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**Federal Railroad
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Locomotive Fuel Vapor Reclamation System Field Evaluation and Cost-Benefit Analysis

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13. ABSTRACT (Maximum 200 words)

This report summarizes the results of the work performed to install a diesel vapor reclamation unit (DVRU) on an SD70 MAC locomotive of BNSF Railways and its performance evaluation during freight railroad service. One complete DVRU with several sensors for monitoring fuel and ambient temperatures as well as the fuel vapor-to-air ratio was installed on BNSF9674. An electronics control unit with digital data acquisition and wireless communication over mobile network and internet constituted the remote DVRU data monitoring system. As BNSF9674 was deployed over its freight carrying routes, the DVRU system performance data could be monitored only over a very limited period of time. Often, the remote data transmission was interrupted due to inadvertent locomotive and/or DVRU maintenance problems. Based on one year's experience with performance monitoring, it was concluded that practical difficulties with day-to-day revenue service operations may not permit smooth operation of the DVRU over a long period. This precluded the scope for further installation of more DVRUs on other locomotives. Because the amount of useful DVRU system performance data from the field tests was insufficient, a cost-benefit estimate was carried out while accounting for the contributions of the DVRU and return fuel cooling. In the best case scenario, the return on investment in DVRUs would take 15 years to recover.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg)
= 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

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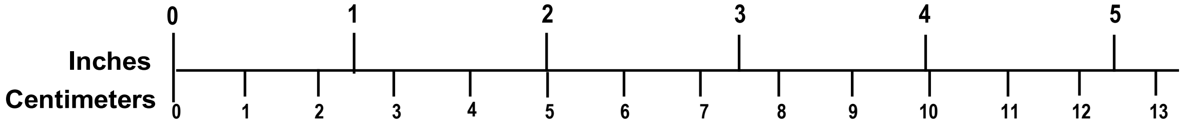
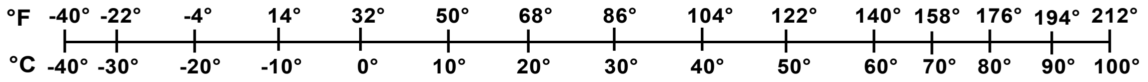


QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

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Executive Summary

QinetiQ North America (QNA) has completed a project to develop and test a diesel vapor reclamation unit (DVRU) with funding from the Federal Railroad Administration (FRA). This final report presents a summary of all the tasks performed under the present program, starting with the installation and performance evaluation of a DVRU and ending with a cost-benefit analysis carried out with a view to assess the financial viability of the DVRU or an alternative return fuel cooling system in Class I freight railroad operations.

Based upon the results of QNA's previous computational fluid dynamics (CFD) analyses of an SD70 fuel tank containing diesel fuel and a mixture of diesel vapor and air at given fuel and ambient temperatures, the DVRU components were designed and fabricated. Following approval of the DVRU installation plan by BNSF Railway management, the manufactured parts and the necessary procured commercial-off-the-shelf items including sensors, were shipped to BNSF's System Maintenance Terminal at Topeka, Kansas for integration with a BNSF locomotive. With the cooperation of BNSF engineering staff at the Topeka depot, the fuel vapor reclamation system was installed on the SD70 MAC locomotive BNSF9674 and integrated with the existing fuel system components along with a few modifications made to the underside of its catwalk structure near the tank.

On successful installation of the DVRU, QNA engineers performed a system integrity check through initial data acquisition and analysis at the BNSF yard in Topeka. They ascertained proper functionality and calibration of the condensed fuel sensor, including the pumping unit integrated with the condensed fuel measuring unit (CFMU).

Several difficulties were encountered over the year the DVRU was in revenue service. These required several visits by the QNA team to BNSF's yards to troubleshoot and make repairs. The difficulties included water ingress to the DVRU control box, broken antenna, overfilling the fuel tank, and incorrect DVRU operation. Although considerable effort was made to overcome these difficulties, it was impractical to maintain the DVRU system fully functional for any appreciable length of time on a revenue service locomotive.

QNA proceeded with an analytic estimation of the fuel vapor reclamation potential considering three alternative approaches: (a) using a DVRU with a 50 percent vapor condensation efficiency, (b) using a DVRU with closed-circuit fuel vapor circulation through the tank and the condenser, and (c) replacing the DVRU with a heat exchanger only to cool-down the return fuel from the engine from 125 ºF to 90 ºF. A typical railroad would have a positive return on investment (ROI) after waiting for over 15 years if the closed circuit diesel vapor is circulated through the tank and the condenser: it would take over 17 years for a positive ROI if return fuel cooling is implemented due to the cost of high BTU chillers.

