WSDOT Building Asset Management An Exploratory Case Study

Impact of Failures at the Corson Avenue TEF Shop on WSDOT Services

WA-RD 824.1

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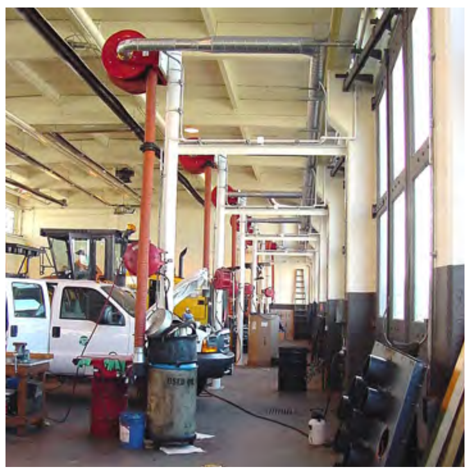
June 2013



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16. ABSTRACT

The mission of the Washington State Department of Transportation (WSDOT) is to keep people and business moving by operating and improving the state's transportation systems vital to our taxpayers and communities. Traditionally, the Department has focused its efforts on the transportation systems. However, a growing portfolio of transportation assets is burdening an old and often outdated portfolio of building assets that support WSDOT core mission and house employees, who design, construct, maintain, and operate state highways. The capacity and condition of these building assets are critically challenged by the failure of various building systems, which, when they happen, can be very disruptive or even hazardous to WSDOT daily operations. Considering the long overdue preservation and replacement of these assets, there is an urgent need to (1) understand how the asset performance influences the various functions that support the Department's core mission, (2) identify the impact of alternative funding levels upon building asset performance, and (3) prioritize the Department's funding decisions in order to fulfill its core mission through a safe and sustainable working environment. This research project is the first step in a series of potential research projects designed to develop an in-depth understanding of building asset management processes, challenges, and opportunities for WSDOT. This project is an exploratory case study focusing on the Vehicle Repair Shop in the Northwest Region Maintenance Facility in South Seattle. This shop was built in 1954 and is located in a site complex with 33 separate structures, totaling 114,025 SF of space that houses staff and equipment for the maintenance and operation of state highways. The analysis outcomes show that failures occurring at the TEF shop can significantly affect its ability to service the department's vehicles and equipment. Given the importance of some of these vehicle and equipment in operating the state's transportation system, failures at the TEF shop can also significantly affect WSDOT's ability to fulfill its mission.

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WSDOT BUILDING ASSET MANAGEMENT

AN EXPLORATORY CASE STUDY

"Impact of Failures at the Corson Avenue TEF Shop on WSDOT Services"

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June, 2013

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Executive Summary

As for most of state and local DOTs, vehicles and equipment are among the key assets necessary to perform many crucial activities, such as providing transportation to incident response crews; managing traffic through travel information equipment; removing snow from roads; allowing efficient communication among personnel even in remote areas; and, providing transportation to departmental personnel. To ensure proper care and maintenance of most of the state vehicles and equipment, the Washington State Department of Transportation (WSDOT) established several Transportation Equipment Fund (TEF) shops in the state. In particular, the TEF shop personnel are in charge of performing routine maintenance procedure on WSDOT vehicles and equipment; repairing damaged vehicles and equipment; and, upgrading vehicles (e.g., install radio systems in cars and trucks). Although few service and repair activities are outsourced, most activities are performed at the WSDOT's TEF shop facilities. Therefore, WSDOT must maintain such facilities in an effective and prompt manner. In fact, any reduction of TEF shop facilities' capabilities could jeopardize not only WSDOT's vehicles and equipment maintenance but also the department's ability to fulfill its mission.

Given the current economic situation, WSDOT facilities lack the needed funding to be properly maintained. In order to properly allocate the limited available resources for capital facilities, WSDOT must carefully program and direct its maintenance effort to limit impacts on transportation system users. By developing a model capable of simulating the service and repair activities performed and the failures that occurred or are likely to occur at the Corson Avenue South TEF shop (Seattle, WA), the present study estimated how failures can affect TEF operations and, eventually, road users.

Initially, the research team analyzed TEF shop service and repair activities and developed a model capable of simulating the service operations performed in the TEF shop during routine conditions (i.e., no failure affecting the TEF shop). After validating the model, the research team identified the possible failures capable of affecting the shop activities (e.g., damages on floor, interior walls, ceiling, and roof; issues with the welder circuit and lighting system; damaged water pipes and heating units, and leakages) and quantified the potential consequences of failures occurrences at the repair shop by comparing model performance in routine conditions vs. model performance in failure conditions. In particular, three analyses were performed.

First, by simulating the TEF shop service and repair activities under the identified failures, the loss in number of serviced vehicles was calculated as the difference between the number of vehicles serviced in routine conditions and that when a failure occurs. The analysis outcomes show that the most disruptive failures for the shop activities are the ones causing the closure of repair bays.

Second, by targeting service to vehicles and equipment used to perform Snow and Ice Control (S&IC) operations and considering only the closure of one or more repair bays as failure conditions, the loss in number of serviced S&IC vehicles was calculated as the difference between the number of S&IC vehicles serviced in routine conditions and that when a failure occurs. Similarly, the loss in number of serviced NO-S&IC vehicles (i.e., vehicles and equipment not used for S&IC operations) was also determined. The analysis clearly shows that prioritizing the service of S&IC vehicles can be beneficial in obtaining an acceptable service level for S&IC vehicles but, on the other hand, it can seriously jeopardize the level of service of vehicles not used for S&IC operations.

Third, by targeting plow trucks and considering only the closure of one or more repair bays as failure conditions, this analysis quantified the delay in servicing a specified number of plow trucks as the difference between the time necessary to service the plow trucks in routine conditions and that when a failure occurs. Then, by multiplying the delay with the average plowing speed (in lane-miles per hour) during an emergency situation, the loss in number of plowed lane-miles was calculated. Therefore, by identifying how many lane-miles cannot be cleaned within a certain period because of failures occurring at the TEF shop, this analysis clearly shows how failures can impact road-users.

In conclusion, the analysis outcomes show that failures occurring at the TEF shop can significantly affect its ability to service the department's vehicles and equipment. Given the importance of some of these vehicle and equipment in operating the state's transportation system, failures at the TEF shop can also significantly affect WSDOT's ability to fulfill its mission.

1. Introduction

Washington State Department of Transportation Mission Statement

> *The mission of the Washington State Department of Transportation is to keep people and business moving by operating and improving the state's transportation systems vital to our taxpayers and communities.*
>
> WSDOT (2013)

To manage a statewide transportation system, Washington State Department of Transportation (WSDOT) employs about 7,000 permanent and seasonal employees (WSDOT, 2012) engaged in extremely diverse and wide range of activities, from managing the delivery of construction projects worth hundreds of millions of dollars to cleaning roads. Further, WSDOT manages hundreds of different vehicles and pieces of equipment, including trucks and equipment that maintain roadways and boats that clean rivers and channels from debris to prevent damages to bridge structures. To house and support its employees, vehicles, and equipment, WSDOT operates about 3.8 million square feet of owned and leased buildings and unique facilities, such as "region headquarters complexes, traffic management centers, maintenance crew facilities, commercial vehicle repair shops, welding and fabrication shops, project engineer offices, testing laboratories, material storage, and wireless communication sites" (WSDOT, 2011, p. 10).

Excluding the ferry program related facilities and rest areas, WSDOT occupies 3.2 million square feet of buildings. In particular, WSDOT leases 0.57 million square feet, and owns and manages 2.63 million square feet (WSDOT, 2011). Among the owned buildings and facilities, WSDOT capital facility program focuses its efforts in managing 289 primary buildings (WSDOT, 2012) accounting for more than 2.3 million square feet (Figure 1). These buildings include offices and crew spaces with a size of at least 2,000 square feet that house the department's staff, vehicles, and equipment (WSDOT, 2010).

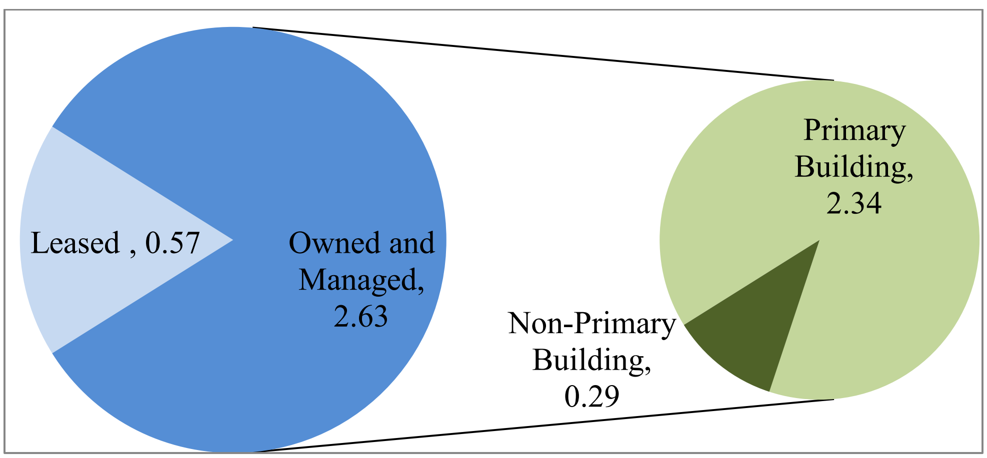


Figure 1: WSDOT occupied building space in millions of square feet as of October 2010 (Data retrieved from WSDOT Computer Aided Facility Management, CAFM, System Building Inventory)

1.1 An overview of Primary Building Facility Management

The following sections provide a brief overview on how primary building issues and deficiencies are identified and addressed.

1.1.1 Primary Building Condition Assessment Procedure

WSDOT developed a building condition assessment procedure to identify the issues affecting the primary buildings and the sites in which the buildings are located. This procedure is performed by the Regional Facility Managers and their staff and is repeated every two years. To perform this assessment process, each building is inspected and a building/site condition assessment form is filled out. The form records information on several building/site characteristics, systems, and components (Table 1). To fill out the form, it is necessary to:

1) Rate each item on a scale from 1 to 5 (1 – optimal condition to 5 – poor condition; Table 2);
2) Provide comments if necessary;
3) For items rated 4 or 5, provide specific comments on the issues and generate a cost estimate to correct the issues according to the RSMeans (Norwell, MA) cost information (Figure 2); and,
4) Multiply the item ratings by the related weights (Table 1) and add the weighted ratings together to obtain the overall condition of the building/site. In particular, WSDOT determines the overall conditions of each primary building according to the ranges in Figure 3.

As of September 2012, WSDOT determined that the total backlog (i.e., cost estimate) to correct all the deficiencies of its primary buildings is equal to $132.5 million and that only 22 (8%) primary buildings are in good conditions (WSDOT, 2012). 150 (52%) primary buildings are in fair conditions and 117 (40%) are in poor conditions.

Table 1: Site and Building Condition Assessment Form Items and Weight

Section	Item	Weight
A. Site General	1. Location	6
	2. Access	6
	3. Useable Size	6
	4. Site Security	4
	5. Site Drainage	5
	6. Surfacing	4
	7. Surrounding Land Use	6
	8. Landscaping/ Screening	2
	9. Site Signage	2
B. Site Service Systems	10. Water	6
	11. Sanitary	6
	12. Site Electrical Lighting/Power	5
C. Site Safety Standard	13. Site Code Violations	10
	14. Site Unauthorized Modifications	5
D. Site Functional Standards	15. Site Materials Storage	6
	16. Number of Bays/Vehicle	6
E. Site Barrier Free Access	17. Site ADA Circulation	9
F. Site Environmental	18. Site Chemical Petrol Contamination	7
G. Building General	19. Building Security	4
	20. Building Drainage	5
	21. Building Signage	2
H. Building Primary Systems	22. Foundation/Slab	5
	23. Superstructure	5
	24. Exterior Closure	6
	25. Roofing	8

Table 1: Site and Building Condition Assessment Form Items and Weight (continued)

Section	Item	Weight
I. Building Secondary System	26. Door/Hardware 27. Wall Finishes 28. Floor Finishes 29. Ceiling Finishes	3 3 3 3
J. Building Service Systems	30. Conveying 31. Mechanical Plumbing 32. Mechanical Heating 33. Mechanical Cooling/ Ventilation 34. Electrical Service Distribution 35. Emergency Power 36. Bldg. Electrical Lighting/Power 37. Voice and Data	3 5 8 5 5 8 5 6
K. Building Safety Standards	38. Building Code Violations 39. Fire Safety 40. Non-Structural Seismic 41. Bldg. Unauthorized Modification	10 10 8 5
L. Building Functional Standards	42. Storage Space 43. Bay Size 44. Crew Facilities 45. Working Environment	6 6 6 6
M. Building Energy Conservation	46. Source of Energy 47. HVAC 48. Lighting 49. Insulation	4 4 4 4
N. Building Barrier Free Access	50. Building ADA Circulation 51. ADA Services	9 9
O. Building Environmental	52. Bldg. Chemical/Petrol. Contam.	7

Table 2: Sample of Site and Building Condition Assessment Form Guidelines

Section	Item	Rating Guideline
H. Primary Systems	24. Exterior Closure	1 – Sound, waterproof, tight, well maintained exterior walls, doors, windows, and finishes 3 – Sound, weatherproof, some wear and tear 5 – Deteriorated, leaking, significant air infiltration
J. Service Systems	32. Mechanical Heating	1 – Favorable building user comments, adequate capacity, easily controlled 3 – Require routine maintenance, balancing, generally adequate 5 – Inadequate capacity, zoning, distribution

J. Service Systems			39	I. Rating Subtotal	I. Estimate Subtotal: $70,910	
30. Conveying	3	x 3	9	Bridge crane repaired in 2009	$0	$0
31. Mechanical Plumbing	5	x 5	25	Corroded and broken, needs repair. Some areas not working.	$300,000	$0
32. Mechanical Heating	4	x 8	32	Boiler fired hot water heat. Electric baseboard. Gas fired tublar radiant heat. Controls and valves need replacing. Cost in line 33	$0	$0
33. Mechanical Cooling/Ventilation	4	x 5	20	Through wall electric AC units in offices. Need roof mounted gas pack units. Need rooftop AC in office. Awnings would help.	$320,000	$0
34. Electrical Service Distribution	1	x 5	5	Distribution panels replaced in 2005.	$0	$0
35. Emergency Power	2	x 8	16	3 generators on site could be consolidated in one large one.	$0	$0
36. Bldg. Electrical Lighting/Power	3	x 5	15	Good illimination in shop, adequate in office. Could be improved with more efficient fixtures in parts room.	$0	$0
37. Voice and Data	2	x 6	12	Adequate telecommunications system but not most current.	$0	$0
			134	J. Rating Subtotal	J. Estimate Subtotal: $620,000	

Figure 2: Section of an actual building condition assessment form

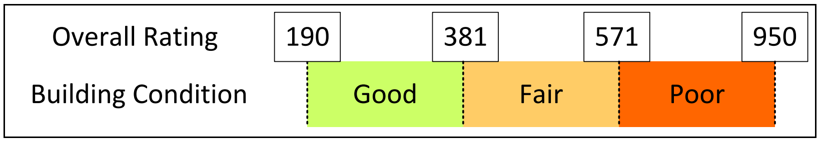


Figure 3: Building overall condition range (site item ratings are excluded)

1.1.2 Deficiencies Prioritization Procedure

WSDOT developed a procedure to prioritize the issues identified in the site and building assessment forms. The issues can be rectified either by repair and replacement projects or preventive maintenance operations. Prioritization procedure characteristics are described in the following paragraphs.

<u>Repair and replacement projects</u>

If the estimated cost to correct the deficiency is greater than $1 million, the repair/replacement is considered major. First, each region identifies the major repair/replacement projects by considering operational importance and condition of the facility, as well as region strategic planning efforts (WSDOT, 2012). Then, the projects are prioritized at the state level using a matrix considering four criteria (WSDOT, 2012):

- Amount of facility occupant deficiencies (i.e., deficiencies that put the facility at high risk of failure or citation);
- Amount of preservation deficiencies (i.e., deficiencies related with deteriorated building or site components);
- Amount of occupational deficiencies (i.e., deficiencies related with the need to have more crew, vehicle, or material storage space); and,
- Age of building.

If the estimated cost to correct the deficiency is less than $1 million, the repair/replacement project is considered minor and is prioritized at the region level into three categories:

> - Occupant projects are those that contain hazardous site or building conditions that may jeopardize health and safety of staff, the public, and the environment, and/or are immediate violations of local, state, or federal regulations.
> - Preservation projects replace and preserve failing buildings systems or elements that have a high risk of failure and require constant corrective maintenance.
> - Operational projects correct insufficient building space, provide wireless communication, and/or improve facility components that impact 'mission critical' operations.
>
> (WSDOT, 2011, p. 11)

The repair/replacement projects falling into the occupant category are addressed first.

<u>Preventive maintenance</u>

Issues to be addressed by preventive maintenance are prioritized according to the level of criticality (Table 3). Given the actual budget, "nearly one third of Category 6 and all Categories 5 and lower are not funded" (WSDOT, 2012, p. 10).

Table 3: Prevention Maintenance Level of Criticality (adapted from WSDOT 2012)

Level of Criticality	Activities
10 – Life safety	Hazardous building or site conditions that jeopardize life safety of occupants and impact building occupancy
9 – Code compliance	Mandated compliance with local, state or federal building regulations
8 – Critical systems	Prevention of serious facility deterioration and significantly higher costs if not immediately addressed
7 – Environmental compliance	Mandated compliance with local, state or federal environmental regulations which do not impact building occupancy
6 – Primary systems	Required to support primary systems and equipment. Comprises the majority of site and building equipment and systems
5 – Secondary Systems	Required to support secondary systems and equipment
4 – Long-term cost effective measures	Energy or functional conservation measures with a rapid return on investment
3 – Non-structural maintenance	Prevents facility component deterioration and/or potential loss of use or affects economies of operation
2 – Appearance	Required to maintain the image of WSDOT facilities

1.2 Importance of WSDOT Vehicles and Equipment in Fulfilling Its Mission

As stated in the WSDOT mission statement, WSDOT is in charge of operating, maintaining, and improving all state routes in Washington in a timely and efficient manner. To operate and maintain all the state routes, WSDOT employees perform and/or manage numerous activities. In particular, vehicles (e.g., cars, trucks, and boats) and equipment (e.g., radio systems, pumps, arrow boards, and signs) are among the key assets necessary to perform most of these activities. For instance, vehicles and equipment are necessary to:

- Provide transportation to Incident Response Teams (Figure 4);
- Manage traffic through travel information equipment (Figure 5);
- Perform Snow and Ice Control (S&IC) operations (Figure 6);
- Allow efficient communication among personnel even in remote areas (Figure 7); and,
- Provide transportation to departmental personnel to accomplish official state business in an effective manner.

Figure 4: Incident Response Team truck (credit: WSDOT)

Figure 5: A trailer mounted arrow board

Figure 6: A snow blower (credit: WSDOT)

Figure 7: WSDOT radio crews installing dishes and antennas (credit: WSDOT)

In particular, vehicles and equipment for S&IC operations are extremely important during the cold season. Delays and/or inefficiencies in removing the snow and preventing or delaying the formation of ice can generate extremely serious consequences on the road-users in terms of traffic delays and disruptions as well as accidents (Figure 8).

Figure 8: Highway I-5 near Martin Luther King Jr. Way on November 22, 2010 (credit: WSDOT)

1.2.1 The Role of Transportation Equipment Fund Shops

To ensure proper care and maintenance of most of the state vehicles and equipment, WSDOT established several Transportation Equipment Fund (TEF) shops in the state. In particular, the TEF shop personnel are in charge of:

- Performing routine maintenance procedure on WSDOT vehicles (e.g., change oil, filters, and tires) and equipment (e.g., change plow blades);
- Repair damaged vehicles (e.g., repair broken engines) and equipment (e.g., repair radio antennas); and,
- Upgrade vehicles (e.g., install radio systems in cars and trucks).

