights:Interior		1	36	20	16
253715	Engine:Won't Start	1		37	21	16
253824	Brakes:Slack Brakes	1		38	22	16
253824	Doors:Won't Close	1		39	23	16
254156	Bus HVAC:Aux. Heater:Repair		1	40	23	17
256318	Brakes: ABS System Light	1		41	24	17
256318	Lights:Interior		1	42	24	18
256424	Indicators:Air Pressure	1		43	25	18
256913	Brakes:Slack Brakes	1		44	26	18
258573	Engine:Q.W.R.	1		45	27	18
258573	Brakes:Slack Brakes	1		46	28	18
258573	Heat - A/C:Too Warm Driver		1	47	28	19
260226	Brakes:Slack Brakes	1		48	29	19
260226	Lights:4 Way/Turn Signal		1	49	29	20
260226	Transmission:Retarder Light	1		50	30	20
261302	Brakes:Slack Brakes	1		51	31	20
261900	Lights:Head Light		1	52	31	21
262131	Brakes:Grab	1		53	32	21
262676	Heat - A/C:Too Cool Driver		1	54	32	22
262676	Lights:Interior		1	55	32	23
263422	Windows:Wiper Blades		1	56	32	24

Miles	Description	Ma	Mi	Cum	C Ma	C Mi
264226	Bus Air System:Air Dryer:Repair		1	57	32	25
264475	Engine:Leaks	1		58	33	25
266188	Brakes:Grab	1		59	34	25
268654	Bus Wheels and Hubs:Tires:Repair		1	60	34	26
269175	Suspension:Ride Height or Leaning	1		61	35	26
269304	Bus Wheels and Hubs:Tires:Repair		1	62	35	27
269685	Bus Body Frame:Welding:Repair	1		63	36	27
269685	Engine:Q.W.R.	1		64	37	27
269685	Heat - A/C:Too Cool Driver		1	65	37	28
269926	Lights:Head Light		1	66	37	29
270434	Bus Wheels and Hubs:Tires:Repair		1	67	37	30
270461	Bus Wheels and Hubs:Tires:Repair		1	68	37	31
270461	Heat - A/C:Too Cool Interior		1	69	37	32
270461	Heat - A/C:Too Cool Interior		1	70	37	33
270690	Transmission:Retarder Light	1		71	38	33
271156	Heat - A/C:Too Cool Interior		1	72	38	34
271562	Brakes:Slack Brakes	1		73	39	34
272305	Heat - A/C:Too Cool Driver		1	74	39	35
272375	Engine:Leaks	1		75	40	35
273436	Engine:Won't Start	1		76	41	35
273601	Engine:Won't Start	1		77	42	35
274099	Brakes:Pulls Right/Left	1		78	43	35
276132	Lights:Brake/Tail		1	79	43	36
276767	Indicators:Air Pressure	1		80	44	36
277244	Doors:Won't Close	1		81	45	36
278531	Mirrors:Right Outside		1	82	45	37
278531	Suspension:Kneeler	1		83	46	37
280872	Doors:No Interlock	1		84	47	37

Miles	Description	Ma	Mi	Cum	C Ma	C Mi
280872	Windows:Wiper Blades		1	85	47	38
281944	Bus Wheels and Hubs:Tires:Repair		1	86	47	39
282644	Bus Braking:Drive Lining:Repair	1		87	48	39
282644	Bus Air System:Air Dryer:Repair		1	88	48	40
282644	Bus Wheels and Hubs:Tires:Replace		1	89	48	41
282644	Bus Electrical:Exterior Lights:Repair		1	90	48	42
282757	Heat - A/C:Too Warm Interior		1	91	48	43
283544	Doors:No Interlock	1		92	49	43
283816	Engine:Won't Start	1		93	50	43
283816	Bus Electrical:Generator 24V:Replace	1		94	51	43
284135	Mirrors:Left Outside		1	95	51	44
284583	RAD FAN SHATTERED//BUS TO	1		96	52	44
284799	Doors:Won't Close	1		97	53	44
284799	Doors:Won't Close	1		98	54	44
284799	Heat - A/C:Too Warm Interior		1	99	54	45
285264	Heat - A/C:Too Warm Interior		1	100	54	46
285347	Windows:Cracked Glass	1		101	55	46
285751	Brakes:Slack Brakes	1		102	56	46
285838	Heat - A/C:Too Warm Interior		1	103	56	47
285838	Heat - A/C:Too Warm Interior		1	104	56	48
285838	Heat - A/C:Too Warm Interior		1	105	56	49
285959	Brakes:Air Leak	1		106	57	49
286414	Bus Wheels and Hubs:Tires:Replace		1	107	57	50
286562	Doors:No Interlock	1		108	58	50
286715	Heat - A/C:Too Warm Interior		1	109	58	51
286834	Heat - A/C:Too Warm Interior		1	110	58	52
286834	Heat - A/C:Too Warm Interior		1	111	58	53
287391	Doors:No Interlock	1		112	59	53