1. Introduction

It is common knowledge that emissions of fossil fuel vapors and their combustion products contribute significantly to environmental pollution and, to some extent, are responsible for global warming. Through the imposition of regulatory compliance, retail gas stations and tanker refueling stations utilize gasoline vapor reclamation. However, Environmental Protection Agency (EPA) regulations do not currently cover diesel vapor emission at locomotive refueling stations. Hydrocarbon fuel vapors, including diesel vapor, are proven toxins in nature and their inhalation is harmful to human health. There is a need to control this environmental pollution..

Another issue with the build-up of diesel vapor concentration within the fuel tank of long-haul freight locomotives is the increased fire risk in the event of a collision or derailment. In a previous R&D effort under a separate FRA program, QinetiQ North America (QNA) had shown that with No. 2 diesel temperature rising close to its flash point, or about 120^0F and beyond, the vapor concentration in air within a scaled test tank could exceed the fuel Lower Explosive Limit (LEL). According to the locomotive operational practice information received from Electro-Motive Diesel, the maximum fuel temperature in a long-haul freight SD70 locomotive could reach up to 140^0F before refueling. In the event of an accidental puncture of the fuel tank due to collision or derailment, there is a danger of the combustible fuel vapor escaping out of the tank and causing a fire hazard with flash-back into the tank.

In this context, adoption of a diesel vapor reclamation process in a locomotive fuel tank has the potential to offer triple benefits: (a) fire hazard mitigation in the event of a collision or derailment (b) reduced environmental pollution, and (c) improved fuel economy through fuel vapor recovery and reuse by the locomotive engine. QNA has investigated the feasibility of achieving these potential benefits in a phased manner through this research and development project. Practical viability of installing such systems, maintaining them in operational condition under harsh freight railroad operating environments, and their cost-effectiveness for the railroad industry required a thorough assessment.

1.1 Background

In the previous phase of this research and development program, QNA, in cooperation with BNSF Railway had designed, developed, and installed a diesel vapor reclamation system (DVRU) on a BNSF identified SD70 MAC. The locomotive went into revenue service freight operations while the DVRU performance was remotely monitored by QNA through a cellphone network and QNA's FTP site.

1.2 Objectives

The present research and development efforts were aimed at facilitating the evaluation of the DVRU system performance on two or more locomotives under revenue service conditions. Another important objective was to carry out a cost – benefit analysis in order to assess the practical utility of employing such a system for the overall economic benefit of U. S. railroads.

1.3 Overall approach

QNA installed and monitored the DVRU while this locomotive was deployed in revenue service. The components of the DVRU were integrated with the fuel system of the SD70 MAC, including all sensors used for monitoring the temperature of the fuel, the vapor-air mixture, and the ambient atmosphere, as well as the fuel vapor-to-air ratio (FAR). A control box with GPS, a data acquisition system, and a transceiver was installed to allow remote data communications over a mobile network and the internet; it allowed QNA to monitor the health of DVRU, as well as output of various system parameters, including the amount of diesel vapor condensed by the condenser and the liquid fuel pumped out of the small collector container for reuse in the fuel tank. For the initial verification of proper functioning of the DVRU on the running locomotive, two members of the QNA team were scheduled to ride the train and check the system and data communication with QNA's remote web portal functionality.

BNSF continued to operate the locomotive over its revenue service routes with instructions not to overfill the fuel tank. In the event of any noticeable malfunctioning of the DVRU, both BNSF and QNA agreed to exchange information and devise a plan for corrective action at the earliest possible opportunity.

1.4 Organization of the report

This report is organized as follows:

Section 2 provides the details of the DVRU installation process and on the spot modifications to the original installation plan carried out at BNSF maintenance depot. The post-installation DVRU system inspections, functionality test and calibration conducted to ensure proper remote monitoring of test parameters are also described. Long term remote monitoring of DVRU data including trouble-shooting of data interruption problems at Mandan, North Dakota, necessary repair and maintenance of the system carried out at Glendive, Montana are also described in this section for the sake of completeness.

Section 3 describes the cost-benefit analysis, which considered all modes of fuel loss in the conventional freight locomotives and the locomotive that was fitted with a diesel vapor reclamation system that had open-loop and closed-loop diesel vapor circulation through the tank. A further alternative (return fuel cooling), including its benefit and associated cost, is also presented in Section 3.