Although few activities are outsourced, most activities are performed in WSDOT's TEF shop facilities. Therefore, WSDOT must maintain such facilities in an effective and prompt manner.

In fact, any reduction of TEF shop facilities' capabilities could jeopardize not only WSDOT vehicles and equipment maintenance but also WSDOT's ability to fulfill its mission (Figure 9).

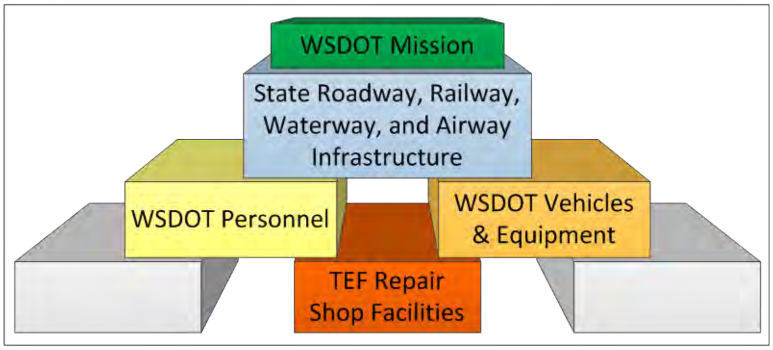


Figure 9: Role of TEF shop facilities in Washington State Department of Transportation (WSDOT) mission fulfillment

2. Aim of the Study

The aim of this study is to investigate how WSDOT operations can be affected by failures that have occurred or are likely to occur in TEF shops by analyzing operations of these facilities. In particular, the research team analyzed how failures occurring at the TEF shop located in Corson Avenue South (Seattle, WA) (Figure 10) can affect the TEF shop repair bays area service activities and WSDOT snow and ice control (S&IC) operations.

The Corson Avenue South TEF shop was selected for this study because it is the biggest TEF shop in the state, services most of the vehicles and equipment used in area 5 (Figure 11), and services vehicles from other areas when necessary (e.g., when another TEF shop does not have any bay available to service a vehicle or a vehicle is too big for the TEF shop).

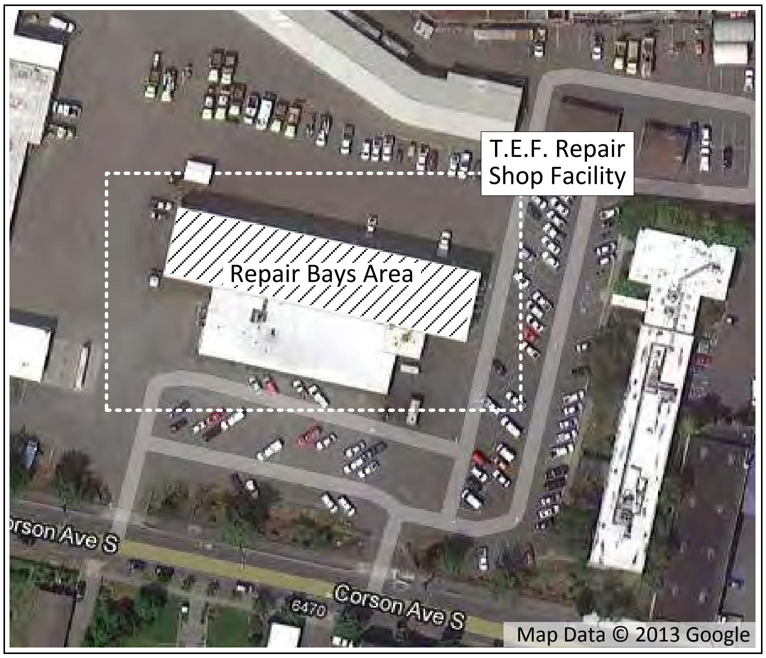


Figure 10: The Corson Avenue South TEF shop

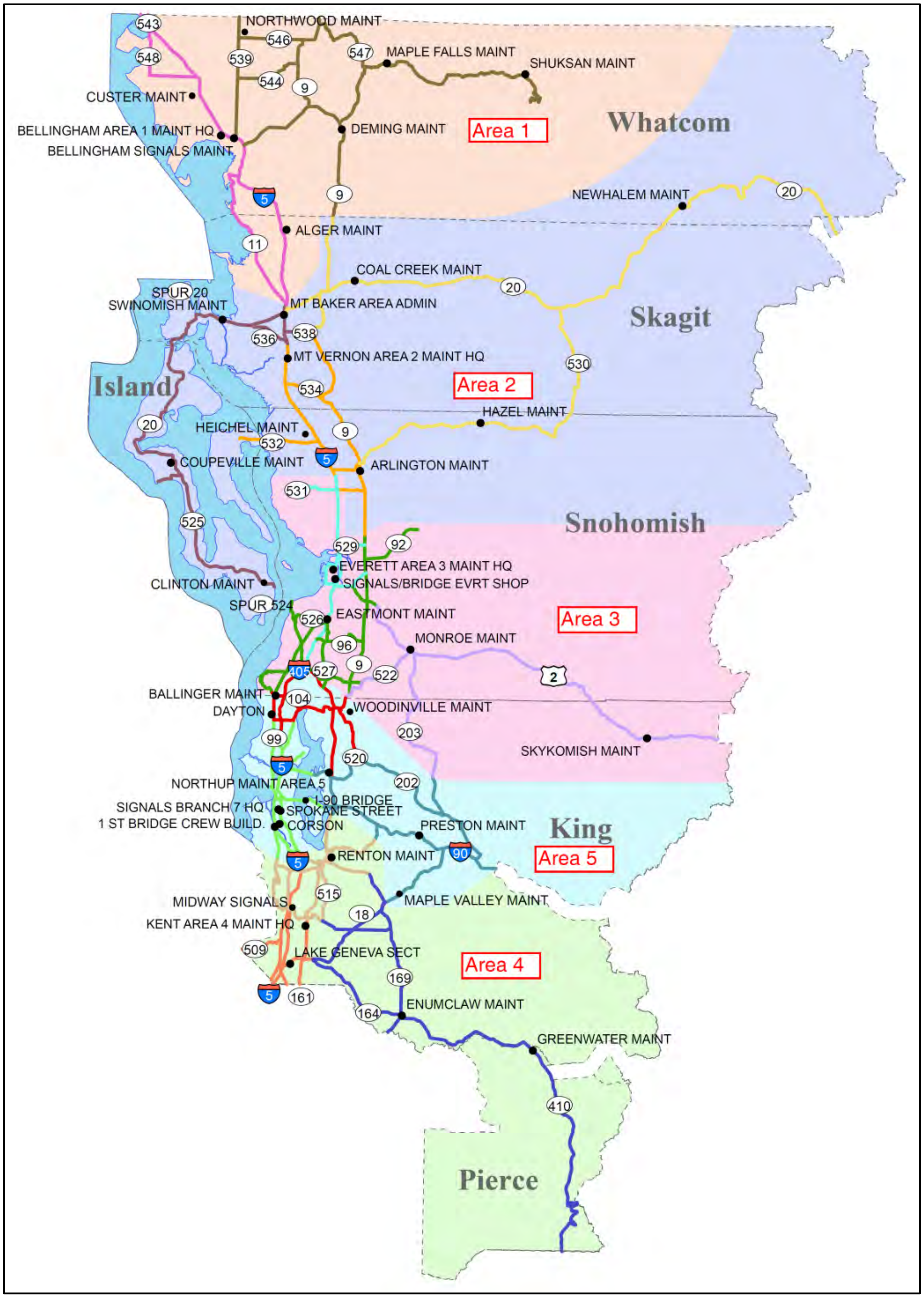


Figure 11: WSDOT areas for the Northwest region (credit: WSDOT)

3. Research Design

Research activities included:

- Data Collection
  The research team gathered data about the TEF shop activities, facility conditions, and failures.

- Modeling of the repair bays area activities during routine conditions
  The research team used a discrete-event simulation tool to create a model capable of simulating the activities performed in the repair bays area during routine conditions.

- Analysis of the consequences of failures
  The research team analyzed the failures that occurred at the TEF shop and determined failures' consequences on TEF shop repair bays area activities and WSDOT S&IC operations. Three analyses were performed:
  - Analysis #1 – Loss in number of serviced vehicles (and equipment)
    By simulating the consequences of failures on the shop service activities, the loss in number of serviced vehicles was determined as:

$$\textit{Loss in number of serviced vehicles} = \textit{Number of vehicles serviced in routine conditions} - \textit{Number of vehicles serviced when a failure occurs}$$

  - Analysis #2 – Loss in number of serviced Snow and Ice Control (S&IC) vehicles (and equipment)
    By simulating the consequences of failures on the shop service activities, the loss in number of serviced S&IC vehicles was determined as:

$$\textit{Loss in number of serviced S\&IC vehicles} = \textit{Number of S\&IC vehicles serviced in routine conditions} - \textit{Number of S\&IC vehicles serviced when a failure occurs}$$

  - Analysis #3 – Loss in number of plowed lane-miles
    First, by simulating the consequences of failures on the shop service activities, the delay in servicing S&IC trucks was determined as:

$$\textit{Delay in servicing S\&IC trucks} = \textit{Time necessary to serve a certain number of S\&IC trucks in routine conditions} - \textit{Time necessary to serve the same number of S\&IC trucks when a failure occurs}$$

    Second, by using the average speed of trucks plowing snow from state routes, the loss in number of plowed lane-miles was determined as:

$$\textit{Loss in plowed lane-miles} = \textit{Delay in servicing S\&IC trucks} \times \textit{Average lane-mile plowing speed}$$

4. Data Collection

The research team gathered data from several sources to examine the activities performed, the procedures adopted, and the failures occurred in the shop. First, the research team visited the repair shop. Second, several meetings were held with WSDOT personnel in charge of managing the repair shop facility and activities. Then, the work orders of all the vehicles serviced in the repair shop from 2009 to 2011 (over 20,000 work items) were collected (Table 4). Finally, the service requests for maintenance operations performed at the repair shop from 2009 to 2012 were also analyzed.

Table 4: Sample of the Collected Work Order Data

Collected Information	Information Description	Sample Information
Location	TEF shop location	NWRTEF
Unit No	Vehicle/ piece of equipment information	06A06060
Description		TRK; ABOVE 38KGVW; 4X2; CONT B
Year		2001
Make		INTERNATL
Model		2574
Using Department		415520
WO No	Work order number	371107
Job Code	Service operation information	CM-034-006
Job Reason		Q
WAC Code		CM
WAC Description		Cmaq
System Code		034
System Description		Lighting System
Component Code		006
Component Description		Warning Lights - Special App
WO Open Dt	Work order opening date	18-Jan-2009
WO Close Dt	Work order closing date	22-Jan-2009
Job Part Quantity	Service operation cost and time information	1
Job Part Do		$127.49
Job Comm Do		$0.00
Job Labor Hours		14.93
Job Labor Do		$501.01

5. Modeling the Repair Bays Area Activities during Routine Conditions

The following sections describe the procedure followed by the research team to develop a repair bays area model capable of simulating the activities performed in routine conditions. First, the used simulation software tool is presented. Second, the data analysis steps are described. Third, the model structure is discussed and validated.

5.1 The Simulation System

Operations performed in the repair bays area are modeled using a discrete-event simulation software tool called Stroboscope through its graphical user interface, EZStrobe. Both were developed by Prof. Julio Martinez (Martinez, 1996, 2001). For simplicity, we will identify this simulation system as S/EZ throughout the rest of the report. This simulation system allows simulating a sequence of activities by:

- Utilizing inputs, such as the resources necessary to perform each activity, and the duration of each activity;
- Recording the activities' outputs; and,
- Executing a simulation of the activities sequence according to the user defined network.

For instance, let's consider a typical activity occurring at an auto repair shop consisting of a mechanic repairing a car. First, it is necessary to determine the inputs and outputs for the activity:

- Inputs. To repair a car the mechanic needs a car to be fixed and an available bay inside the repair shop. Thus, we can determine that the resources necessary to perform the activity are one car and one bay. Further, it is necessary to know the activity duration (e.g., 2 hours).
- Outputs. Two resources are released by executing the activity. First, the car has been repaired. Second, the bay in the shop is available for another car.

The inputs and outputs are summarized in Table 5.

Table 5: Conditions Needed to Start, Outputs, And Duration of the Activity

Activity	Conditions Needed to Start	Outputs	Duration
The mechanic repairs the car	• One car waiting to be repaired • One staffed bay available in the shop	• One car is repaired • One staffed bay is now available in the shop	2 hr.

Second, it is necessary to develop the activity network by using an activity cycle diagram (aka flow diagram). In activity cycle diagrams, activities are represented as squares, and resources are stored in queues and represented as circles. Further, arrows are used to determine the relationship among diagram elements. Figure 12 shows the network developed for the activity.

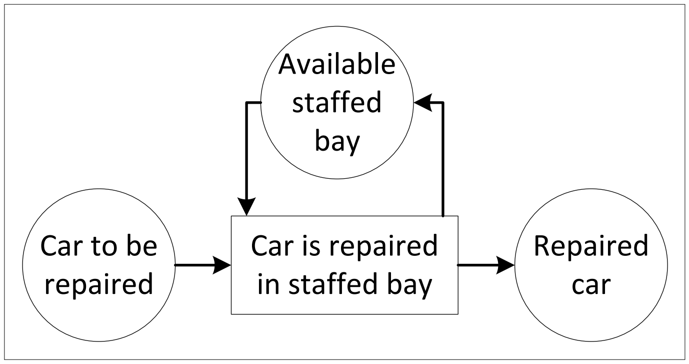
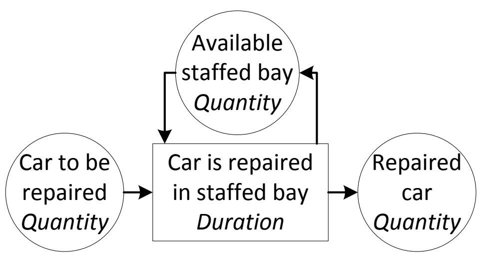


Figure 12: Activity network

Once the model has been developed, S/EZ is capable of simulating the modeled activities and recording how resources and outputs change over time (see Table 6).

Table 6: Simulation Steps - First Example

<table>
<tr><th colspan="2">Step 1 – Resources are loaded in the model</th></tr>
<tr><td>Description: S/EZ reads the inputs and loads them in the corresponding activity, resources, or outputs</td><td>Time in Simulation
0 hr.</td></tr>
<tr><td>Unloaded Model

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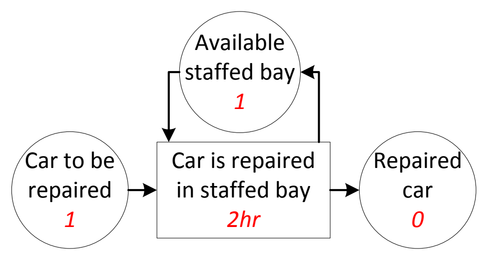
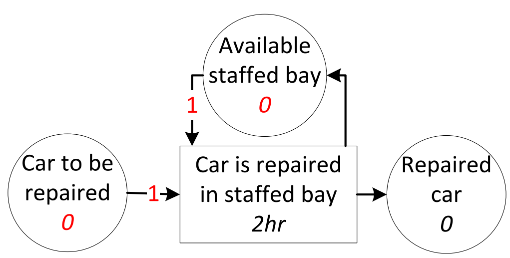
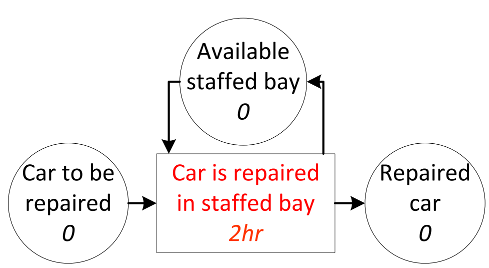
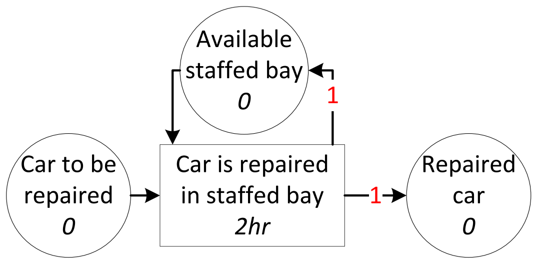

</td></tr>
<tr><th colspan="2">Step 2 – Activities are selected</th></tr>
<tr><td>Description: S/EZ determines if the activity can be started by analyzing if all the necessary resources are available, and transfers such resources to the activity.</td><td>Time in Simulation
0 hr.</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><th colspan="2">Step 3 – Activities are performed</th></tr>
<tr><td>Description: S/EZ performs the activity.</td><td>Time in Simulation
From to 0 to 2 hr.</td></tr>
<tr><td colspan="2">
</td></tr>
</table>

Table 6: Simulation Steps - First Example (continued)

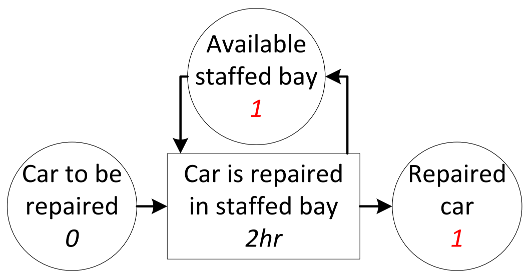
Step 4 – The Activity is accomplished

Description	Time in Simulation
Description: S/EZ determines that the activity is accomplished (two hours has passed since the beginning of the simulation) and generates the related outputs (releases the resources).	2 hr.



Step 5 – End of the simulation

Description	Time in Simulation
Description: S/EZ determines the available resources and outputs.	2 hr.



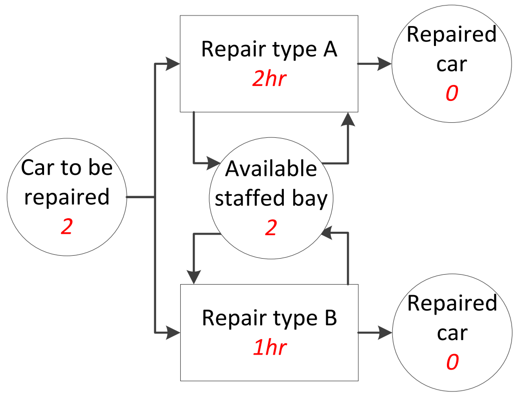
In the previous example just one activity was performed. Let's now consider if two staffed bays are available in the repair shop. Therefore, two cars can be repaired at the same time. Further, it is also assumed that the repair activities on the cars have different time durations. The inputs and outputs are summarized in Table 7, and the simulation steps are illustrated in Table 8.

Table 7: Conditions Needed to Start, Outputs, And Duration of the Activities

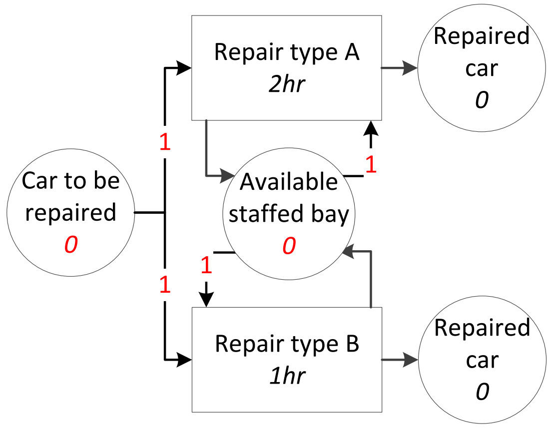
Activity	Conditions Needed to Start	Outputs	Duration
Mechanic 1 performs repair type A	• One car waiting to be repaired • One staffed bay available in the shop	• One car is repaired • One staffed bay is now available in the shop	2 hr.
Mechanic 2 performs repair type B	• One car waiting to be repaired • One staffed bay available in the shop	• One car is repaired • One staffed bay is now available in the shop	1 hr.