Miles	Description	Ma	Mi	Cum	C Ma	C Mi
288999	Doors:Won't Close	1		113	60	53
289245	Doors:No Interlock	1		114	61	53
289245	Transmission:Leaks	1		115	62	53
290166	Engine:Leaks	1		116	63	53
290236	Doors:No Interlock	1		117	64	53
290236	Doors:Won't Close	1		118	65	53
290537	Bus Cooling:Plumbing:Repair		1	119	65	54
290537	Transmission:MiscCodes	1		120	66	54
291129	Bus Exterior Body: Hood:Repair		1	121	66	55
292570	Lights:Brake/Tail		1	122	66	56
292795	Lights:4 Way/Turn Signal		1	123	66	57
292795	Lights:Head Light		1	124	66	58
292795	Lights:Interior		1	125	66	59
292795	Farebox:Not Registering		1	126	66	60
292909	Heat - A/C:Too Cool Driver		1	127	66	61
294033	Heat - A/C:Too Cool Interior		1	128	66	62
296789	Bus Engine:Lines:Repair	1		129	67	62
296789	Bus Transmission:Cooler:Repair	1		130	68	62
296789	Bus Electrical:Exterior Lights:Repair		1	131	68	63
296789	6. Bus Exterior Body:Glass:Replace	1		132	69	63
296789	Bus Electrical:Exterior Lights:Repair		1	133	69	64
296789	Bus Exterior Body:Frame:Repair	1		134	70	64
296789	Bus Interior Body:Flooring:Repair		1	135	70	65
298412	Lights:Markers/Clearance		1	136	70	66
299194	Heat - A/C:Too Cool Interior		1	137	70	67
299194	Heat - A/C:Too Cool Interior		1	138	70	68
300002	Bus Air System:Air Compressor:Repair	1		139	71	68
300333	Lights:Head Light		1	140	71	69

Miles	Description	Ma	Mi	Cum	C Ma	C Mi
302659	Indicators:Check Engine Light	1		141	72	69
302659	Mirrors:Rear View		1	142	72	70
303174	Brakes:Pulls Right/Left	1		143	73	70
303478	Heat - A/C:Too Cool Interior		1	144	73	71
304489	Indicators:Check Engine Light	1		145	74	71
307211	Mirrors:Rear View		1	146	74	72
307999	Heat - A/C:Too Cool Driver		1	147	74	73
310487	Lights:Interior		1	148	74	74
311943	Heat - A/C:Too Cool Driver		1	149	74	75
312205	Doors:Won't Open	1		150	75	75
313302	Brakes:Slack Brakes	1		151	76	75
313302	Engine:Overheats	1		152	77	75
313452	Heat - A/C:Too Warm Interior		1	153	77	76
313566	Bus Engine:Undefined:Replace	1		154	78	76
314820	Heat - A/C:Too Warm Interior		1	155	78	77
315479	Brakes:Slack Brakes	1		156	79	77
315479	Suspension:Ride Height or Leaning	1		157	80	77
315563	Heat - A/C:Too Warm Interior		1	158	80	78
315563	Bus Wheels and Hubs:Tires:Repair		1	159	80	79
316118	Mirrors:Right Outside		1	160	80	80
316396	Windows:Wiper Blades		1	161	80	81
318126	Doors:Won't Close	1		162	81	81
319022	Bus Cooling:Fan Belts:Replace	1		163	82	81
319022	Bus Cooling:Fan Belts:Replace	1		164	83	81
319022	Bus Electrical:Ext. Lights:Replace		1	165	83	82
319022	Bus Electrical:Int. Lights:Replace		1	166	83	83
319073	Bus Braking:Controls:Replace	1		167	84	83
319073	Bus Air System:Air Dryer:Rebuild	1		168	85	83