Section 4 summarizes the results of the cost-benefit analysis, followed by the *References*, *Abbreviations* and *Acronyms* sections.

Appendix A contains BNSF locomotive # 9674 fuel line temperature data, while *Appendix B* contains an extract of an earlier QNA report from a FRA study that identified key accident parameters from locomotive fuel tank breach and fires in Class I freight railroads.

2. DVRU Installation and Long Term Field Evaluation

QNA installed a DVRU on a SD70 MAC freight locomotive in the previous phase of this program. For the sake of completeness of this final report, a brief summary of all associated efforts are included. The installation required modifications to the fuel system vent box and the flange of the catwalk to assemble all the components of the DVRU in close proximity to the fuel tank, except a chiller unit that had to be located under the cab floor because of its relatively larger size. To facilitate continuous monitoring of the DVRU performance parameters over long periods, QNA installed an electronics control box with remote data communication capabilities with a QNA's FTP portal using cellphone network and internet service. In practice, the remote data communications from the locomotive were interrupted often resulting in the dearth of DVRU performance data, even after one year operation. The following sections include the pertinent details of DVRU installation and performance evaluation.

2.1 Installation of DVRU on BNSF SD70 MAC Locomotive BNSF9674

BNSF communicated the availability of locomotive # 9674, including the tentative schedule of the next maintenance at BNSF yard in Topeka, Kansas. QNA fabricated and shipped all component subsystems to the BNSF yard with a lead time of a couple of days. A four-member technical team of QNA traveled to Topeka installed the DVRU and all associated sensors and subsystems on the locomotive. A few surprises occurred during the installation process and the relative positions of some subcomponents had to be reorganized, as described in the following subsections. Figure1 below shows available clear space near the fuel tank of the locomotive before installation of the DVRU.

Figure 1. Space available for DVRU installation near the fuel tank of BNSF9674

2.1.1 Modification of Vent Pipe Box

The original vent pipe was disconnected from a small vent box that permitted venting out the vapor-air mixture to the ambient. An "L" shaped pipe was connected to the top of the float valve assembly as shown in Figure 2. The float valve was intended to prevent flooding of the DVRU vapor suction pump and the condenser by the excess fuel in the event of accidental overfill of the tank by the BNSF maintenance staff during routine railroad refueling operations.

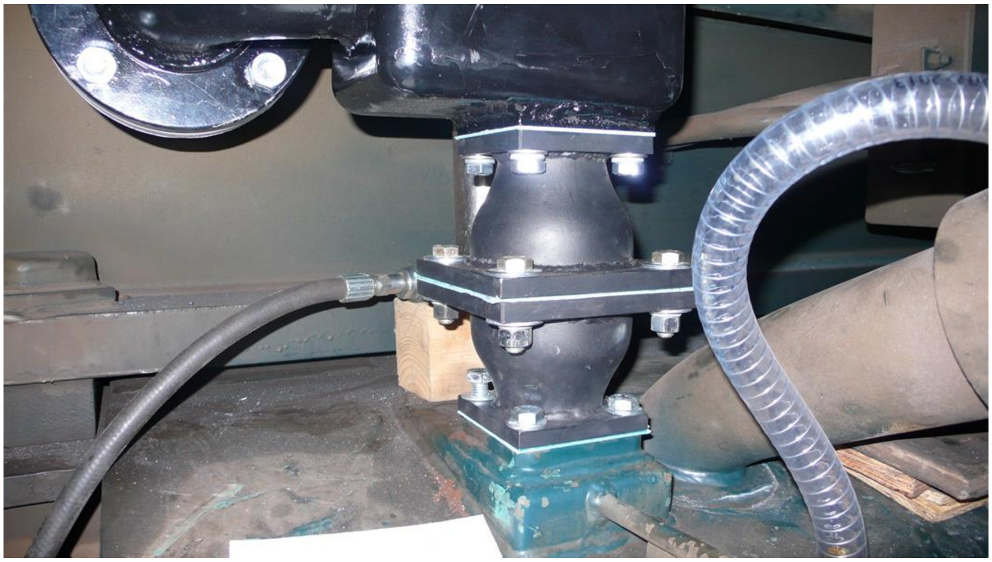


Figure 2. Modified vent pipe with float valve fitting

2.1.2 Modification of Catwalk Underside for Condenser Installation

QNA’s technical team encountered practical difficulties with the DVRU installation. QNA altered the locations of a few existing brackets underside of the catwalk to run and hold the vapor-carrying pipe between the vent box and the condenser firmly. The condenser unit height did not permit insertion between the tank upper surface and the catwalk. This necessitated cutting part of the catwalk flange and stitch-welding the condenser top flange to the underside of catwalk. This modification and installation work is shown in Figure 3.