Table 8: Simulation Steps - Second Example

Step 1 – Resources are loaded in the model	
Description: S/EZ reads the inputs and loads them in the corresponding activities, resources, or outputs	**Time in Simulation** 0 hr.



Step 2 – Activities are selected	
Description: S/EZ determines which activities can be started by analyzing if all the necessary resources are available, and transfers such resources to the activities.	**Time in Simulation** 0 hr.



Step 3 – Activities are performed	
Description: S/EZ performs the activities.	**Time in Simulation** From 0 to 1 hr.

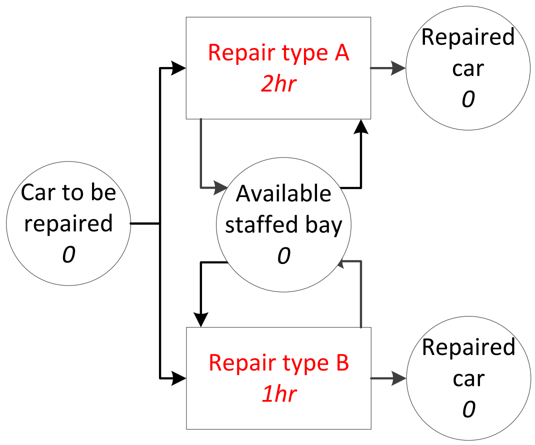
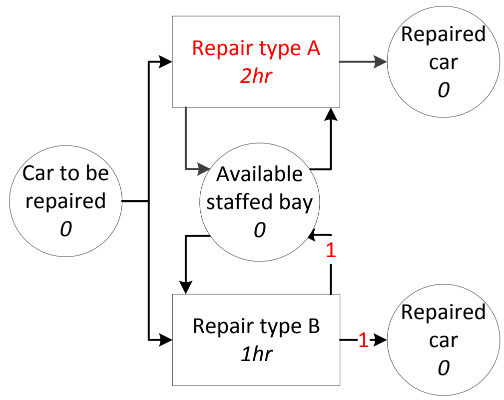
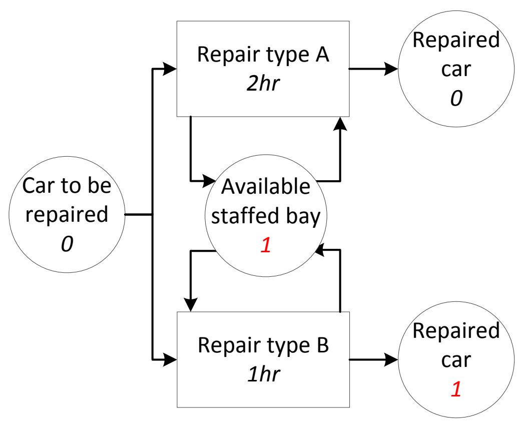


Table 8: Simulation Steps - Second Example (continued)

Step 4 – Activity Repair Type B is accomplished	
Description: S/EZ determines that the activity Repair Type B is accomplished and generates the related outputs.	**Time in Simulation** 1 hr.



Step 5 – End of Activity Repair Type B	
Description: After 1 hour, one car is repaired (Type B) and the corresponding bay becomes available. S/EZ determines the available resources and outputs.	**Time in Simulation** 1 hr.



Step 6 – Activity Repair Type A is accomplished	
Description: S/EZ determines that the activity Repair Type A is accomplished and generates the related outputs.	**Time in Simulation** 2 hr.

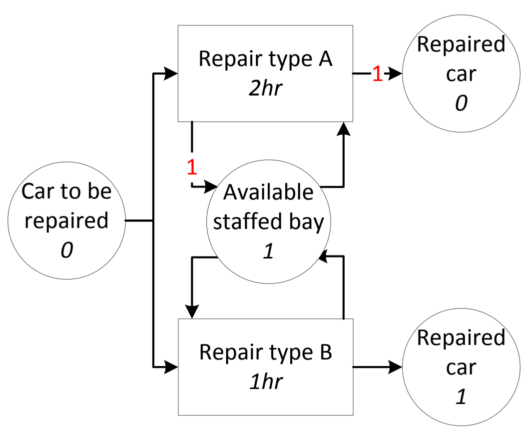
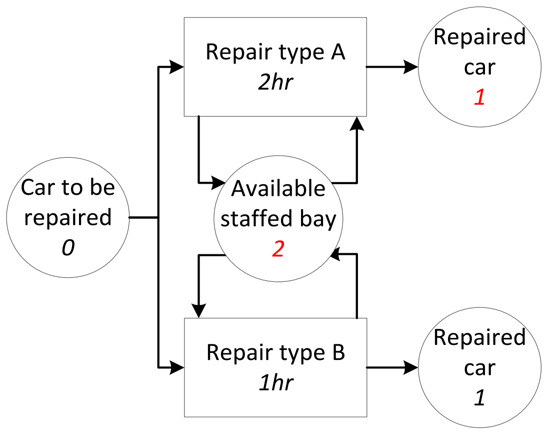


Table 8: Simulation Steps - Second Example (continued)

Step 5 – End of the simulation	
Description: S/EZ determines the available resources and outputs.	**Time in Simulation** 2 hr.



5.2 The Repair Bays Area Model

According to the collected information, the TEF shop personnel perform and oversee a wide range of activities. The model described in the following sections focuses on the activities performed in the repair bays area (Figure 13), such as repairing, maintaining, and upgrading WSDOT vehicles.

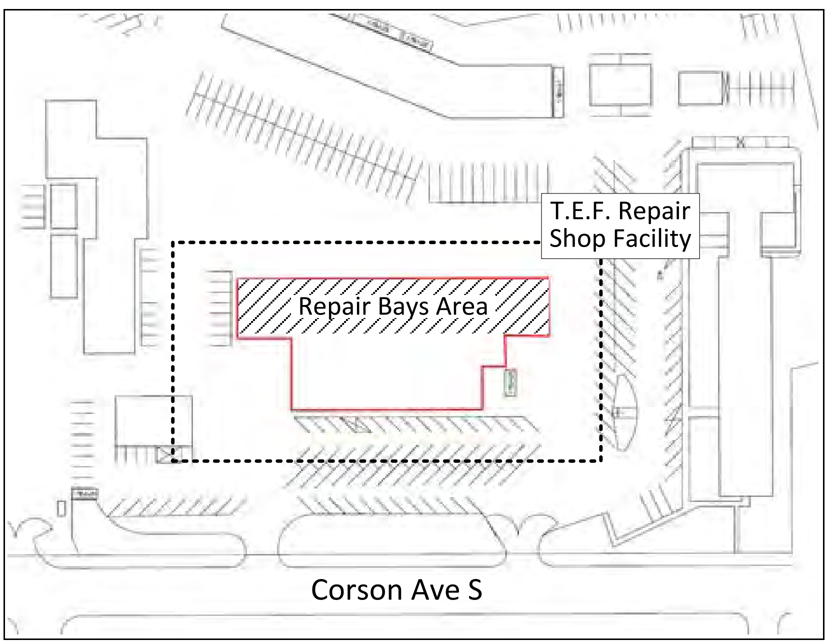


Figure 13: TEF repairs shop facility plan

5.2.1 Data Analysis

A preliminary review of the all the TEF shop work orders closed from 2009 to 2011 revealed that over 170 different types of vehicles were serviced, repaired, and/or upgraded. Further, repair shop personnel close hundreds of work orders per month. Generally, the winter season is critical for the repair shop activities. Snowstorms can create serious issues to road-users. Therefore, the repair shop has to be ready in preparing and servicing the Snow and Ice Control (S&IC) vehicle fleet. Thus, the research team decided to analyze the work orders completed in January, February, and March of 2009, 2010, and 2011.

In order to obtain the information necessary for the model, the research team analyzed the data according to the following steps (Figure 14). First, the research team grouped the data to obtain homogeneous vehicle groups according to three parameters (Table 9 and Appendix A):

- Vehicle characteristics (e.g., pick-up trucks vs. trucks);
- Priority in being serviced; and,
- Number of bays occupied while being serviced.

Further, to target S&IC vehicles, the vehicle groups containing SI&C vehicles were subdivided into S&IC vehicles and NO-S&IC vehicles (i.e., vehicles not used for snow and ice control operations).

Second, for each vehicle group, the research team analyzed the work order durations to determine the frequency distribution (Figure 15). Finally, probability distribution fitting tools were used to determine which probability distribution could best fit each work order duration frequency distribution (Table 10 and Appendix B).

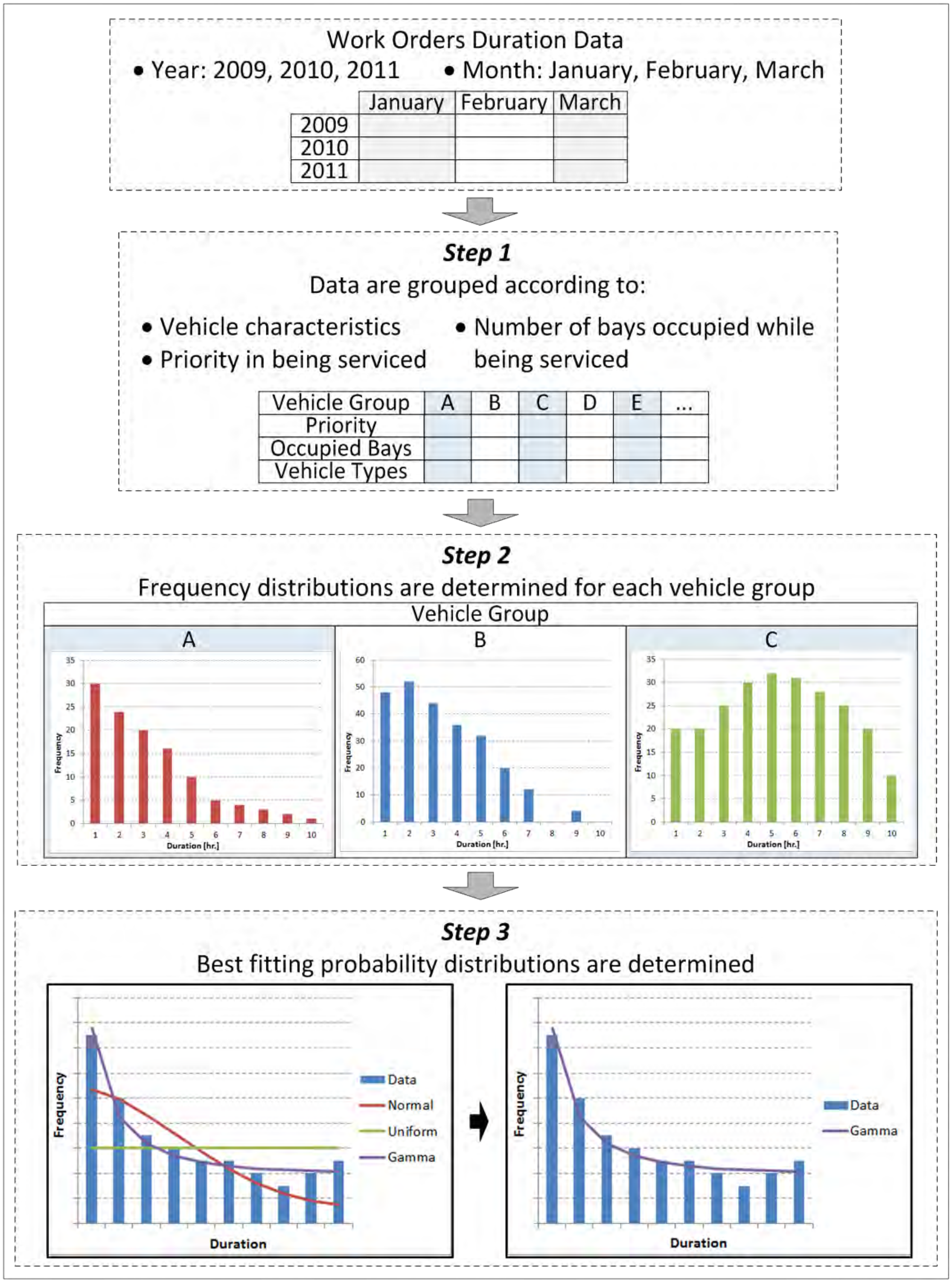


Figure 14: Data analysis steps.

Table 9: Sample of Vehicle Groups Main Characteristics

Vehicle group A	
Priority: 2 (1 least important, 5 most important)	*Number of occupied bays*: 1
Vehicles Types: 1 TON, CREW CAB; GAS; 4X2 ~ 1 TON; CREW CAB; DSL; 4X2 ~ 1/2 TON CREW CAB 4X4 ~ 1/2 TON, EXTENDED CAB; 4X2 ~ 1/2 TON, REGULAR OR EXTENDED C ~ 1/2 TON; CREW CAB 4X2 ~ 1/4 TON; EXTENDED CAB; 4X2 ~ 1/4 TON; EXTENDED CAB; 4X4 ~ 3/4 & 1 TON, CREW CAB; GAS; 4X ~ 3/4 TON; EXT CAB; DSL; 4X2 ~ 3/4 TON; EXT CAB; DSL; 4X4 ~ 3/4 TON; EXT CAB; GAS; 4X2 ~ 3/4 TON; EXT CAB; GAS; 4X4 ~ 3/4 TON; REGULAR CAB; DSL; 4X2 ~ PICKUP TRUCKS ~ SEDAN; GAS-ELECTRIC HYBRID ~ SEDAN; MID SIZE ~ STATION WAGON ~ PASSENGER CARRYING VEHICLE	
Vehicle group M (vehicle groups with S&IC vehicles)	
Priority: 5 (1 least important, 5 most important)	*Number of occupied bays*: 1
Vehicles Types: NO-S&IC vehicles: HERB SPRAY / ANTIICER; SKID MT ~ HERBICIDE SPARAYER; SKID MTD ~ S&IC vehicles: HOPPER SANDER; 10/12 YARD; W/ ~ HOPPER SANDER; 5/6 YARD ~ HOPPER SANDER; LESS THAN 2 YD ~ SANDER; TAILGATE ~ HOPPER SANDER; HITCH MOUNTED	

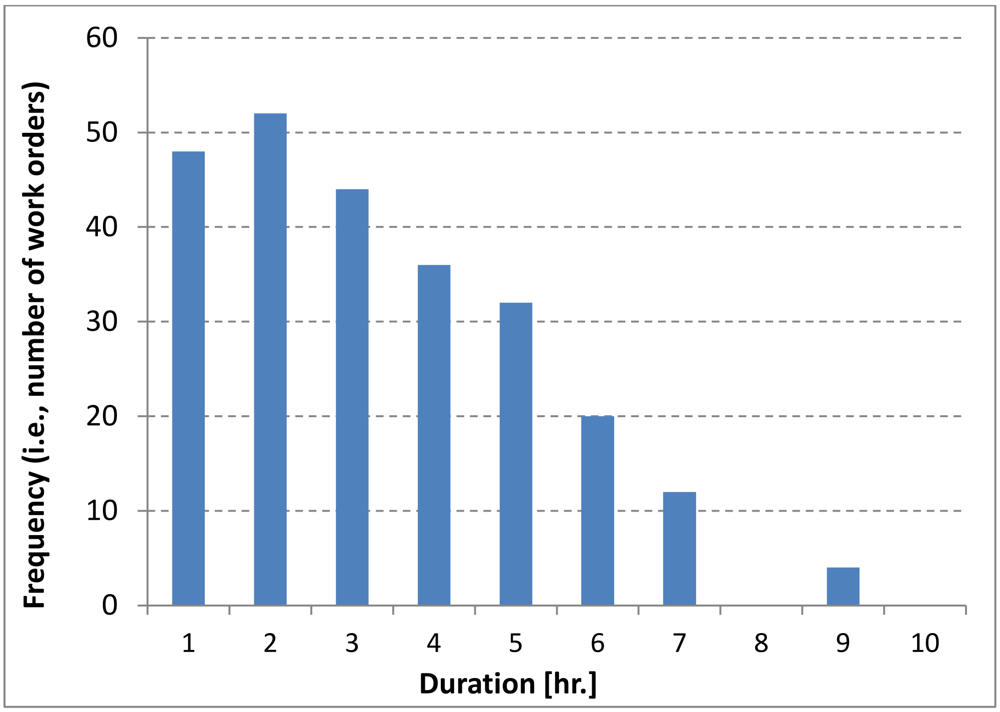
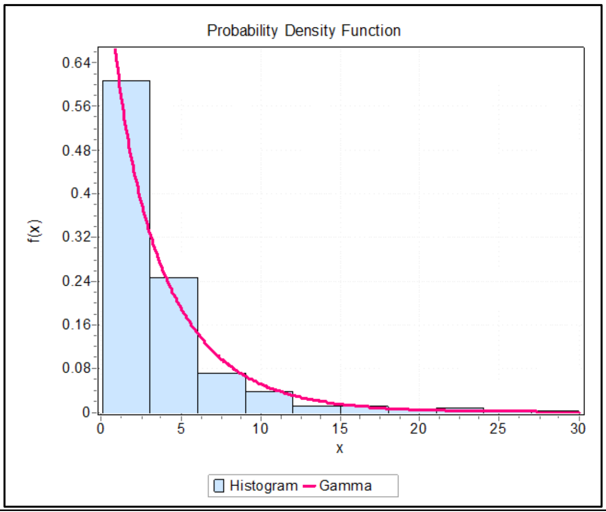
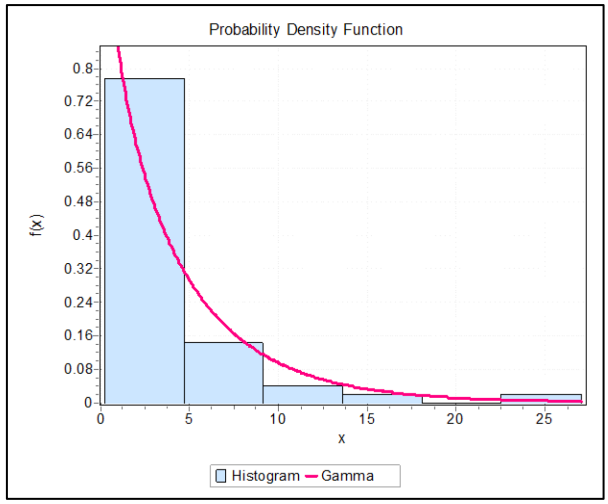


Figure 15: Example of frequency distribution.

Table 10: Sample of Best Fitting Probability Distribution for Each Vehicle Group

<table>
<tr><th>Vehicle Group A</th><th>Vehicle Group B</th></tr>
<tr><td>Number of work orders: 518
Work orders total duration: 1842 hr.
Best Fitting Distribution: Gamma
Distribution Parameters: Alfa= 0.845 and Beta = 4.185</td><td>Number of work orders: 49
Work orders total duration: 205 hr.
Best Fitting Distribution: Gamma
Distribution Parameters: Alfa= 0.845 and Beta = 4.917</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

5.2.2 Service Operation Steps

Any service operation performed on a vehicle can be represented as a series of steps (Figure 16):

- *Step 1.* When a vehicle needs to be serviced, it is parked outside the TEF repair shop;
- *Step 2.*When repair bays are available, the vehicle can be selected to be serviced in the repair bays area. The selection is based on the number of repair bays necessary to service the vehicle and its priority in being serviced;
- *Step 3.*When the vehicle is in a repair bay, it is serviced; and,
- *Step 4.*When the service is completed, the vehicle is taken out of the repair bays area.