Miles	Description	Ma	Mi	Cum	C Ma	C Mi
319073	Wheel Well Fender:Repair		1	169	85	84
319073	Air System:Concept Valve:Replace	1		170	86	84
320854	Windows:Cracked Glass	1		171	87	84
320934	Doors:Won't Close	1		172	88	84
320934	Doors:Won't Open	1		173	89	84
322673	Lights:4 Way/Turn Signal		1	174	89	85
322673	Indicators:Air Pressure	1		175	90	85
325350	Bus Wheels and Hubs:Tires:Repair		1	176	90	86
325538	Bus Wheels and Hubs:Tires:Repair		1	177	90	87
325538	Lights:Interior		1	178	90	88
326018	Heat - A/C:Too Warm Interior		1	179	90	89
326018	Lights:Brake/Tail		1	180	90	90
326481	Bus Wheels and Hubs:Tires:Repair		1	181	90	91
327143	Windows:Wiper Blades		1	182	90	92
329548	Bus HVAC:Aux. Heater:Repair		1	183	90	93
331740	Doors:No Interlock	1		184	91	93
332823	Heat - A/C:Too Cool Interior		1	185	91	94
334854	Bus Wheels and Hubs:Tires:Repair		1	186	91	95
336546	Bus Cooling:Fan Belts:Replace		1	187	91	96
336546	Bus HVAC:Belts:Replace		1	188	91	97
337373	Doors:No Interlock		1	189	91	98
337373	Suspension:Ride Height or Leaning	1		190	92	98
337916	Lights:Head Light		1	191	92	99
338234	Farebox:Bill Side Jamb		1	192	92	100
338816	Bus Exterior Body:Trim:Replace		1	193	92	101
338816	Bus Body Frame: Tubular Steel: Repair	1		194	93	101
338816	Heat - A/C:Too Cool Interior		1	195	93	102
339122	Bus Exterior Body:Undefined:Replace		1	196	93	103

Miles	Description	Ma	Mi	Cum	C Ma	C Mi
339122	Bus Air System:Air Dryer:Rebuild	1		197	94	103
339122	Bus Exterior Body:Undefined:Replace		1	198	94	104
339122	Bus Electrical:Generator 24V:Repair	1		199	95	104
339122	Bus Transmission:Undefined:Repair	1		200	96	104
339122	Bus Electrical:Ext.Lights:Replace		1	201	96	105
339798	Transmission:Slips	1		202	97	105
340076	Brakes:Slack Brakes	1		203	98	105
340076	Transmission:MiscCodes	1		204	99	105
340206	Bus Axles:Differential Seal:Replace	1		205	100	105
340258	Heat - A/C:Too Cool Interior		1	206	100	106
340467	Transmission:Rough Shift	1		207	101	106
341493	Heat - A/C:Too Cool Interior		1	208	101	107
343486	Engine:Won't Start	1		209	102	107
344081	Mirrors:Right Outside		1	210	102	108
344335	Brakes:Parking Brake	1		211	103	108
345468	Heat - A/C:Defrosters		1	212	103	109
345683	Brakes:Slack Brakes	1		213	104	109
345779	Heat - A/C:Too Cool Interior		1	214	104	110
345954	Bus HVAC:Aux. Heater:Repair		1	215	104	111
345954	Bus Wheels and Hubs:Tires:Repair		1	216	104	112
347094	Heat - A/C:Defrosters		1	217	104	113
347354	Bus HVAC:Defroster Motor:Repair		1	218	104	114
347773	Bus Transmission:Undefined:Repair	1		219	105	114
347773	Bus Suspension:Undefined:Repair	1		220	106	114
348007	Heat - A/C:Too Cool Interior		1	221	106	115
348952	Bus Wheels and Hubs:Tires:Repair		1	222	106	116
349486	Lights:4 Way/Turn Signal		1	223	106	117
350340	Engine:Lack of Power	1		224	107	117