2.1.3 Vapor Suction Fan Installation

Due to the space constraint, the vapor suction fan was relocated downstream of the condenser. The vapor flow path from the vent box passed through the condenser and permitted the fan to suck a lean mixture of air-vapor at its exit end. A longer pipe was attached to deliver the mixture of diesel vapor and air to the inlet of the condenser; the fan was attached at the outlet end of the condenser. An exhaust pipe was added to the exit end of fan to vent out air and a small fraction of vapor that could not be condensed. Two flexible pipe pieces were attached to the flanges of the fan at either end of the fan for proper flow alignment as shown in Figure 3.

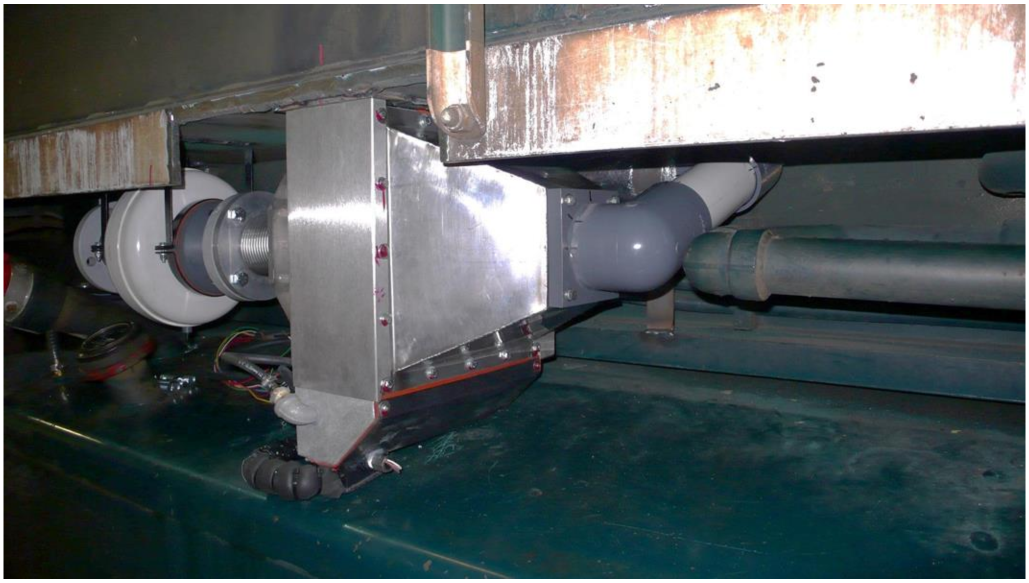


Figure 3. Vapor suction fan installed at condenser outlet

2.1.4 Exhaust Pipe Attachment to Fan Outlet

A matching diameter pipe with its flange attached to the fan exit end flange provided the exhaust flow path. This fan outlet end piping was routed around the tank vent box for ease of installation as shown in Figure 4. The flow path of warm vapor/air mixture rising from tank and the cooled air path from the condenser and passing through the exhaust pipe can be visualized in Figure 5.

Figure 4. Exhaust pipe attachment to the fan outlet

Figure 5. Exhaust pipe wrap-around the vent box

2.1.5 Chiller Unit Installation

The size of the chiller unit did not permit its installation close to the fuel tank location. Following the suggestions of BNSF engineering, a relatively less crowded place was located in the vestibule below the cab. After slight reorganization, QNA found enough vacant space for the installation of the REMCOR chiller. The chiller unit is shown in Figure 6. It was necessary to have enough length of the outward and return coolant circulation tubing for closed-loop circulation of the condenser coils.

Figure 6. Chiller unit installed in the vestibule below the cab floor

2.1.6 Installation of the Power Inverter

A 110 V AC power supply was required for the REMCOR chiller, with the use of an inverter. An adequate capacity EXELTECH inverted the 74 V DC power available in the freight locomotive into 110 V AC. The team routed the AC power to the chiller and the vapor suction fan. Both the chiller and the fan had continuous rating for trouble-free operation. The inverter was wall-mounted near the power supply board as shown in Figure 7.