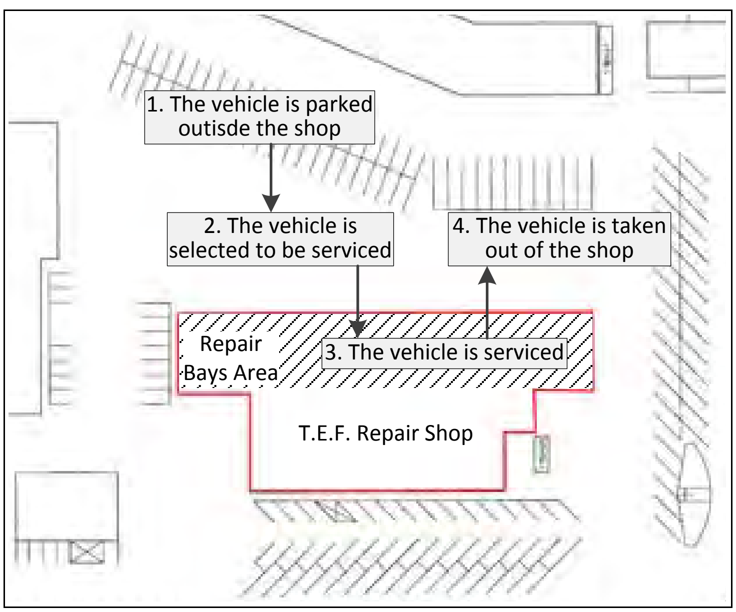


Figure 16: The service operation steps contextualized on the TEF repairs shop facility plan.

5.2.3 Model Structure

The service operation steps can be modeled with the simulation software tool as a series of activities and queues (Figure 17). The model is based on two activities, the Feed activity and the Service activity. The Feed activity models the operation of parking the vehicles that need to be serviced outside the repair shop (i.e., Step 1), while the Service activity models the operations of selecting the vehicles to be serviced, servicing the vehicles, and moving the serviced vehicles out of the repair shop (i.e., Step 2, 3, and 4). The characteristics of the Feed and Service activities are described in Table 11.

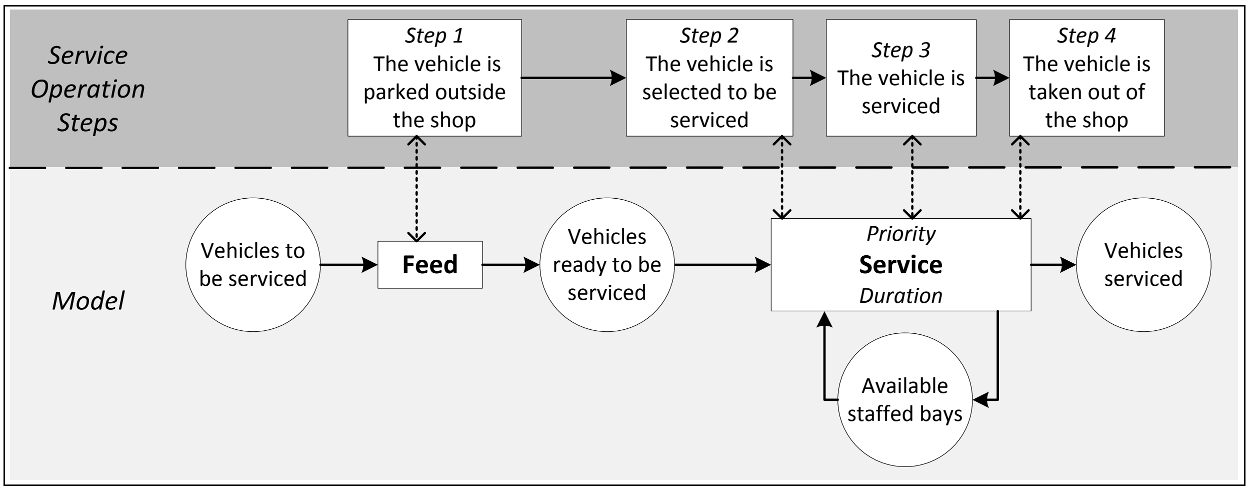


Figure 17: Service operation steps vs. model activities and queues.

Table 11: Logic, Conditions Needed to Start, and Outputs, of the Feed and Service Activities

Activity	*Feed*	*Service*
Logic	This activity can process only one vehicle at a time from the "vehicle to be serviced" queue to the "vehicle ready to be serviced" queue;	This activity can process several vehicles simultaneously from the "vehicle ready to be serviced" queue to the "vehicle serviced" queue. Further, this activity has to obtain the necessary bays from the "available staffed bays" queue before processing a vehicle, and it gives them back to the queue when the vehicle has been processed.
Conditions Needed to Start	• One vehicle from the "vehicles to be serviced" queue	• One vehicle from the "vehicles ready to be serviced" queue • One or more bays from the "available staffed bays" queue
Outputs	• One vehicle in the "vehicles ready to be serviced" queue	• One vehicle in the "vehicles serviced" queue • One or more bays in "available staffed bays" queue (same amount of bays necessary to start the activity)

Although all service operations can be modeled with the same activities, the characteristics of the Service activity (i.e., priority and duration) and the number of work orders are substantially different for each vehicle group (see Appendix A and Appendix B). Thus, it is necessary to repeat the basic series of activities and queues for each vehicle group to correctly model all the vehicles (Figure 18).

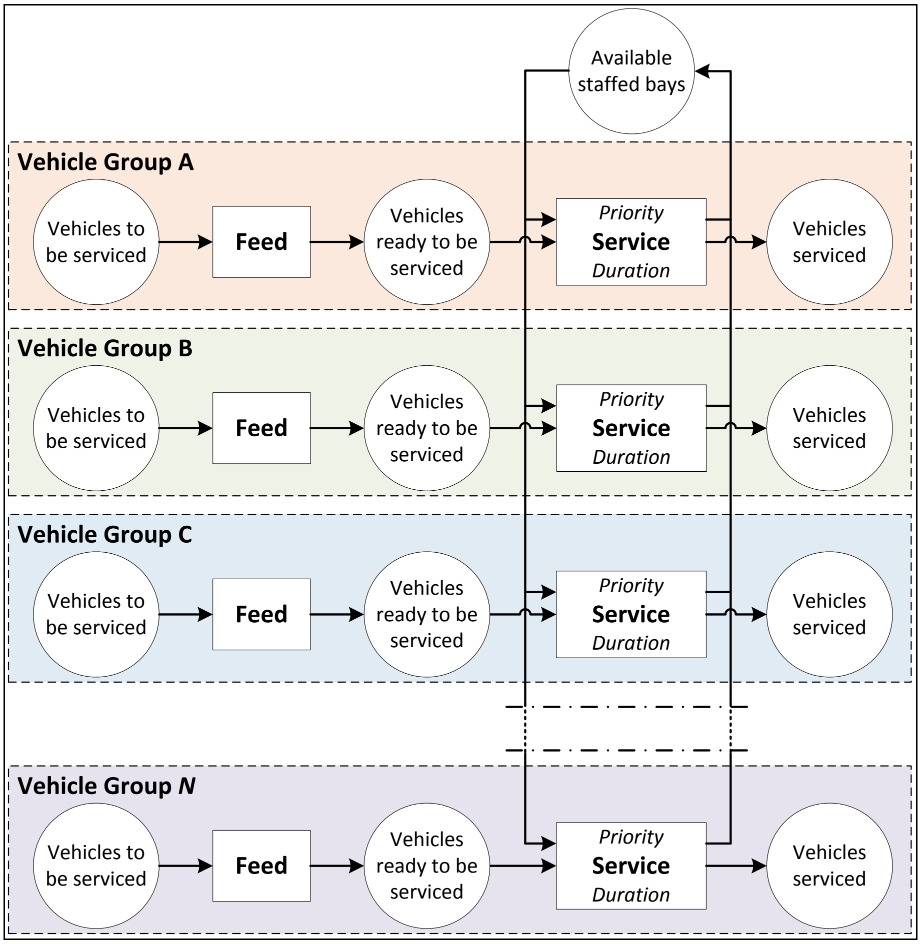


Figure 18: Repair bays area model structure.

Figure 18 clearly shows that all the Service activities are linked to the same "available staffed bays" queue. This condition mirrors the fact that only a finite number of repair bays are available in the shop to service all the vehicles. Further, it is possible to determine for each Service activity a specific priority in receiving resources. Therefore, the simulation software tool is able to allocate the available staffed bays to the Service activities according to the specified priorities.

5.2.4 Model Time vs. Actual Time

The research team analyzed work order data for a total duration of 13,809 hr. over a period of 9 months (i.e., January, February, and March of 2009, 2010, and 2011) as shown in Table 12.

Table 12: Work Order Duration and Number of Work Orders for Each Vehicle Group

Vehicle Group	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*	*L*	*M*	*N*	***Total***
Work order duration [hr.]	1842	205	672	20	0	273	2911	3596	2049	916	35	60	490	740	***13,809***
Number of Serviced Vehicles	518	49	126	4	0	11	370	254	211	45	2	4	33	48	***1675***

Considering that these work orders were performed on 12 repair bays over a period of 9 months, it is possible to determine that the average monthly working hours per bay is equal to 128 hr./(month × bay), where

$$128 \text{ hr./(month} \times \text{bay)} = \frac{13{,}809 \text{ hr.}}{12 \text{ bays} \times 9 \text{ months}}$$

The TEF shop is open 5 days per week from 6 am to 4 pm. Considering that TEF shop employees have a lunch break of 30 minutes and two breaks of 15 minutes each, each repair bay is used for a total of 180 hr./(month × bay), where

$$180 \text{ hr./(month} \times \text{bay)} = 4 \text{ weeks} \times 5 \text{ days} \times 9 \text{ hr.}$$

Thus, the collected data covers only 0.71 of the actual working hours, where

$$0.71 = \frac{128 \text{ hr./(month} \times \text{bay)}}{180 \text{ hr./(month} \times \text{bay)}}$$

Therefore, the model can simulate only 71% of the actual working hours. Thus, a *Simulation Coefficient* equal to 0.71 can be established to transform actual time to model time and vice versa:

$$\text{Simulation Coefficient} = 0.71$$

$$\text{model time} = \text{actual time} \times 0.71$$

For instance, if it is necessary to model the activity of the repair shop over a period of time of 1,000 hr., the models will have to run only for 710 hr. (1,000 hr. × 0.71 = 710 hr.).

5.2.5 Repair Bays Area Model Inputs – Routine Conditions

According to the model structure and data analysis results, the model inputs determined for the queues and activities in standard conditions were:

- *“Available staffed bays” queue*. The 12 available repair bays in the shop are used as resource in the queue;
- *“Vehicles to be serviced” queues*. The total number of work orders for each vehicle group (Appendix B) minus 1 is used as resource for the queue;
- *“Vehicles ready to be serviced” queues*. These queues are loaded with resources equal to 1 for each vehicle group;
- *“Vehicles serviced” queues*. Since no vehicle is serviced when the simulation starts, these queues are empty (i.e., resource = 0);
- *Feed activities*. To mirror real conditions, the duration for each vehicle group is equal to the ratio between 9 months expressed in model time (i.e., 9 months × Simulation Coefficient) over the total number of work orders for the vehicle group:

$$\text{Total Duration} = 9 \text{ months} \times 4 \text{ weeks/month} \times 5 \text{ days/week} \times 9 \text{ hr./day} = 1620 \text{ hr.}$$

$$\text{Feed Activity Duration for vehicle group } X = \frac{\text{Total Duration} \times \text{Simulation Coefficient}}{\text{Total number of work orders for vehicle group } X}$$

The feed activity durations are shown in Table 13; and,

Table 13: Feed Activity Duration for Each Vehicle Group

Vehicle Group	*A*	*B*	*C*	*D*	*F*	*G*	*H*	*I*	*J*	*K*	*L*	*M*	*N*
Feed Activity Duration [hr.]	2	23	9	288	105	3	5	5	26	575	288	35	24

- *Service activities*. The probability distribution (Appendix B) and priority (Appendix A) determined for each vehicle group are used as duration and priority, respectively.

5.3 Validation of the Repair Bays Area Model

To test the validity of the model, the research team determined the model accuracy by comparing the number of vehicles serviced by the model with the collected data in several time periods. In particular, the following procedure was implemented:

- *Step 1.* Calculate the Expected average number of Serviced Vehicles in a specific time period (ESV):

  ESV= (Total number of serviced vehicles in 9 months / 9 months) × Time Period

- *Step 2.* Calculate the Model Time Period (MTP):

  MTP = Time Period × 0.71 = number of weeks × 5 days/week × 9 hr./day × 0.71

- *Step 3.* Utilize the model in standard conditions to determine the total number of Serviced Vehicles (SV) during the MTP. To obtain statistically reliable results, the model iterated the simulation 1,000 times and, based on the 1,000 model iterations' outcomes, four parameters were generated:
  - Average: arithmetic means of SV values
  - St. Dev.: standard deviation of SV values
  - Max.: maximum SV value
  - Min.: minimum SV value
- *Step 4.* Calculate the Model Accuracy as:

  Model Accuracy = ESV - Average SV

The simulation results are summarized in Table 14.

Table 14: Validation Procedure Analysis Results

Time period	ESV [vehicle]	MTP [hr.]	SV [vehicle] – 1,000 Iterations				Model Accuracy	
			Average	St. Dev.	Max.	Min.	Vehicle	%
1 week	47	32	47	2.9	31	53	0	0.0
2 weeks	93	64	91	5.9	53	100	2	1.9
3 weeks	140	96	136	9.0	76	146	3	2.4
4 weeks	186	128	180	14.5	117	197	6	3.3
5 weeks	233	160	222	19.8	127	244	10	4.4
6 weeks	279	192	268	23.4	167	291	11	4.0
7 weeks	326	224	310	29.4	161	340	16	4.9
8 weeks	372	256	354	33.0	227	389	19	5.0

5.4 Discussion of Model Results

The obtained results show that the model is able to predict the expected number of serviced vehicles within an error of 5% in time periods from 1 week to 8 weeks (Figure 19). Therefore, it can be concluded that the model is accurate in capturing and simulating the service operations performed in the repair bays area of the TEF repair shop.

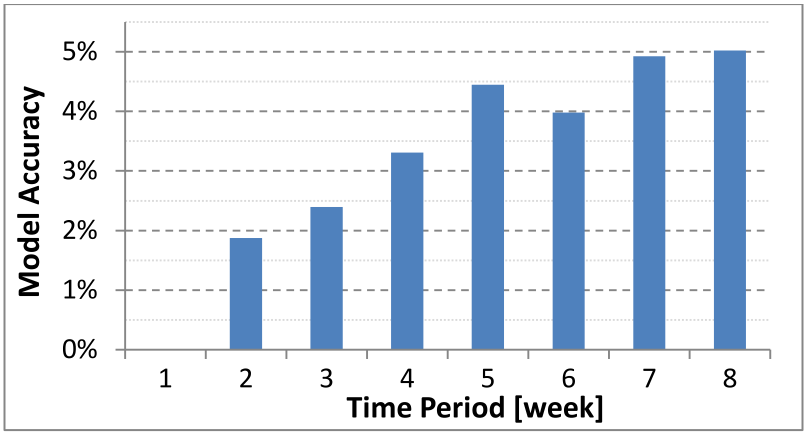


Figure 19: Model accuracy.

Analysis Limitations

The model is not capable of exactly simulating the repair bays operations mostly due to how the work order information is collected. Three typical scenarios may occur when a vehicle is serviced in the repair bays. TEF shop personnel may:

- Scenario A:
  1. Bring a vehicle in the shop and open the work order
  2. Service the vehicle, close the work order, and determine job labor hours
- Scenario B:
  1. Bring a vehicle in the shop and open the work order
  2. Move the vehicle out of the shop without servicing it (e.g., a spare part is not readily available). If the issue is minor, the vehicle can be used by WSDOT employees while waiting for the spare part
  3. Bring the vehicle back to the shop when it can be serviced (e.g., the spare part is now available). When the vehicle is serviced, the work order can be closed and the job labor hours can be determined
- Scenario C:
  1. Bring a vehicle in the shop and open the work order
  2. Move the vehicle out of the shop without servicing it (e.g., a spare part is not readily available). If the issue is major, the vehicle cannot be used while waiting for the spare part and, therefore, it is parked outside the shop
  3. Bring a vehicle in the shop when it can be serviced (e.g., the spare part is now available). When the vehicle is serviced, the work order can be closed and the job labor hours can be determined

As showed in Table 4, for each work order it is recorded the date in which the work order is opened (i.e., WO Open DT) and closed (i.e., WO Close DT), and the total job labor hours (i.e., Job Labor Hours). However, it is not recorded how many times a vehicle is brought in and out the shop before being serviced, and if and for how long the vehicle has to be parked in the TEF shop parking lot. Further, the date in which a work order is opened may not be the date in which the service operations start, and there is no certainty that work orders are closed as soon as vehicles are serviced. Therefore, although it is known how long it takes to service the vehicle (i.e., job labor hours), it is not possible to determine the exact days in which a vehicle is serviced. Given this lack of information, it was possible to build a model capable of simulating only Scenario A type service activities.

6. Analysis #1 – Loss in Number of Serviced Vehicles (and Equipment)

By analyzing the service requests for maintenance operations performed in the repair shop from 2009 to 2012, the research team identified the failures capable of affecting the repair bays area activities and caused by elements older than their expected life and/or worn out elements. Then, these failures were categorized in homogenous failure groups (Table 15). Finally, the research team performed a qualitative and quantitative analysis of the consequences for each failure group. In particular, the quantitative analysis (i.e., determine the loss in number of serviced vehicles) was accomplished by 1) using the model to determine the number of vehicles serviced when a specific failure occurs and the number of vehicles serviced in routine conditions, and 2) calculating the loss in number of serviced vehicles as

$$\text{Loss in number of serviced vehicles} = \text{Number of vehicles serviced in routine conditions} - \text{Number of vehicles serviced when a failure occurs}$$

Table 15: Failure Groups

Failure Group	Example of Failures
Air compressor system	Damaged air compressor and leakages
Building element	Damages on floor, interior walls, ceiling, and roof
Electric system	Issues with the welder circuit and lighting system
Exhaust gas removal system	Damaged exhaust fan and leakages
Heating system	Damaged water pipes and heating units, and leakages
Shop doors	Rotten door frame
Shop crane	Damaged crane tracks and supporting elements

Furthermore, the loss in number of serviced vehicles was calculated over three time periods:

- 1 week
  time period = 1 week × 5 days/week × 9 hr./day = 45 hr.
  model time period = time period × Simulation Coefficient = 45 hr. × 0.71 = 32 hr.
- 2 weeks
  time period = 2 weeks × 5 days/week × 9 hr./day = 90 hr.
  model time period = time period × Simulation Coefficient = 90 hr. × 0.71 = 64 hr.
- 3 weeks
  time period = 3 weeks × 5 days/week × 9 hr./day = 135 hr.
  model time period = time period × Simulation Coefficient = 135 hr. × 0.71 = 96 hr.

The outcomes of the analysis are presented in the following sections.

6.1 Air Compressor System

The role of the air compressor system is to supply compressed air to pneumatic tools, such as wrenches and drills. Most of these tools are essential for many service operations. In fact, the repair shop cannot fully operate without a supply of compressed air. In case of issues with the air compressor system, the shop personnel generally bring in a trailer or truck mounted air compressor until the shop air compressor system is repaired. Although the additional air compressor allows the repair shop to operate, it decreases the shop productivity. Since the mechanics cannot use the standard compressed air plugs located in each repair bay, they have to continuously move the air hoses connected to the additional air compressor. It is reasonable to assume that the increase in the duration of each activity is between 5% and 10%.

Failure Simulation

To simulate the consequences of this type of failure, the duration of the Service activities was increased once by 5% and once by 10%. All the model inputs for the routine and failure conditions are summarized in Table 16.