Miles	Description	Ma	Mi	Cum	C Ma	C Mi
351519	Heat - A/C:Too Warm Interior		1	225	107	118
352041	Bus Engine:Turbo:Replace	1		226	108	118
353329	Doors:Won't Open	1		227	109	118
354059	Engine:Won't Start	1		228	110	118
354183	Bus Wheels and Hubs:Tires:Repair		1	229	110	119
354712	Bus Cooling:Plumbing:Replace		1	230	110	120



Matlab Source Code

B.1 The Sliding Window

B.1.1 Sliding Window Main File

2 % The following script runs a sliding window derivative approximation e 3 % function (sliding_window.m) to create failure rate plots for obtained % % non-scheduled work preformed on various bus models. The plots describe % 4 % the cumulative and subsystem failure rates as specified by the user. 음 6 % The user needs to: % (1) Select a file name from the list below 9 10 % (2) Input that name into the appropriate lines calling data from select excel files. 응 11 % (3) Determine which subsystems are desired to plot 12% (4) Adjust the plotted axes to only view appropriate range of data 13 14 1516 % (1) Failure rate script created by Joseph Yutko, 12/13/07, The ÷ Pennsylvania State University. ÷ 17 %

```
18 %
                                           2
19 % (2) Sliding window function script created by Kshitij Jerath, 11,27,07, %
     The Pennsylvania State Unversity, and modified by Joseph Yutko,
 응
                                           ÷
20
     12/13/07, The Pennsylvania State University
                                           2
 2
21
 22
23
^{24}
25 % Choose from the following bus files (names are case sensitive) obtained
26 % from transit agencies:
27
 28
 % Pittsburgh, PA (Port Authority of Allegheny Co) - 1994 Neoplan AN 440L %
29
    Pitt_5001 Pitt_5002 Pitt_5003 Pitt_5080
                                  Pitt_5085
30
 8
                                           8
     Pitt_5086 Pitt_5087 Pitt_5091 Pitt_5092 Pitt_5120
31
 8
                                           8
     Pitt_5122 Pitt_5123 Pitt_5133 Pitt_5134
                                  Pitt_5135
                                           ÷
32
 2
 33
34
 35
 % Manchester, NH (Manchester Transit Authority) - 1995 Thomas Built Vista %
36
    Manchester_9602 Manchester_9604 Manchester_9606
                                           2
37 %
 38
39
 40
 % Long Beach, CA (Long Beach Transit) - 1994 New Flyer D40LF
                                           8
41
     LongBeach_9410
               LongBeach_9414 Longbeach_9419
                                           2
42
 43
44
 ^{45}
 % Greeley,CO (City of Greeley Transit Services) - 1993 BlueBird QBRE 2903 %
46
 2
    Greeley_939 Greeley_940 Greeley_941 Greeley_942
                                           음
47
 ^{48}
49
 50
 % Dover,DE (Delaware Transit Corp.) - 1996 Champion Contender TB-2242
                                           2
51
 8
    Dover_613 Dover_614
                                           8
52
 53
54
```
```
55
  % Cocoa Beach, FL (Space Coast Area Transit) - 1994/5 Thomas Built Vista %
56
       CocoaBeach_9409
                     CocoaBeach_9418
  8
                                    CocoaBeach_9420
                                                            ÷
57
  58
59
  60
  % Abingdon, MD (Harford Co. Transportation Services) - 2000 Star Trans.
                                                            ÷
61
  % Supreme Corp - BSSN25
                                                            ÷
62
       Abingdon_802
                   Abingdon_804
                                Abingdon_807
63
  2
                                            Abingdon_821
                                                            2
       Abingdon_828
                   Abingdon_841
  ÷
                                                            2
64
  65
66
  67
  % Nashville, TN (Metropolitan Transit Authority) - 1993 Neoplan AN440
                                                            2
68
                    Nashville_301 Nashville_302
       Nashville_161
                                              Nashville_303
                                                            ÷
69
  2
       Nashville_304
                    Nashville_305
                                Nashville_306
                                              Nashville_307
70
 2
                                                            8
       Nashville_308
                                                            2
^{71}
  8
  72
73
74 clear all;
  clc;
75
76
  [type, sheets] = xlsfinfo('Pitt_5087');
77
78
  cumulative=xlsread('Pitt_5087','Cumulative','A4:A1200');
79
  drivetrain=xlsread('Pitt_5087','Drivetrain','A4:A500');
80
  acheat=xlsread('Pitt_5087','AC HEAT','A4:A500');
81
  suspension=xlsread('Pitt_5087','Suspension','A4:A500');
82
  trans=xlsread('Pitt_5087','Transmission','A4:A500');
83
 steering=xlsread('Pitt_5087','Steering','A4:A500');
84
  frame=xlsread('Pitt_5087','Frame and Mounting','A4:A500');
85
  wheel=xlsread('Pitt_5087','Wheels and Tires','A4:A500');
86
  control=xlsread('Pitt_5087','Controls','A4:A500');
87
  notest=xlsread('Pitt_5087','Not Tested','A4:A500');
88
89
  [cumulative_rate, cumulative_miles]=sliding_window_function (cumulative);
90
 [drivetrain_rate, drivetrain_miles]=sliding_window_function (drivetrain);
91
```