Table 16: Analysis #1 – Air Compressor System Model Inputs

	Routine Conditions	Failure Conditions
Available Staffed Bays Queue	12 available staffed bays	
Vehicles to Be Serviced Queues	The total number of work orders for each vehicle group (Appendix B) minus 1 is used as resource for the queue	
Vehicles Ready to Be Serviced Queues	These queues are loaded with resources equal to 1 for each vehicle group	
Duration of Feed Activities	Activity duration for each vehicle group is presented in Table 13	
Priority of Service Activities	Activity priority for each vehicle group is presented in Appendix A	
Duration of Service Activities	*Activity duration for each vehicle group is presented in Appendix B*	*The activity duration for each vehicle group is equal to the one presented in Appendix B increased once by 5% and once by 10%*

The simulation results based on 1,000 model iterations are presented in Table 17.

Table 17: Analysis #1 – Air Compressor System Failure Simulation Results

Time Period	Scenario	Number of Serviced Vehicles - 1,000 Iterations				Loss in Number of Serviced Vehicles	
		Average	St. Dev.	Min.	Max.	Vehicle	%
1 week	Routine Cond.	46.5	2.9	31	53	-	-
	Failure, +5%	46.3	3.0	32	53	-0.3	-0.6
	Failure, +10%	45.9	3.1	29	52	-0.6	-1.3
2 weeks	Routine Cond.	91.3	5.9	53	100	-	-
	Failure, +5%	90.5	6.2	53	99	-0.8	-0.9
	Failure, +10%	89.5	6.9	52	99	-1.8	-1.9
3 weeks	Routine Cond.	136.2	9.0	76	146	-	-
	Failure, +5%	134.1	10.6	83	147	-2.1	-1.6
	Failure, +10%	133.4	11.0	79	147	-2.9	-2.1

6.2 Building Element

Given the age of the TEF shop facility (it was built in 1954), its building elements, such as floor, interior walls, and roof, are prone to damages and failures. Repairing building element damages in an outdated industrial facility generally involves invasive construction activities, such as the erection of temporary structures. Therefore, in case of issues with one of the building elements, the shop personnel generally have to close one or more repair bays to allow the maintenance personnel to work in a safe environment.

Failure Simulation

To simulate the consequences of this type of failure, the number of available staffed bays was reduced to 11, 10, and 9. All the model inputs for the routine and failure conditions are summarized in Table 18.

Table 18: Analysis #1 – Building Element Model Inputs

	Routine Conditions	Failure Conditions
Available Staffed Bays Queue	*12 available staffed bays*	*11,10, and 9 available staffed bays*
Vehicles to Be Serviced Queues	The total number of work orders for each vehicle group (Appendix B) minus 1 is used as resource for the queue	
Vehicles Ready to Be Serviced Queues	These queues are loaded with resources equal to 1 for each vehicle group	
Duration of Feed Activities	Activity duration for each vehicle group is presented in Table 13	
Priority of Service Activities	Activity priority for each vehicle group is presented in Appendix A	
Duration of Service Activities	Activity duration for each vehicle group is presented in Appendix B	

The simulation results based on 1,000 model iterations are presented in Table 19.

Table 19: Analysis #1 – Building Element Simulation Results

Time Period	Scenario	Number of Serviced Vehicles - 1,000 Iterations				Loss in Number of Serviced Vehicles	
		Average	St. Dev.	Min.	Max.	Vehicle	%
1 week	Routine Cond.	46.5	2.9	31	53	-	-
	11 Bays Available	46.3	3.5	27	54	-0.2	-0.5
	10 Bays Available	45.7	4.3	24	53	-0.8	-1.8
	9 Bays Available	43.8	5.9	17	53	-2.7	-5.9
2 weeks	Routine Cond.	91.3	5.9	53	100	-	-
	11 Bays Available	89.7	7.8	48	101	-1.6	-1.8
	10 Bays Available	87.7	9.6	51	100	-3.7	-4.0
	9 Bays Available	82.3	12.4	38	100	-9.0	-9.9
3 weeks	Routine Cond.	136.2	9.0	76	146	-	-
	11 Bays Available	132.6	12.3	81	147	-3.6	-2.6
	10 Bays Available	127.0	16.7	65	149	-9.2	-6.8
	9 Bays Available	118.5	19.1	57	148	-17.7	-13.0

6.3 Electric System

The electric system is essential for the repair shop because it provides light and electricity for all the welding operations. In case of minor issues (e.g., necessity to repair a lamp), the shop personnel generally have to close one repair bay while the maintenance personnel are in the shop. Furthermore, the shop electric system is divided into three main circuits (Figure 20). Two circuits cover five bays each, and one circuit covers the two bays used for all the welding operations. Therefore, in case of major issues (e.g., necessity to re-wire an electric circuit), the shop personnel have to close two or five bays.

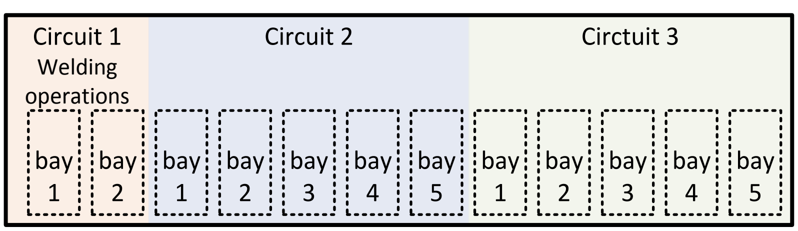


Figure 20: Repair bays area electric circuits.

<u>Failure Simulation</u>

To simulate the consequences of this type of failure, the number of available staffed bays was reduced to 11, 10, and 7. All the model inputs for the routine and failure conditions are summarized in Table 20.

Table 20: Analysis #1 – Electric System Model Inputs

	Routine Conditions	Failure Conditions
Available Staffed Bays Queue	*12 available staffed bays*	*11,9, and 7 available staffed bays*
Vehicles to Be Serviced Queues	The total number of work orders for each vehicle group (Appendix B) minus 1 is used as resource for the queue	
Vehicles Ready to Be Serviced Queues	These queues are loaded with resources equal to 1 for each vehicle group	
Duration of Feed Activities	Activity duration for each vehicle group is presented in Table 13	
Priority of Service Activities	Activity priority for each vehicle group is presented in Appendix A	
Duration of Service Activities	Activity duration for each vehicle group is presented in Appendix B	

The simulation results based on 1,000 model iterations are presented in Table 21.

Table 21: Analysis #1 – Electric System Simulation Results

Time Period	Scenario	Number of Serviced Vehicles - 1,000 Iterations				Loss in Number of Serviced Vehicles	
		Average	**St. Dev.**	**Min.**	**Max.**	**Vehicle**	**%**
1 week	Routine Cond.	46.5	2.9	31	53	-	-
	11 Bays Available	46.3	3.5	27	54	-0.2	-0.5
	10 Bays Available	43.8	5.9	17	53	-2.7	-5.9
	7 Bays Available	37.7	8.7	12	53	-8.8	-19.0
2 weeks	Routine Cond.	91.3	5.9	53	100	-	-
	11 Bays Available	89.7	7.8	48	101	-1.6	-1.8
	10 Bays Available	82.3	12.4	38	100	-9.0	-9.9
	7 Bays Available	67.1	16.0	25	99	-24.2	-26.6
3 weeks	Routine Cond.	136.2	9.0	76	146	-	-
	11 Bays Available	132.6	12.3	81	147	-3.6	-2.6
	10 Bays Available	118.5	19.1	57	148	-17.7	-13.0
	7 Bays Available	92.9	21.4	33	146	-43.4	-31.8

6.4 Exhaust Gas Removal System

The role of the exhaust gas removal system is to collect and remove the exhaust gas produced by internal combustion engines. Since exhaust fumes contain numerous harmful gases and particles (e.g., carbon monoxide and hydrocarbons), any issue to the exhaust gas removal system has to be carefully addressed. In case this system cannot function properly, the shop personnel have to lay down hoses with one end attached to the vehicle exhaust pipes, and place the other end outside the shop. Although this solution allows the repair shop to operate, it does not collect and remove exhaust fumes as efficiently as the exhaust gas removal system. Further, it decreases the shop productivity because the mechanics have to manually lay down the hoses. It is reasonable to assume that the increase in the duration of each activity is at least of 15 minutes.

Failure Simulation

To simulate the consequences of this type of failure, the duration of the Service activities was increased of 15 minutes. All the model inputs for the routine and failure conditions are summarized in Table 22.

Table 22: Analysis #1 – Exhaust Gas Removal System Model Inputs

	Routine Conditions	Failure Conditions
Available Staffed Bays Queue	12 available staffed bays	
Vehicles to Be Serviced Queues	The total number of work orders for each vehicle group (Appendix B) minus 1 is used as resource for the queue	
Vehicles Ready to Be Serviced Queues	These queues are loaded with resources equal to 1 for each vehicle group	
Duration of Feed Activities	Activity duration for each vehicle group is presented in Table 13	
Priority of Service Activities	Activity priority for each vehicle group is presented in Appendix A	
Duration of Service Activities	*Activity duration for each vehicle group is presented in Appendix B*	*The activity duration for each vehicle group is equal to the one presented in Appendix B increased by 15 minutes*

The simulation results based on 1,000 model iterations are presented in Table 23.

Table 23: Analysis #1 – Exhaust Gas Removal System Simulation Results

Time Period	Scenario	Number of Serviced Vehicles - 1,000 Iterations				Loss in Number of Serviced Vehicles	
		Average	St. Dev.	Min.	Max.	Vehicle	%
1 week	Routine Cond.	46.5	2.9	31	53	-	-
	Failure, +15'	46.5	3.0	35	54	0.0	-0.1
2 weeks	Routine Cond.	91.3	5.9	53	100	-	-
	Failure, +15'	91.4	5.3	57	100	0.1	0.1
3 weeks	Routine Cond.	136.2	9.0	76	146	-	-
	Failure, +15'	135.7	9.1	87	148	-0.6	-0.4

6.5 Heating System

The heating system is essential to provide a comfortable work environment during cold weather. Although the shop personnel are expected to work even in a cold environment, their capacity to perform can be significantly impaired. For instance, they have to wear more and/or heavier clothes than usual and, therefore, their mobility is reduced. Further, wearing a pair of gloves can considerably hinder hand sensibility, precision, and grip. Therefore, heating system issues may decrease the shop productivity. It is reasonable to assume that the increase in the duration of each activity is between 10% and 15%.

Failure Simulation

To simulate the consequences of this type of failure, the duration of the Service activities was increased once by 10% and once by 15%. All the model inputs for the routine and failure conditions are summarized in Table 24.

Table 24: Analysis #1 – Heating System Model Inputs

	Routine Conditions	Failure Conditions
Available Staffed Bays Queue	12 available staffed bays	
Vehicles to Be Serviced Queues	The total number of work orders for each vehicle group (Appendix B) minus 1 is used as resource for the queue	
Vehicles Ready to Be Serviced Queues	These queues are loaded with resources equal to 1 for each vehicle group	
Duration of Feed Activities	Activity duration for each vehicle group is presented in Table 13	
Priority of Service Activities	Activity priority for each vehicle group is presented in Appendix A	
Duration of Service Activities	*Activity duration for each vehicle group is presented in Appendix B*	*The activity duration for each vehicle group is equal to the one presented in Appendix B increased once by 10% and once by 15%*

The simulation results based on 1,000 model iterations are presented in Table 25.

Table 25: Analysis #1 – Heating System Simulation Results

Time Period	Scenario	Number of Serviced Vehicles - 1,000 Iterations				Loss in Number of Serviced Vehicles	
		Average	St. Dev.	Min.	Max.	Vehicle	%
1 week	Routine Cond.	46.5	2.9	31	53	-	-
	Failure, +10%	45.9	3.1	29	52	-0.6	-1.3
	Failure, +15%	45.3	3.6	25.0	52.0	-1.2	-2.6
2 weeks	Routine Cond.	91.3	5.9	53	100	-	-
	Failure, +10%	89.5	6.9	52	99	-1.8	-1.9
	Failure, +15%	88.3	7.8	44	99	-3.0	-3.3
3 weeks	Routine Cond.	136.2	9.0	76	146	-	-
	Failure, +10%	133.4	11.0	79	147	-2.9	-2.1
	Failure, +15%	130.4	13.1	68	147	-5.8	-4.3

6.6 Shop Door

The access to each repair bay is provided by bi-fold door. These doors have not been replaced for a long time. Therefore, these doors are prone to damages and failures. Although small damages (e.g., a broken glass panel) disrupt the routine shop activities, they do not severely affect them. Nevertheless, these doors may also suffer of severe damages that prevent them from being properly opened and/or closed. Therefore, in case a shop door cannot be used, the shop personnel generally have to close the bay served by the door.

Failure Simulation

To simulate the consequences of this type of failure, the number of available staffed bays was reduced to 11. All the model inputs for the routine and failure conditions are summarized in Table 26.

Table 26: Analysis #1 – Shop Door Model Inputs

	Routine Conditions	Failure Conditions
Available Staffed Bays Queue	*12 available staffed bays*	*11 available staffed bays*
Vehicles to Be Serviced Queues	The total number of work orders for each vehicle group (Appendix B) minus 1 is used as resource for the queue	
Vehicles Ready to Be Serviced Queues	These queues are loaded with resources equal to 1 for each vehicle group	
Duration of Feed Activities	Activity duration for each vehicle group is presented in Table 13	
Priority of Service Activities	Activity priority for each vehicle group is presented in Appendix A	
Duration of Service Activities	Activity duration for each vehicle group is presented in Appendix B	

The simulation results based on 1,000 model iterations are presented in Table 27.

Table 27: Analysis #1 – Shop Door Simulation Results

Time Period	Scenario	Number of Serviced Vehicles - 1,000 Iterations				Loss in Number of Serviced Vehicles	
		Average	St. Dev.	Min.	Max.	Vehicle	%
1 week	Routine Cond.	46.5	2.9	31	53	-	-
	11 Bays Available	46.3	3.5	27	54	-0.2	-0.5
2 weeks	Routine Cond.	91.3	5.9	53	100	-	-
	11 Bays Available	89.7	7.8	48	101	-1.6	-1.8
3 weeks	Routine Cond.	136.2	9.0	76	146	-	-
	11 Bays Available	132.6	12.3	81	147	-3.6	-2.6

6.7 Shop Crane

The shop crane is an essential piece of equipment because it allows moving heavy loads (e.g., vehicle engines) within the shop. Thus, any crane issue can significantly affect the ability of the shop to perform several repair activities (e.g., replace a vehicle engine). Further, crane accidents due to failures or operator errors can seriously affect the shop personnel's safety. Therefore, it is imperative to properly maintain and operate such piece of equipment. In 2007, the shop crane suffered major damages to the tracks and support elements. In addition to rising safety concerns about the structural solidity of the crane, these damages prevented the shop personnel from using the crane on two repair bays. Therefore, those two bays had to be used only for activities that did not require the use of the crane.

<u>Failure Simulation</u>

Since the model cannot determine which activities need the crane to be accomplished, the consequences of this failure could not be simulated in the model.

6.8 Analysis #1 - Discussion of Model Results

The results obtained from all the performed simulations are summarized in Figure 21. The chart displays the simulated failure conditions on the x-axis, and loss in number of serviced vehicles between the routine condition and the failure condition on the y-axis. The simulation outcomes show that for most of the failure conditions the loss in number of serviced vehicles is less than 5 vehicles for all the three time periods. This roughly corresponds to a loss of -5% of serviced vehicles and, therefore, it is expected to not seriously impact overall WSDOT operations. However, <u>failures causing the loss of three or more repair bays can significantly impact the TEF shop service activities. In fact, the loss in number of serviced vehicles ranges from -3 (9 bays available; 1 week) to -43 vehicles (7 bays available; 3 week). Therefore, considering that the failures causing the closure of three or more repair bays can easily take at least one week to be fixed, it can be concluded that the loss of repair bays can seriously affect TEF shop service activities and, therefore, WSDOT overall operations.</u>

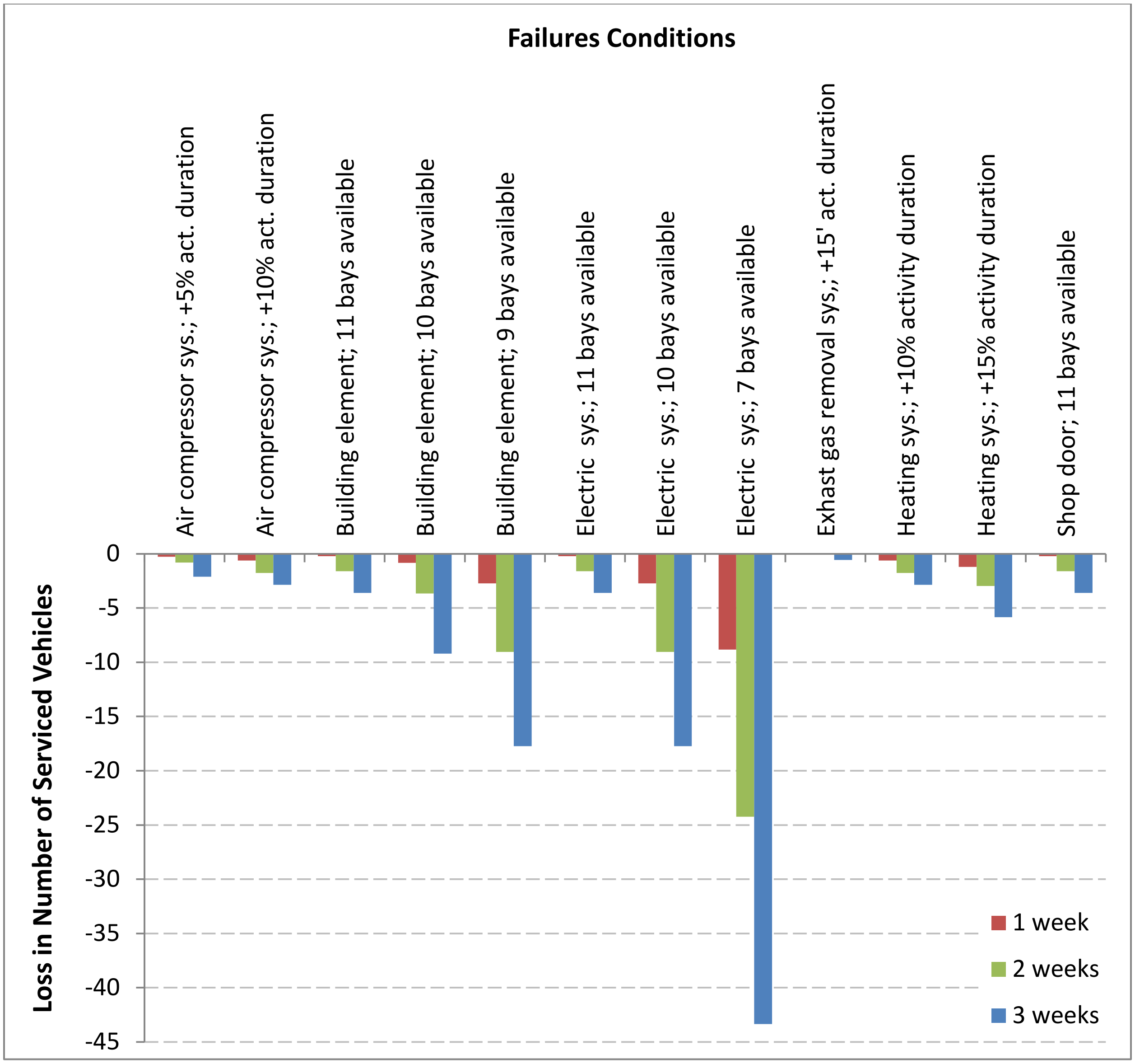


Figure 21: Loss in number of serviced vehicles for each failure conditions

<u>Analysis Limitations</u>

The presented failure conditions are based on information collected from the TEF shop personnel. Whereas some failure conditions can be clearly determine (i.e., a reduction in the number of available staffed bays), other failure conditions are solely based expert judgment (e.g., 10% increase in duration of Service activities).