95

[acheat_rate, acheat_miles]=sliding_window_function(acheat); 92 [suspension_rate, suspension_miles]=sliding_window_function (suspension); 93 [trans_rate,trans_miles]=sliding_window_function(trans); 94[steering_rate, steering_miles]=sliding_window_function(steering); 95 [frame_rate,frame_miles]=sliding_window_function(frame); 96 97 [wheel_rate, wheel_miles]=sliding_window_function(wheel); [control_rate, control_miles]=sliding_window_function(control); 98 [notest_rate, notest_miles]=sliding_window_function(notest); 99 100 101 2 Plot 2 102103 104 figure(1) 105106 plot(cumulative_miles,cumulative_rate,'r'); 107 hold on; 108 plot(drivetrain_miles, drivetrain_rate, 'g'); 109 plot(acheat_miles,acheat_rate,'b'); 110 plot(suspension_miles, suspension_rate, 'm'); 111 plot(trans_miles,trans_rate,'m'); 112 plot(steering_miles,steering_rate,'k'); 113 plot(frame_miles, frame_rate, '---r'); 114 plot(wheel_miles,wheel_rate,'-g'); 115 plot(control_miles,control_rate,'---b') 116 plot(notest_miles, notest_rate, '---c'); 117 axis ([225000 335000 0 30]); 118 legend('Cumulative', 'Drivetrain', 'Suspension', 'Transmission', 'Steering',... .., 'Frame', 'No Test') 119120 legend('Cumulative', 'Drivetrain', 'Suspension', 'No Test') 121 title('Falure Rate Distribution of Pittsburgh 5002'); 122 xlabel('Distance (in miles)'); 123 ylabel('Failure Rate');

```
2 %
                                                                     2
3 %
        This script runs with sliding_window.m. This script is the
                                                                     응
4 %
        sliding window derivative approximation. It calculats the
                                                                     e
S
        approximate derivative of a data set by computing the number
5 %
                                                                     8
6 %
        of failures in a window of indicated size, summing them, and
                                                                     응
        repeating this process numerous times by sliding the window
7 %
                                                                     응
        an indicated increment.
8 %
                                                                     2
9 %
                                                                     8
        Original script written by: Kshitij Jerath
10 %
                                                                     2
        Modified by: Joseph M. Yutko
11 %
                                                                     응
        The Pennsylvania State University, 2008
12 %
                                                                     2
13 %
                                                                     2
  14
15
  function [C,D]=sliding_window_function(Bus_data)
16
17
18
  win_size = 10000;
19 win_inc = 100;
20
21 first_rdng = Bus_data(1);
22 last_rdng = Bus_data(length(Bus_data));
23
24 %Initialization of plot matrices:
25 %C = total number of failures in sliding window interval of size win_size
26 %k = counter for counting total number of failures in win_size
27 %pos = pointer to failure mile reading data in failure matrix x
28
  for(i=1:win_inc:(last_rdng - win_size))
29
      C(1+(i-1)/win_inc)=0;
30
      D(1+(i-1)/win_inc) = win_inc*(1+(i-1)/win_inc)+(win_size/2);
^{31}
  end
32
33
34 pos=1;
```

```
35
36 for(i=1:win_inc:(last_rdng - win_size))
       k = 0;
37
      for(j=i:1:(win_size + i))
38
           while(Bus_data(pos)==j)
39
              k = k+1;
40
              pos=pos+1;
41
           end
^{42}
       end
^{43}
^{44}
       pos=1;
45
           while(Bus_data(pos)<i+win_inc)</pre>
46
             pos=pos+1;
47
^{48}
          end
49
     C(1+(i-1)/win_inc)=k;
50
51 end
52
53 Z=[];
54 Zl=[];
55
56 for(i=1:1:length(Bus_data))
     Z(i) = i;
57
      Z1(i) = i;
58
59 end
```

98

B.2 Sliding Window vs Polynomial Approximation Derivative

```
32
33 win_size = input('Enter size of sliding window (default = 10000) :');
34 if(length(win_size)==0)
      win_size = 10000;
35
36 end
37
38 win_size = 10000;
39
40 win_inc = input('\nEnter sliding window increment (default = 100) :');
41 if(length(win_inc)==0)
     win_inc = 100;
42
43 end
^{44}
45 win_inc = 100;
46
47 first_rdng = Bus_data(1);
  last_rdng = Bus_data(length(Bus_data));
^{48}
^{49}
50 for(i=1:win_inc:(last_rdng - win_size))
       C(1+(i-1)/win_inc)=0;
51
       D(1+(i-1)/win_inc)=win_inc*(1+(i-1)/win_inc)+(win_size/2);
52
53 end
54
55 pos=1;
56
  for(i=1:win_inc:(last_rdng - win_size))
57
       k = 0;
58
       for(j=i:1:(win_size + i))
59
           while(Bus_data(pos)==j)
60
               k = k+1;
61
               pos=pos+1;
62
           end
63
       end
64
65
66
       pos=1;
           while(Bus_data(pos)<i+win_inc)</pre>
67
              pos=pos+1;
68
```

```
end
69
70
      C(1+(i-1)/win_inc)=k;
71
72 end
73
74 Z=[];
75 Z1=[];
76
77 for(i=1:1:length(Bus_data))
      Z(i) = i;
78
      Z1(i) = i;
79
80 end
81
  82
                             Plot
                                                                    응
  8
83
85
86 %Reference Cumulative failure plot
87 % plotyy(D,C,Bus_data,Z); [AX,H1,H2] = plotyy(D,C,Bus_data,Z,'plot');
ss % set(H2,'Linestyle','o'); hold on; title('Failure rate and Cumulative
89 % failures versus Distance'); set(H2,'Linestyle','-'); xlabel('Distance (in
90 % miles)'); set(get(AX(1),'Ylabel'),'String','Failure rate (Total
91 % failures/miles)'); set(get(AX(2),'Ylabel'),'String','Cumulative
92 % Failures'); plot(Bus_data,Z1,'b:'); legend(H1,'Sliding window failure
93 % rate');
              %cancel permanent legend(H2,'Cumulative Failures');
94 % %cancel permanent
95
96 %hold on;
97 p = polyfit(Bus_data,Z,6);
98 f = polyval(p,Bus_data);
99 %plot(Bus_data,Z,'r:');
100
101 hold on;
102 %plot(Bus_data, f, '-');
103 q = polyder(p);
104 f1 = win_size*polyval(q,Bus_data);
105 %[AX,H1,H2] = plotyy(Bus_data,f1,Bus_data,f); plotyy(D,f1,D,C);
```

- 106 [AX,H1,H2] = plotyy(Bus_data,f1,D,C);
- 107 set(H1, 'Linestyle', '*');
- 108 hold on;
- 109 %title('Comparison of Sliding Window and Polynomial Fit Derivative
- 110 %Methods');
- 111 set(H1, 'Linestyle', '-');
- 112 xlabel('Distance (in miles)');
- 113 set(get(AX(1),'Ylabel'),'String','Failure Rate Fitted Polynomial,. . .
- 114 . . . Derivative');
- 115 set(get(AX(2),'Ylabel'),'String','Failure Rate-Sliding Window Derivative');
- 116 legend(H2,'Sliding Window Derivative'); %cancel permanent
- 117 legend(H1,'Fitted Polynomial Derivative'); %cancel permanent

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