7. Analysis #2 – Loss in Number of Serviced Snow and Ice Control vehicles (and Equipment)

The results obtained in Analysis #1 (Figure 21) clearly show that the failures reducing the available staffed bays are the ones capable of generating the highest loss in number of serviced vehicles. Therefore, the research team decided to focus on analyzing the impacts of failures involving a reduction of available staffed bays. Further, to obtain a comprehensive and consistent analysis of how the number of serviced vehicles changes according to the number of available staffed bays, it was decided to use from 11 to 3 available staffed bays as failure conditions. Similarly to Analysis #1, the quantitative analysis (i.e., determine the loss in number of serviced Snow and Ice Control, S&IC, vehicles) was accomplished by 1) using the model to determine the number of S&IC vehicles serviced when a specific failure occurs and the number of S&IC vehicles serviced in routine conditions, and 2) calculating the loss in number of S&IC serviced vehicles as

Loss in number of serviced S&IC vehicles **=** *Number of S&IC vehicles serviced in routine conditions* **–** *Number of S&IC vehicles serviced when a failure occurs*

Furthermore, the model outcomes were also used to determine the loss in number of NO-S&IC serviced vehicles (i.e., vehicles not used for snow and ice control operations) as

Loss in number of serviced NO-S&IC vehicles **=** *Number of NO-S&IC vehicles serviced in routine conditions* **–** *Number of NO-S&IC vehicles serviced when a failure occurs*

Since the S&IC vehicles were targeted in this analysis, the vehicles groups containing S&IC vehicles were subdivided into S&IC vehicles and NO-S&IC vehicles and the related model parameters were updated (see Table 28). It was also assumed that all the S&IC vehicles had to be serviced with the highest priority (i.e., priority = 5) and, therefore, the priority of NO-S&IC vehicles was decreased by 1 unit (Table 28).

Table 28: Analysis #2 –Model Parameters

Vehicle Group	Vehicle Type	Total Number of Work Orders	Feed Activity Duration [hr.]	Priority
A	NO-S&IC	518	2	1
B	NO-S&IC	49	23	1
C	NO-S&IC	126	9	2
D	NO-S&IC	4	288	3
F	NO-S&IC	11	105	3
G	NO-S&IC	342	3	4
	S&IC	***28***	***41***	***5***
H	NO-S&IC	79	15	4
	S&IC	***175***	***7***	***5***
I	NO-S&IC	211	5	3
J	NO-S&IC	15	77	4
K	***S&IC***	***30***	***38***	***5***
L	NO-S&IC	2	575	5
M	NO-S&IC	4	288	1
	S&IC	***4***	***288***	***4***
N	NO-S&IC	29	40	5

As in analysis 1, the loss in number of serviced vehicles was calculated over three time periods:

- <u>1 week</u>
  time period = 1 week × 5 days/week × 9 hr./day = 45 hr.
  model time period = time period × Simulation Coefficient = 45 hr. × 0.71 = 32 hr.
- <u>2 weeks</u>
  time period = 2 weeks × 5 days/week × 9 hr./day = 90 hr.
  model time period = time period × Simulation Coefficient = 90 hr. × 0.71 = 64 hr.
- <u>3 weeks</u>
  time period = 3 weeks × 5 days/week × 9 hr./day = 135 hr.
  model time period = time period × Simulation Coefficient = 135 hr. × 0.71 = 96 hr.

All the model inputs for the routine and failure conditions are summarized in Table 29.

Table 29: Analysis #2 –Model Inputs

	Routine Conditions	**Failure Conditions**
Available Staffed Bays Queue	*12 available staffed bays*	*From 11 to 3 available staffed bays*
Vehicles to Be Serviced Queues	The total number of work orders for each vehicle group and vehicle type (Table 28) minus 1 is used as resource for the queue	
Vehicles Ready to Be Serviced Queues	These queues are loaded with resources equal to 1 for each vehicle group	
Duration of Feed Activities	Activity duration for each vehicle group and vehicle type is presented in Table 28	
Priority of Service Activities	Activity priority for each vehicle group and vehicle type is presented in Table 28	
Duration of Service Activities	Activity duration for each vehicle group and vehicle type is presented in Appendix B	

The outcomes of the analysis based on 1,000 model iterations are presented in Table 30.

Table 30: Analysis #2 – Simulation Results

Time Period	**Scenario**	**Number of Serviced Vehicles (Average) - 1,000 Iterations**		**Loss in Number of Serviced Vehicles**			
				NO-S&IC vehicles		**S&IC vehicles**	
		NO-S&IC vehicles	**S&IC vehicles**	**Vehicle**	**%**	**Vehicle**	**%**
1 week	Routine Cond.	42.5	5.7	-	-	-	-
	11 Bays Available	42.3	5.7	-0.5	-1.2	0.0	-0.5
	10 Bays Available	41.0	5.6	-1.6	-3.8	-0.1	-1.2
	9 Bays Available	38.9	5.6	-4.4	-10.3	-0.1	-2.3
	8 Bays Available	36.0	5.5	-6.8	-16.0	-0.1	-1.7
	7 Bays Available	31.1	5.3	-11.1	-26.1	-0.2	-3.0
	6 Bays Available	26.0	5.1	-17.1	-40.2	-0.3	-5.0
	5 Bays Available	20.6	4.8	-22.7	-53.1	-0.4	-6.2
	4 Bays Available	15.8	4.4	-28.2	-66.1	-0.5	-9.3
	3 Bays Available	12.2	3.2	-32.9	-77.0	-0.7	-12.0

Table 30: Analysis #2 – Simulation Results (continued)

Time Period	Scenario	Number of Serviced Vehicles (Average) - 1,000 Iterations		Loss in Number of Serviced Vehicles			
				NO-S&IC vehicles		S&IC vehicles	
		NO-S&IC vehicles	S&IC vehicles	Vehicle	%	Vehicle	%
2 week	Routine Cond.	81.8	12.5	-	-	-	-
	11 Bays Available	79.8	12.4	-2.4	-3.0	-0.1	-0.5
	10 Bays Available	77.2	12.3	-5.5	-6.8	-0.1	-1.1
	9 Bays Available	72.3	12.1	-11.1	-13.5	-0.2	-1.9
	8 Bays Available	63.7	11.7	-18.5	-22.6	-0.5	-3.7
	7 Bays Available	54.8	11.0	-28.1	-34.4	-0.6	-4.8
	6 Bays Available	45.2	10.3	-38.7	-47.4	-0.8	-6.6
	5 Bays Available	35.1	9.0	-50.0	-61.2	-1.3	-10.2
	4 Bays Available	28.2	7.6	-58.7	-71.9	-2.0	-15.6
	3 Bays Available	21.8	5.3	-67.1	-82.1	-3.1	-24.6
3 week	Routine Cond.	120.0	19.3	-	-	-	-
	11 Bays Available	115.6	19.1	-4.7	-3.9	-0.1	-0.4
	10 Bays Available	109.8	18.8	-10.7	-8.9	-0.1	-0.7
	9 Bays Available	99.7	18.5	-20.1	-16.8	-0.2	-1.0
	8 Bays Available	88.4	17.6	-34.0	-28.3	-0.5	-2.4
	7 Bays Available	74.5	16.5	-48.4	-40.3	-0.7	-3.4
	6 Bays Available	61.9	14.9	-63.4	-52.8	-1.2	-5.9
	5 Bays Available	50.0	12.7	-78.1	-65.1	-1.9	-9.9
	4 Bays Available	40.0	9.9	-91.2	-76.0	-3.2	-16.2
	3 Bays Available	31.3	6.1	-101.9	-84.8	-4.8	-24.6

7.1 Analysis #2 - Discussion of Model Results

The obtained results are summarized in Figure 22 for the 1-week time period, Figure 23 for the 2-week time period, and Figure 24 for the 3-week time period. The charts display the number of available staffed bays on the x-axis, and loss in number of serviced vehicles (in percentage) on the y-axis. The simulation outcomes show that for any given number of available staffed bays the decrease in serviced vehicles is more significant for NO-S&IC vehicles than for S&IC vehicles across the different time periods. This behavior was expected since S&IC vehicles have the highest priority in the model (Table 28). The simulation outcomes also show that it is necessary to have less than 7 available staffed bays to have a decrease of serviced S&IC vehicles equal or worse than 5%. However, the loss of NO-S&IC serviced vehicles is already equal or worse than 10% when 9 bays are available and it drops to ≈ 50% when only 6 repair bays are available. Therefore, although the service level for S&IC vehicles can be "protected" by giving them the highest priority, the service level for NO-S&IC vehicles quickly drops to unacceptable levels as the number of available staffed bays decreases.

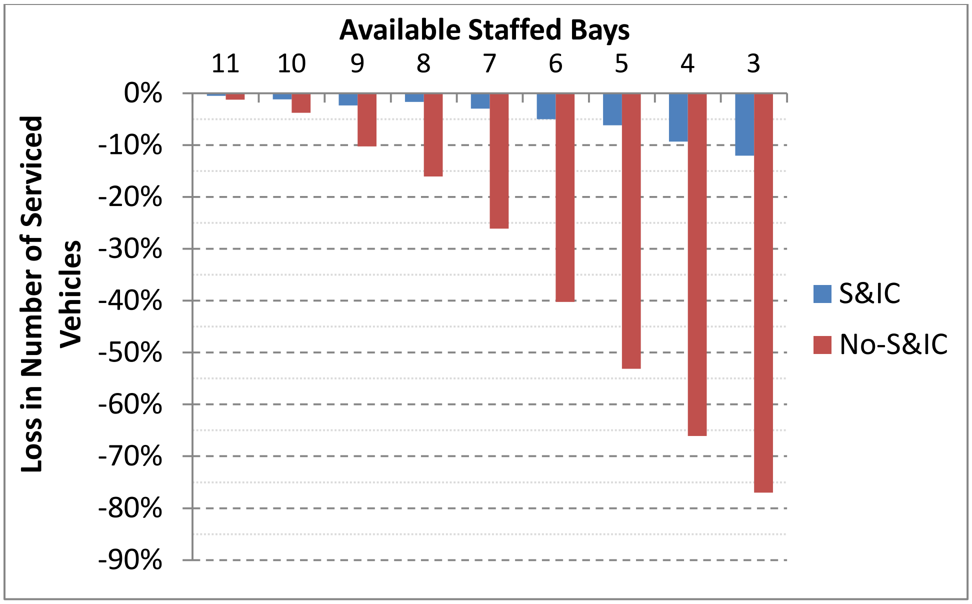


Figure 22: Loss in number of serviced vehicles – 1 week

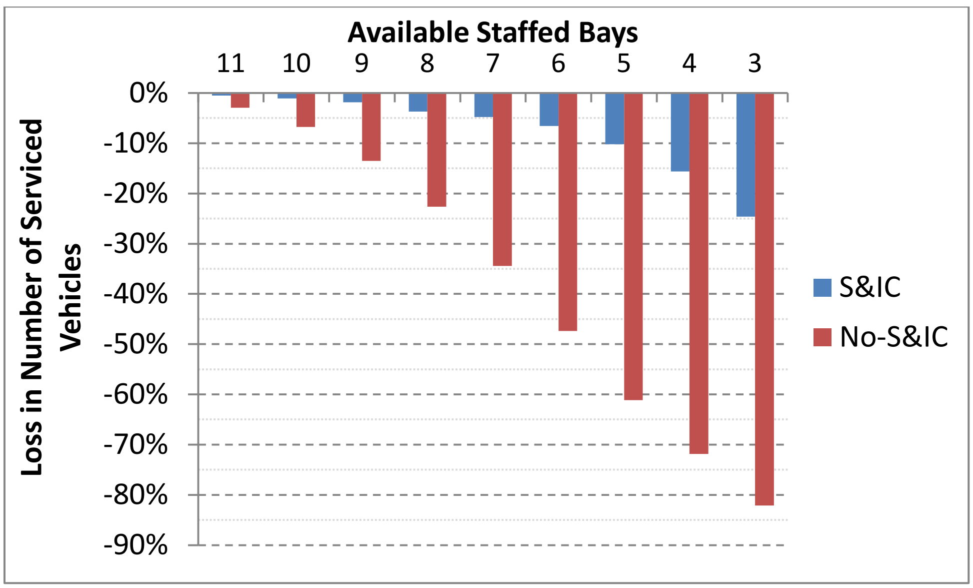


Figure 23: Loss in number of serviced vehicles – 2 weeks

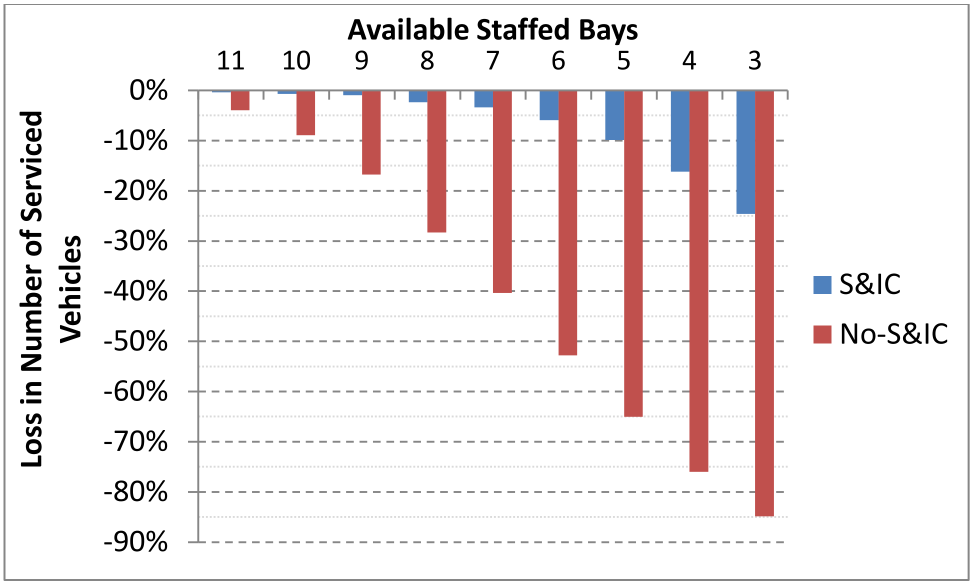


Figure 24: Loss in number of serviced vehicles – 3 week

8. Analysis #3 – Loss in Number of Plowed Lane-Miles

The results obtained in the Analysis #1 and #2 show that a decrease in the number of available repair bays can affect the number of vehicles serviced within a certain time period. Nevertheless, the obtained results do not explicitly show how road-users can be affected by failures occurring in the TEF shop. Therefore, this analysis determines how the decrease in the number of bays can generate a loss in the number of plowed-lane miles. First, by reducing the number of available staffed bays, the delay in servicing Snow and Ice Control (S&IC) trucks (i.e., plow trucks) was determined as:

$$\textit{Delay in servicing S\&IC trucks} = \textit{Time necessary to serve a certain number of S\&IC trucks in routine conditions} - \textit{Time necessary to serve the same number of S\&IC trucks when a failure occurs}$$

Second, by using the average speed of plow trucks, the loss in number of plowed lane-miles was calculated as:

$$\textit{Loss in plowed lane-miles} = \textit{Delay in servicing S\&IC trucks} \times \textit{Average lane-mile plowing speed}$$

Since S&IC trucks had to be targeted in this analysis, the research team analyzed the vehicle groups and identified the S&IC trucks as the S&IC vehicles in the vehicle groups G and H. Furthermore, it was assumed that the TEF shop activities should have been simulated during a "snowstorm emergency situation". Therefore, not only all the S&IC vehicles had to be serviced with the highest priority (i.e., priority = 5), but also the TEF shop was considered open 24 hours per day to service the vehicles. The simulation results were obtained over five time periods:

- 3 days
  time period = 3 days × 24 hr./day = 72 hr.
  model time period = time period × Simulation Coefficient = 72 hr. × 0.71 = 51 hr.
- 4 days
  time period = 4 days × 24 hr./day = 96 hr.
  model time period = time period × Simulation Coefficient = 96 hr. × 0.71 = 68 hr.
- 5 days
  time period = 5 days × 24 hr./day = 120 hr.
  model time period = time period × Simulation Coefficient = 120 hr. × 0.71 = 85 hr.
- 6 days
  time period = 6 days × 24 hr./day = 144 hr.
  model time period = time period × Simulation Coefficient = 144 hr. × 0.71 = 102 hr.
- 7 days
  time period = 7 days × 24 hr./day = 168 hr.
  model time period = time period × Simulation Coefficient = 168 hr. × 0.71 = 119 hr.

All the model inputs for the routine and failure conditions are summarized in Table 31.

Table 31: Analysis #3 – Model Inputs

	Routine Conditions	Failure Conditions
Available Staffed Bays Queue	*12 available staffed bays*	*From 11 to 3 available staffed bays*
Vehicles to Be Serviced Queues	The total number of work orders for each vehicle group and vehicle type (Table 28) minus 1 is used as resource for the queue	
Vehicles Ready to Be Serviced Queues	These queues are loaded with resources equal to 1 for each vehicle group	
Duration of Feed Activities	Activity duration for each vehicle group and vehicle type is presented in Table 28	
Priority of Service Activities	Activity priority for each vehicle group and vehicle type is presented in Table 28	
Duration of Service Activities	Activity duration for each vehicle group and vehicle type is presented in Appendix B	

8.1 Delay in Servicing Snow and Ice Control Trucks

First, the model was used to determine the number of S&CI trucks that can be serviced within the identified time periods in routine conditions (Table 32).

Table 32: Analysis #3 - Number of Serviced S&IC Trucks in Routine Conditions

Time Period	Scenario	Number of Serviced S&IC trucks (Average) - 1,000 Iterations
3 days	Routine Conditions (12 bays available)	9
4 days		11
5 days		14
6 days		17
7 days		19

Then, the model was used to determine the time necessary to service the same amount of S&IC trucks when less than 12 bays are available, and the delay in servicing the S&IC trucks was calculated (i.e., difference between the time necessary to service the S&IC trucks in routine conditions and the time necessary to service the S&IC trucks when less than 12 bays are available). The outcomes of the analysis based on 1,000 model iterations are presented in Table 33.

Table 33: Analysis #3 – Delays in servicing S&IC trucks

Time Period	Number of Serviced S&IC trucks	Scenario	Time Necessary to Service S&IC Trucks (Average) - 1,000 Iterations [hr.]	Delay in Servicing S&IC Trucks	
				hr.	%
3 days	9	Routine Cond.	54.1	-	-
		11 Bays Available	54.5	0.6	0.7
		10 Bays Available	54.7	0.8	1.0
		9 Bays Available	55.2	1.4	1.9
		8 Bays Available	55.2	1.4	1.9
		7 Bays Available	56.9	3.8	5.0
		6 Bays Available	59.2	7.0	9.2
		5 Bays Available	62.5	11.7	15.4
		4 Bays Available	68.1	19.6	25.8
		3 Bays Available	81.1	38.0	49.8

Table 33: Analysis #3 – Delays in servicing S&IC trucks (continued)

Time Period	Number of Serviced S&IC trucks	Scenario	Time Necessary to Service S&IC Trucks (Average) - 1,000 Iterations [hr.]	Delay in Servicing S&IC Trucks	
				hr.	%
4 days	11	Routine Cond.	96.8	-	-
		11 Bays Available	96.9	0.1	0.1
		10 Bays Available	97.2	0.4	0.4
		9 Bays Available	98.3	1.5	1.6
		8 Bays Available	99.6	2.8	2.9
		7 Bays Available	100.8	4.0	4.1
		6 Bays Available	104.3	7.5	7.8
		5 Bays Available	107.6	10.8	11.1
		4 Bays Available	114.4	17.6	18.2
		3 Bays Available	137.8	41.0	42.4
5 days	14	Routine Cond.	121.9	-	-
		11 Bays Available	121.9	0.0	0.0
		10 Bays Available	123.5	1.6	1.4
		9 Bays Available	123.7	1.8	1.5
		8 Bays Available	127.1	5.3	4.3
		7 Bays Available	128.9	7.0	5.8
		6 Bays Available	132.1	10.2	8.4
		5 Bays Available	139.2	17.4	14.2
		4 Bays Available	151.1	29.2	24.0
		3 Bays Available	175.1	53.2	43.7
6 days	17	Routine Cond.	148.8	-	-
		11 Bays Available	149.0	0.2	0.1
		10 Bays Available	149.6	0.8	0.5
		9 Bays Available	150.7	1.9	1.3
		8 Bays Available	152.3	3.6	2.4
		7 Bays Available	154.8	6.0	4.1
		6 Bays Available	158.0	9.3	6.2
		5 Bays Available	162.8	14.1	9.5
		4 Bays Available	177.6	28.8	19.4
		3 Bays Available	214.1	65.4	43.9
7 days	19	Routine Cond.	167.1	-	-
		11 Bays Available	167.5	0.4	0.2
		10 Bays Available	168.3	1.2	0.7
		9 Bays Available	169.8	2.6	1.6
		8 Bays Available	172.0	4.8	2.9
		7 Bays Available	174.2	7.0	4.2
		6 Bays Available	178.1	10.9	6.5
		5 Bays Available	183.9	16.8	10.0
		4 Bays Available	197.8	30.7	18.4
		3 Bays Available	233.0	65.9	39.4

8.2 Loss in Number of Plowed Lane-Miles

Based on expert judgment, WSDOT plow trucks drive at an average speed of 30 mph when cleaning roads outside urban areas. Considering that on average a plow cleans 9.5 ft. of road in one pass and that a lane is 12 ft. wide (Figure 25), it can be concluded that a plow truck clean at a speed of 20.8 lane-mile per hour.

$$\text{Average lane-mile plowing speed} = \text{Average plow truck speed} \times \frac{\text{Plow blade cleaning width}}{\text{Lane width}}$$

$$\text{Average lane-mile plowing speed} = 30 \text{ mph} \times \frac{9.5 \text{ ft.}}{12 \text{ ft.}}$$

$$\text{Average lane-mile plowing speed} = 23.8 \text{ lane-mph}$$

Figure 25: WSDOT plow trucks (credit: WSDOT)

Therefore, the loss in plowed lane-miles can be obtained by multiplying the delay in servicing S&IC trucks for the average lane-mile plowing speed (Table 34).

Table 34: Analysis #3 – Loss in Number of Plowed Lane-Miles

Time Period	Number of Serviced S&IC trucks	Scenario	Delay in Servicing S&IC Trucks [hr.]	Loss in Plowed Lane-Miles
3 days	9	11 Bays Available	0.6	13
		10 Bays Available	0.8	18
		9 Bays Available	1.4	34
		8 Bays Available	1.4	34
		7 Bays Available	3.8	90
		6 Bays Available	7.0	167
		5 Bays Available	11.7	279
		4 Bays Available	19.6	466
		3 Bays Available	38.0	902

Table 34: Analysis #3 – Loss in Number of Plowed Lane-Miles (continued)

Time Period	Number of Serviced S&IC trucks	Scenario	Delay in Servicing S&IC Trucks [hr.]	Loss in Plowed Lane-Miles
4 days	11	11 Bays Available	0.1	2
		10 Bays Available	0.4	9
		9 Bays Available	1.5	36
		8 Bays Available	2.8	67
		7 Bays Available	4.0	94
		6 Bays Available	7.5	178
		5 Bays Available	10.8	256
		4 Bays Available	17.6	419
		3 Bays Available	41.0	974
5 days	14	11 Bays Available	0.0	1
		10 Bays Available	1.6	39
		9 Bays Available	1.8	42
		8 Bays Available	5.3	125
		7 Bays Available	7.0	167
		6 Bays Available	10.2	242
		5 Bays Available	17.4	412
		4 Bays Available	29.2	693
		3 Bays Available	53.2	1264
6 days	17	11 Bays Available	0.2	5
		10 Bays Available	0.8	19
		9 Bays Available	1.9	46
		8 Bays Available	3.6	85
		7 Bays Available	6.0	144
		6 Bays Available	9.3	220
		5 Bays Available	14.1	334
		4 Bays Available	28.8	684
		3 Bays Available	65.4	1552
7 days	19	11 Bays Available	0.4	8
		10 Bays Available	1.2	27
		9 Bays Available	2.6	63
		8 Bays Available	4.8	114
		7 Bays Available	7.0	167
		6 Bays Available	10.9	259
		5 Bays Available	16.8	399
		4 Bays Available	30.7	729
		3 Bays Available	65.9	1565

8.3 Analysis #3 - Discussion of Model Results

The obtained results are summarized in Figure 26 and 27. The chart displays the number of available staffed bays on the x-axis, and loss in plowed lane-miles on the y-axis. By targeting WSDOT plow trucks, this analysis clearly shows how failures occurring at the TEF shop can seriously impact road-users. Since the average lane-mile plowing speed is above 20 mph, even limited delays in servicing the plow trucks can cause severe service disruptions. For instance, the delay in servicing the S&IC trucks is lower than 3 hr. for all the time periods when 9 bays are available. Nevertheless, a 3 hr. delay can cause a loss of more than 60 plowed lane-miles.

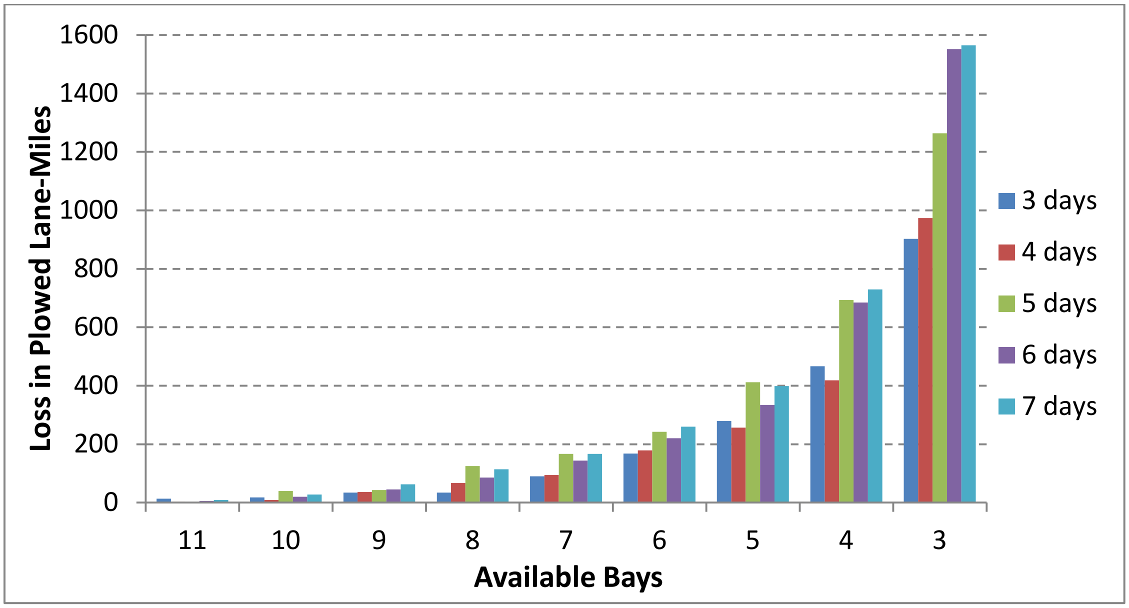


Figure 26: Loss in plowed lane-miles 11-3 available staffed bays

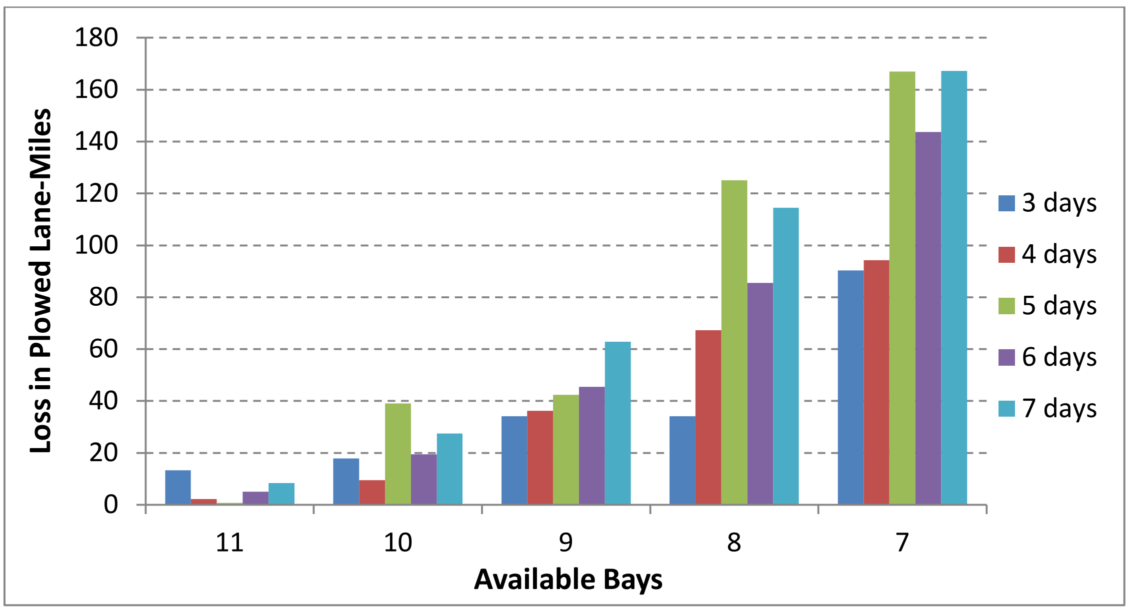


Figure 27: Loss in plowed lane-miles 11-7 available staffed bays

<u>Analysis Limitations</u>

There are two limitations affecting the accuracy of Analysis #3 results. First, it is assumed that the TEF shop is open 24 hr. per day in this analysis. Although this condition occurs during emergency situations (e.g., snowstorms), the great majority of the work order data used to build the model was not opened/closed during emergency situations. Therefore, the used data may not be fully representative of an emergency situation. Second, in this analysis, it is assumed that each vehicle has to be serviced when it is selected by a Service activity. However, this does not always hold true in reality. A problem in a vehicle can be minor and, therefore, the service operations necessary to fix it can be postponed during emergency situations. Since the model is not capable of classifying the type of issues (i.e., minor vs. major problem), it can only assume that all the problems are major.

9. Conclusions

In this study, outcomes show that failures occurring at the TEF shop can significantly affect its ability to service the department's vehicles and equipment. Given the importance of some of these vehicle and equipment in operating the state's transportation system, failures at the TEF shop can also significantly affect WSDOT's ability to fulfill its mission.

The aim of this study was to investigate how WSDOT operations can be affected by failures that occurred or are likely to occur in TEF shops by analyzing operations of these facilities. In particular, the research team analyzed how failures occurring at the TEF shop located in Corson Avenue South can affect the TEF shop repair and service activities, and WSDOT Snow and Ice Control (S&IC) operations.

Firstly, the research team analyzed TEF shop service activities and developed a discrete-event simulation model capable of simulating the service operations performed at the TEF shop.

After validating the model, the research team identified the possible failures capable of affecting the shop activities and quantified the potential consequences of failures occurrences at the repair shop by comparing model performance in routine conditions vs. model performance in failure conditions. Three analyses were performed to determine the impacts to the S&IC operations due to building failures.

Analysis #1 – Loss in number of serviced vehicles

The first analysis determined the loss in number of serviced vehicles. By simulating the identified failures, the loss in number of serviced vehicles was calculated as the difference between the number of vehicles serviced in routine conditions and the number of vehicles serviced when a failure occurs.

The analysis outcomes show that the most disruptive failures for the shop activities are the ones causing the closure of repair bays. For instance, a 6% reduction of serviced vehicles would occur if 3 of the 12 bays were closed for one work week due to a building failure and a 27% reduction of serviced vehicles would occur if 5 of the 12 bays were closed for two work weeks due to a building failure.

Analysis #2 – Loss in number of serviced S&IC vehicles

The second analysis determined the loss in number of serviced S&IC vehicles. By targeting the vehicles (and equipment) used to perform S&IC operations and considering only the closure of one or more repair bays as failure conditions, the loss in number of serviced S&IC vehicles was calculated as the difference between the number of S&IC vehicles serviced in routine conditions and the number of S&IC vehicles serviced when a failure occurs. Similarly, the loss in number of serviced NO-S&IC vehicles (i.e., vehicles and equipment not used for S&IC operations) was also determined.

Although the analysis outcomes do not determine how a reduction in serviced S&IC vehicles can affect WSDOT S&IC operations, they clearly show that prioritizing the service of S&IC vehicles can be beneficial in obtaining an acceptable service level for S&IC vehicles but, on the other hand, it can seriously jeopardize the level of service of vehicles not used for S&IC operations. For instance, a 5% reduction of serviced S&IC vehicles would occur if 6 of the 12 bays were closed for one work week due to a building failure, whereas a 40% reduction of serviced NO-S&IC vehicles would occur if 6 of the 12 bays were closed for one work week.

Analysis #3 – Loss in number of plowed lane-miles

The final analysis determined the loss in number of plowed lane-miles. By targeting plow trucks and considering only the closure of one or more repair bays as failure conditions, this analysis quantified the delay in servicing a specified number of plow trucks as the difference between the time necessary to service the plow trucks in routine conditions and the time necessary to service the plow trucks when a failure occurs. Then, by multiplying the delay with the average plowing speed (in lane-miles per hour), the loss in number of plowed lane-miles was calculated.

Therefore, by identifying how many lane-miles cannot be cleaned within a certain period because of failures occurring at the TEF shop, this analysis clearly shows how failures can impact road-users. For instance, a loss 90 miles in plowed lane miles would occur if 5 of the 12 bays were closed for 3 work days due to a building failure and a loss of 1,264 miles in plowed lane miles would occur if 9 of the 12 bays were closed for five work days due to a building failure.

10. References

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Appendix A

This appendix presents the main characteristics of each vehicle group.

Vehicle group A	
Priority: 2 (1 least important, 5 most important)	*Number of occupied bays*: 1
Vehicles Types: 1 TON, CREW CAB; GAS; 4X2 ~ 1 TON; CREW CAB; DSL; 4X2 ~ 1/2 TON CREW CAB 4X4 ~ 1/2 TON, EXTENDED CAB; 4X2 ~ 1/2 TON, REGULAR OR EXTENDED C ~ 1/2 TON; CREW CAB 4X2 ~ 1/4 TON; EXTENDED CAB; 4X2 ~ 1/4 TON; EXTENDED CAB; 4X4 ~ 3/4 & 1 TON, CREW CAB; GAS; 4X ~ 3/4 TON; EXT CAB; DSL; 4X2 ~ 3/4 TON; EXT CAB; DSL; 4X4 ~ 3/4 TON; EXT CAB; GAS; 4X2 ~ 3/4 TON; EXT CAB; GAS; 4X4 ~ 3/4 TON; REGULAR CAB; DSL; 4X2 ~ PICKUP TRUCKS ~ SEDAN; GAS-ELECTRIC HYBRID ~ SEDAN; MID SIZE ~ STATION WAGON ~ PASSENGER CARRYING VEHICLE	

Vehicle group B	
Priority: 2 (1 least important, 5 most important)	*Number of occupied bays*: 0.5
Vehicles Types: AIR COMPRESSOR; TRL MTD; 250 C ~ BRUSH CHIPPER, TRAILER MOUNTED ~ CATCH BASIN CLEANER; TRAILER M ~ CME 45/55 SKID DRILL UNIT TRAI ~ DRILL UNIT SKID MTD ~ DRILL UNIT, HAND OPERATED ~ DRILL UNIT, TRAILER MTD ~ FORK LIFT; 10L LBS ~ FORKLIFT; WAREHOUSE; TO 6K LBS ~ PUMP UNIT, WATER. TRAILER OR S ~ TRAFFIC PAINT REMOVER; W/GRIND	

Vehicle group C	
Priority: 3 (1 least important, 5 most important)	*Number of occupied bays*: 1
Vehicles Types: ARROW BOARD; TRAILER MOUNTED ~ ARROWBOARD VEHICLE MOUNTED ~ TRAILER, ROLLBACK RAMP / FLATB ~ TRAILER, UTILITY, SINGLE AXLE; ~ TRAILER; OFFICE LAB; 48 FOOT ~ TRAILER; OFFICE/LAB; 32 FOOT ~ TRAILER; TILT; 24,000 LBS ~ TRAILERS ~ TRCTR; UTIL; 18-35 HP; TURF TY ~ EPOXY RPR PATCH SYS W/ TRAILER ~ IMPACT ATTENUATOR; TRUCK MOUNT ~ LOAD TESTER (TRAILER MTD) ~ MESSAGE SIGN; TRAILER MOUNTED ~ MESSAGE SIGN; VEHICLE MTD; 3 L ~ POLE TRAILER ~ TILT / FLATBED TRAILER; 50K LB ~ TILT TRAILER; 12K LBS ~ OTHER NON-SELF-PROPELLED EQUIP.	

Vehicle group D	
Priority: 4 (1 least important, 5 most important)	*Number of occupied bays*: 1
Vehicles Types: BACKHOE, EXCAVATOR, COMPACT, T ~ BACKHOE, EXCAVATOR, TRACK MOUN ~ BACKHOE;EXCAVATOR; COMPACT;TRAC ~ CRANES AND SHOVELS	

Vehicle group F	
Priority: 4 (1 least important, 5 most important)	*Number of occupied bays*: 1
Vehicles Types: TRK, BRIDGE RPR, W/ HYDRAUCRAN ~ TRK, BRIDGE RPR;W/SCISSOR LIF ~ TRK, CATCH BASIN CLEANER; 10 Y	

Vehicle group G (vehicle groups with S&IC vehicles)	
Priority: 5 (1 least important, 5 most important)	*Number of occupied bays*: 1
Vehicles Types: <u>NO-S&IC vehicles:</u> TRK, FLATBED, TRAFFIC CONTROL; ~ BODY WRECKER ~ TRK, FLATBED; 38KGVW; W/OUT CR ~ TRK, FLATBED; GRDRAIL RPR; 54K ~ VAN; 1 TON; W/ SERVICE BODY ~ TRK, FLATBED; PNT STRPR SPT; 5 ~ VAN; 6-9 PASSENGER ~ TRK, FLUSH/ANTIIC; 54 KGVW; 28 ~ VAN; CARGO ~ TRK, TRAFFIC LINE STRIPER ~ TRUCK, 1 TON; W/SERVICE BODY; ~ TRK; 1 TON; W/DUMP BODY; EXT/C ~ TRUCK; IRL; DSL ~ TRUCK; IRL; GAS ~ TRUCK; IRV; CAB & CHASSIS; DSL ~ TRUCK; IRV; CAB & CHASSIS; GAS ~ TRUCK; LUBE AND SERVICE; DSL ~ TRUCK; W/BOX VAN BODY; 40KGVW ~ TRUCK; WRECKER C&C ~ TRUCK; WRECKER; CAB&CHASSIS; D ~ UTILITY VEHICLE SMAL LIGHT 4X4 ~ UTILITY VEHICLE, ELECTRIC PWR ~ UTILITY VEHICLE; FULL SIZE ~ UTILITY VEHICLE; SMALL; LIGHT~ VAN; 1 TON; MAXI VAN ~ INCIDENT RESPONSE VEHICLES ~ LIGHT W/SPECIAL BODIES/EQUIP <u>S&IC vehicles:</u> TRUCK; LESS THAN 38KGVW; W/FRO	

Vehicle group H (vehicle groups with S&IC vehicles)	
Priority: 5 (1 least important, 5 most important)	*Number of occupied bays*: 1
Vehicles Types: NO-S&IC vehicles: TRK; CAB&CHASSIS; 4X2; MULTI-P ~ TRK; CAB&CHASSIS; 6X4; MULTI-P ~ TRK; DIGGER DERRICK; 6X4; W/ S ~ TRK; DRILL SPRT; WATER TANK; 5 ~ TRK; FLATBED; 38KGVW; W/KNUCK ~ TRK; MANLIFT; 40 FOOT; W/SERVB ~ TRUCK; MANLIFT; 65 FT ~ TRUCK; REFUSE; WITH COMPACTOR ~ TRUCK; TRACTOR; 54KGVW; 6X4 ~ VAN; MANLIFT; 30 FOOT ~ STEP VAN; WITHOUT MAN LIFT DIE ~ MANLIFT PLATFORM, OVER 30 FT ~ MANLIFT PLATFORM; TO 30 FT ~ POST DRIVER; TRUCK MTD ~ STEP VAN; WITHOUT MAN-LIFT GAS ~ STEPVAN; MAN-LIFT; 40 FT S&IC vehicles: TRK; ABOVE 38KGVW; 4X2; CONT B ~ TRK; ABOVE 38KGVW; 4X2; FRINKB ~ TRK; ABOVE 38KGVW; 4X4; W/PLOW ~ TRK; ABOVE 38KGVW; AUTOTRANS; ~ TRK; TNDM AXLE; 54KGVW; 6X4; C ~ TRK; TNDM AXLE; 54KGVW; 6X4; F ~ WINGPLOW; TRUCK MTD	

Vehicle group I	
Priority: 4 (1 least important, 5 most important)	*Number of occupied bays*: 1
Vehicles Types: TRK; W/ HYDRAUCRANE; 54K GVW, ~ TRK;, ATTENUATOR; NOT FOR REPL ~ TRUCK, MANLIFT; 54 FOOT; W/LIF ~ TRUCK, MANLIFT; 54 FOOT; W/OUT ~ TRUCK, THERMOPLASTIC UNIT ~ TRUCK, TUNNEL WASHER ~ TRUCK; 1 TON; W/DUMP BODY; EXT ~ TRUCK; 1 TON; W/DUMP BODY; REG ~ TRUCK; 1/2 TON REGULAR CAB 4*2 ~ TRUCK; 1/2 TON REGULAR CAB 4*3 ~ TRUCK; 1/4 TON; CREW CAB; 4X2 ~ TRUCK; 15,000 GVW; WITHOUT PLO ~ TRUCK; BUTTON APPLICATOR; DOUB ~ TRUCK; FLATBED; EXTENDED CAB; ~ GT 15K GVW W/ SPECIAL BODIES	

Vehicle group J (vehicle groups with S&IC vehicles)	
Priority: 4 (1 least important, 5 most important)	*Number of occupied bays*: 1 or 2[1]
Vehicles Types: NO-S&IC vehicles: SNOW CAT ~ GRINDER; PAVEMENT; LARGE RIDIN ~ LOADER; 2+1/2 CY BUCKET ~ TRACK; DRILL UNIT S&IC vehicles: SNOW BLOWER, LOADER MOUNTED ~ SNOW BLOWER, SP ~ SNOW REMOVAL ATTACHMENTS	

Vehicle group K (vehicle groups with only S&IC vehicles)	
Priority: 5 (1 least important, 5 most important)	*Number of occupied bays*: 1
Vehicles Types: NO-S&IC vehicles: None S&IC vehicles: SPREADER; LIQUID; ANTI-ICE; 10 ~ SPREADER; LIQUID; ANTI-ICER; 1	

Vehicle group L	
Priority: 2 (1 least important, 5 most important)	*Number of occupied bays*: 1
Vehicles Types: TRACTOR; SLOPE MOWER; 72" CUT ~ TRACTOR; W/LOADER & BACKHOE ~ SIDE MOUNT ~ MOWER; SP; RIDING; 18-22 HP; 3 ~ MOWER; TOWED	

Vehicle group M (vehicle groups with S&IC vehicles)	
Priority: 5 (1 least important, 5 most important)	*Number of occupied bays*: 1
Vehicles Types: NO-S&IC vehicles: HERB SPRAY / ANTIICER; SKID MT ~ HERBICIDE SPARAYER; SKID MTD ~ S&IC vehicles: HOPPER SANDER; 10/12 YARD; W/ ~ HOPPER SANDER; 5/6 YARD ~ HOPPER SANDER; LESS THAN 2 YD ~ SANDER; TAILGATE ~ HOPPER SANDER; HITCH MOUNTED	

Vehicle group N	
Priority: 3 (1 least important, 5 most important)	*Number of occupied bays*: 1
Vehicles Types: SELF-PROPELLED MOWERS/TRACTORS ~ SKID STEER; BOBCAT ~ SKID STEER; TRACK MOUNTED ~ SWEEPER; SP; MECHANICAL PICKUP ~ SWEEPER; SP; PATH; AIR/VAC PIC	

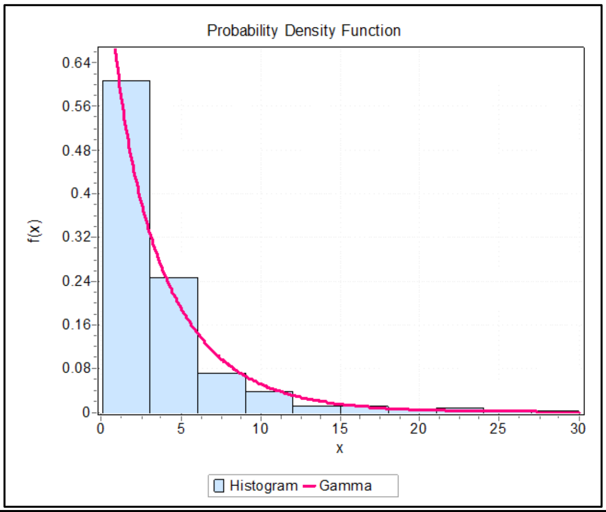
[1] One bay for 80% of the work orders, and two bays for 20% of the work orders

Appendix B

This appendix presents the best fitting probability distribution for each vehicle group.

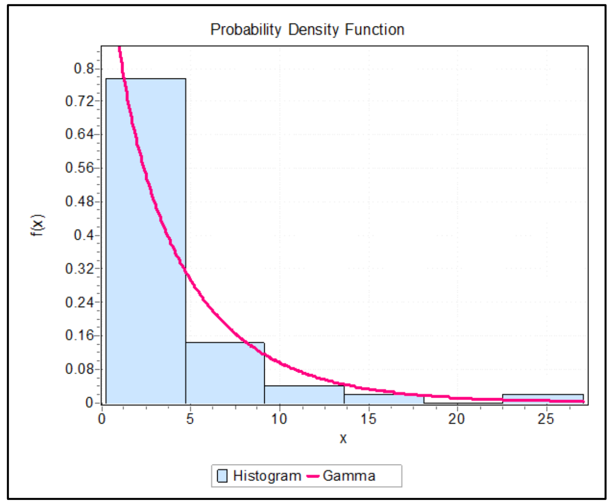
Vehicle Group A

Number of work orders: 518
Work orders total duration: 1842 hr.
Best Fitting Distribution: Gamma
Distribution Parameters: Alfa= 0.845 and Beta = 4.185



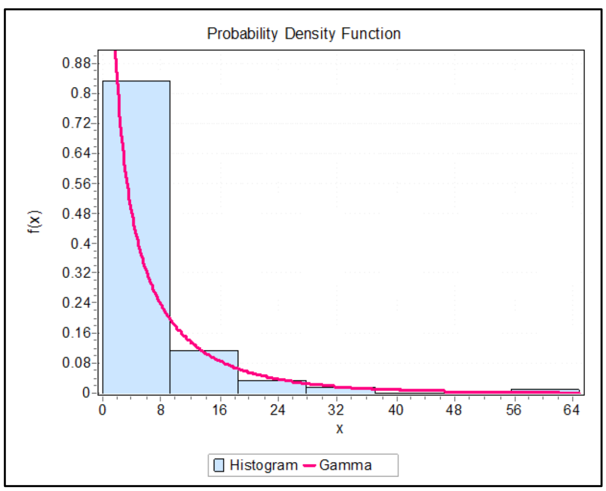
Vehicle Group B

Number of work orders: 49
Work orders total duration: 205 hr.
Best Fitting Distribution: Gamma
Distribution Parameters: Alfa= 0.845 and Beta = 4.917



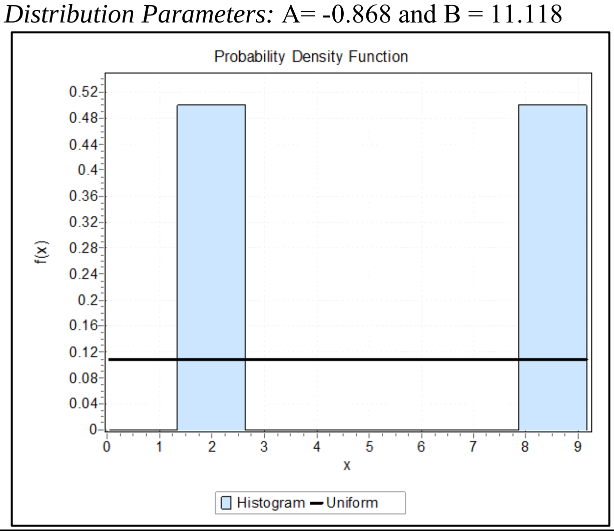
Vehicle Group C

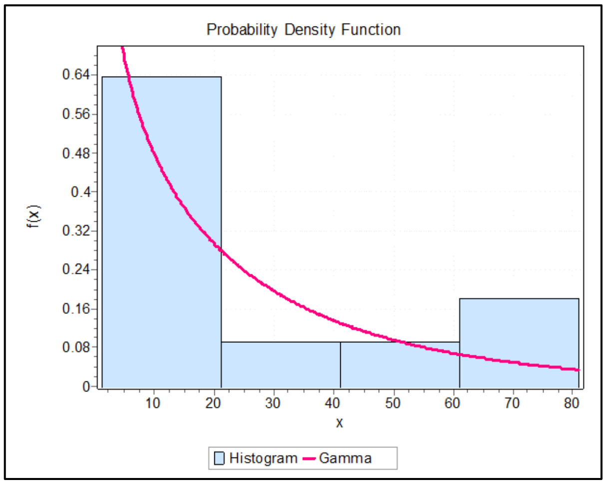
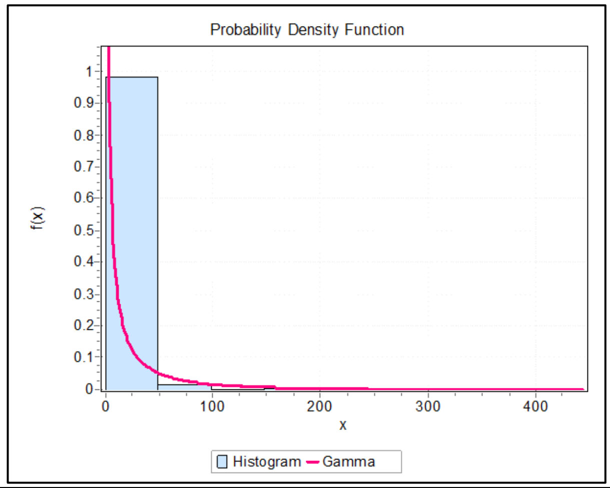
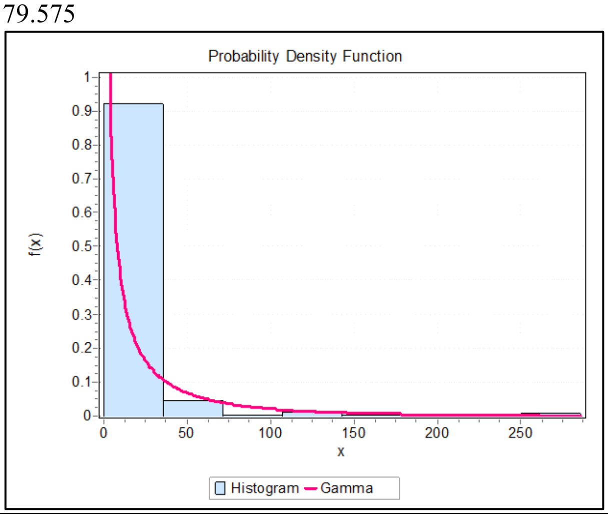
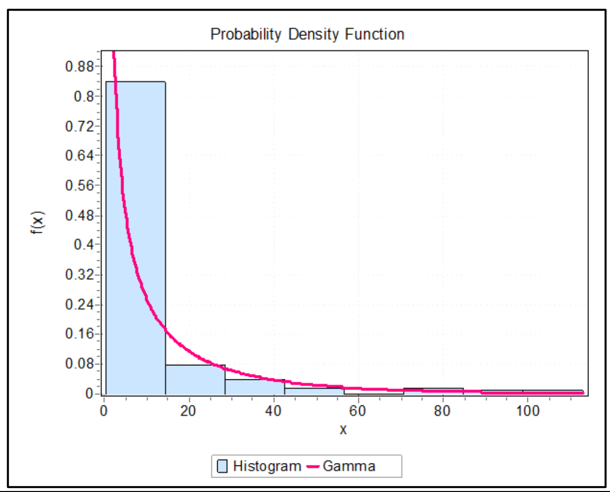
Number of work orders: 126
Work orders total duration: 672 hr.
Best Fitting Distribution: Gamma
Distribution Parameters: Alfa= 0.407 and Beta= 13.095

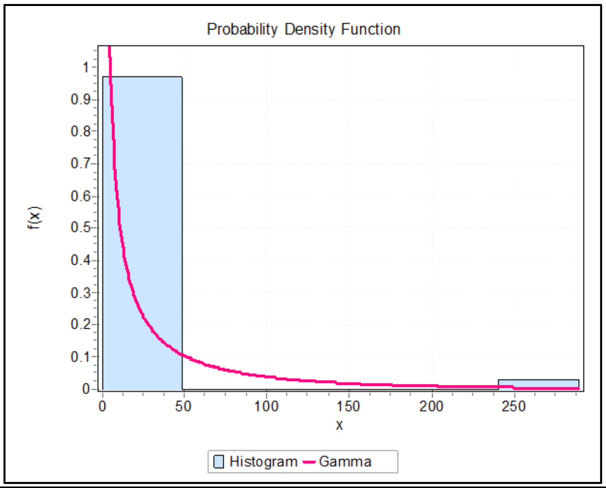
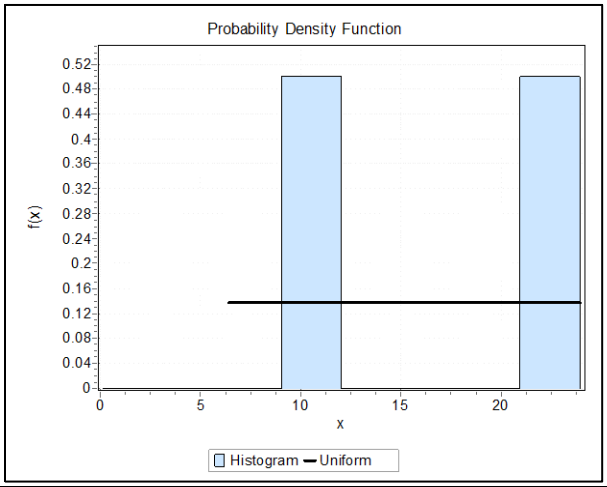
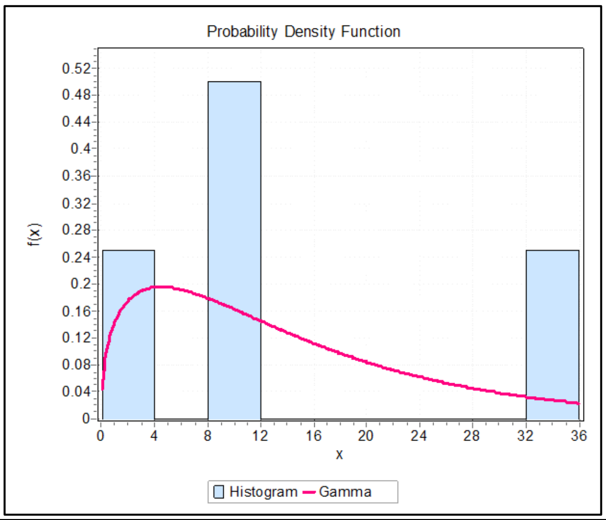
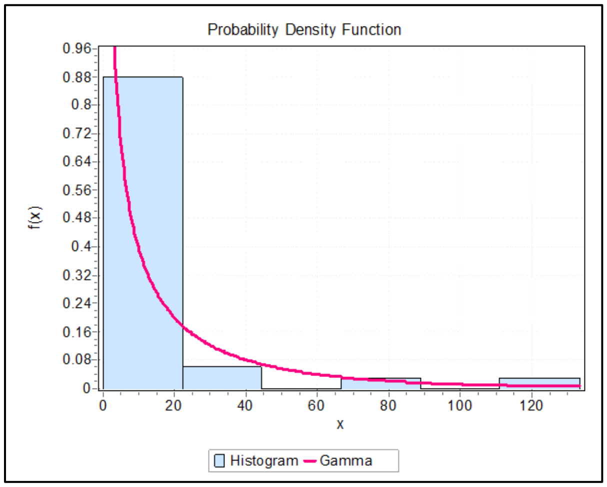


Vehicle Group D

Number of work orders: 4
Work orders total duration: 20 hr.
Best Fitting Distribution: Uniform
Distribution Parameters: A= -0.868 and B = 11.118



Vehicle Group F	Vehicle Group G
Number of work orders: 11 *Work orders total duration:* 273 hr. *Best Fitting Distribution:* Gamma *Distribution Parameters:* Alfa= 0.708 and Beta = 35.082  	*Number of work orders:* 370 (342 NO-S&IC vehicles; 28 S&IC vehicles) *Work orders total duration:* 2911 hr. *Best Fitting Distribution:* Gamma *Distribution Parameters:* Alfa= 0.089 and Beta = 88.367 
Vehicle Group H	**Vehicle Group I**
Number of work orders: 254 (79 NO-S&IC vehicles; 175 S&IC vehicles) *Work orders total duration:* 3597 hr. *Best Fitting Distribution:* Gamma *Distribution Parameters:* Alfa= 0.178 and Beta = 79.575  	*Number of work orders:* 211 *Work orders total duration:* 2049 hr. *Best Fitting Distribution:* Gamma *Distribution Parameters:* Alfa= 0.315 and Beta = 30.787 

Vehicle Group J	Vehicle Group K
Number of work orders: 45 (15 NO-S&IC vehicles; 30 S&IC vehicles) *Work orders total duration:* 916 hr. *Best Fitting Distribution:* Gamma *Distribution Parameters:* Alfa= 0.175 and Beta = 118.24 	*Number of work orders:* 2 (0 NO-S&IC vehicles; 2 S&IC vehicles) *Work orders total duration:* 35 hr. *Best Fitting Distribution:* Uniform *Distribution Parameters:* A= 6.388 and B = 28.212 
Vehicle Group L	**Vehicle Group M**
Number of work orders: 4 *Work orders total duration:* 60 hr. *Best Fitting Distribution:* gamma *Distribution Parameters:* Alfa= 1.427 and B = 10.443 	*Number of work orders:* 33 *Work orders total duration:* 490 hr. *Best Fitting Distribution:* Gamma *Distribution Parameters:* Alfa= 0.328 and Beta = 45. 22 

Vehicle Group N
Number of work orders: 48 (4 NO-S&IC vehicles; 29 S&IC vehicles) *Work orders total duration:* 740 hr. *Best Fitting Distribution:* Gamma *Distribution Parameters:* Alfa= 0.432 and Beta = 35.64