Figure 7. Wall-mounted Power Inverter installed

2.1.7 Attachment of Condensed Fuel Measuring Unit to the Condenser

QNA developed a condensed fuel measuring unit (CFMU), essential for the remote monitoring of the DVRU performance. The 200 ml capacity small container was fed with the condensed diesel fuel by the copper tubing below the condenser unit. Because of the height restriction anticipated for the condenser installation and the flow of condensed fuel by gravity, the fuel sensor and measuring unit were deliberately made compact to fit into the lower-end contour of the condenser as shown in Figure 8. All the external tubing of the CFMU was flexible for easy routing to the fuel tank for remote monitoring and reuse.

Figure 8. Condensed fuel measuring unit attached to the lower part of condenser

2.1.8 Installation of Tank Air Inlet Tubing

QNA modified the original vent outlet box for the diesel vapor withdrawal from the tank. The vapor flow path was rerouted to pass through the suction fan, the condenser and finally exiting to the atmosphere. This necessitated providing adequate quantity air inlet into the tank with the help of tubing; at the same time, it prevented fuel spill over in the event of a locomotive rollover. The fitted end of a steel tube to a T-joint, was inserted into the opening in tank for the fuel back-flow tubing insert. The other end of the steel tube was drawn across the width of the fuel tank and then raised with pipe-elbow fittings to prevent fuel spill during the unlikely, but plausible event of a locomotive rollover. Figure 9 (a) shows the tubing joint for air inlet into the tank. Based on the suggestion of BNSF engineering personnel, the QNA team installed another similar air inlet tube on the opposite side of the fuel tank at far end of the DVRU main installation unit as can be seen in Figure 9 (b).

(a) (b)

Figure 9. Installed tubing for air inlet into the fuel tank: (a) connection with T-pipe joint, (b) two air inlet tubes laid across the tank width

2.1.9 Temperature Sensor and Vapor Suction Tube Installation Within Tank

To monitor the fuel temperature and the fuel-vapor to air ratio (FAR) within the tank, it was necessary to insert a few sensors into the fuel tank. Accordingly, a hermetically sealed thermocouple was inserted through a 4-way-pipe fitting deep into the fuel tank with its other end connected to the signal conditioner in the Data Taker. A vapor sampling flexible tubing was connected to the upper end of the above pipe joint along with a small float valve to prevent accidental fuel gushing up to soak Mine Safety Appliances' (MSA) filters in the event of a fuel overfill. The back flow tubing from the fuel-fill-port was connected to another arm of the pipe joint. The remaining pipe joint arm was fitted with a return fuel tube coming from the CFMU overflow port and from the bottom of the suction fan manifold. Figure 10 shows the above connections to the fuel tank through the 4-way-pipe connector.

Figure 10. Temperature sensor and vapor sampling tube connection details to the fuel tank

2.1.10 Electronics Control and Data Communication Box

The test data for DVRU performance evaluation were captured by the data acquisition (DAQ) system onboard the locomotive and subsequently communicated to QNA's FTP site wirelessly. To achieve these goals, a compact NEMA-4X compliant steel box was procured to accommodate the following:

(a) Data acquisition module consisting of
    (i) Signal conditioners for the deployed sensors
    (ii) GPS module
    (iii) Wireless data communication module
(b) MSA vapor sampling pump
(c) MSA's XIR sensor unit
(d) MSA's digital FAR as percent LEL readout unit
(e) DC power converter for 74 V DC to 12 V DC

(f) Relays for the control and activation of the small fuel pump in the CFMU

All the above components were laid out and fixed inside a water-proof electronics box, which was NEMA 4X compatible to withstand the harsh environment of the railroad service. All the sensor wires, cables and pipes entered into this box through small gasket-fitted openings in the bottom wall of the box. Figure 11 shows the inside of the fully instrumented electronics box and also in the closed condition with all external cable and pipe connections running underneath the box.

Figure 11. Electronics control and data communication box inside view

2.1.11 GPS Sensor and Antenna Installation

The team needed to know the instantaneous physical location of the locomotive along with the date and time stamp to facilitate remote monitoring of data acquired by the DVRU. A GARMIN GPS sensor and a GSM antenna were mounted on the roof of the locomotive to communicate the locomotive positional information and all the acquired performance data of the DVRU to QNA wirelessly. With the cooperation of BNSF staff, QNA attached the GPS and the antenna with a strong adhesive to the roof of BNSF9674 and the cables were routed through a plastic conduit to the electronics control box as shown in Figure 12.

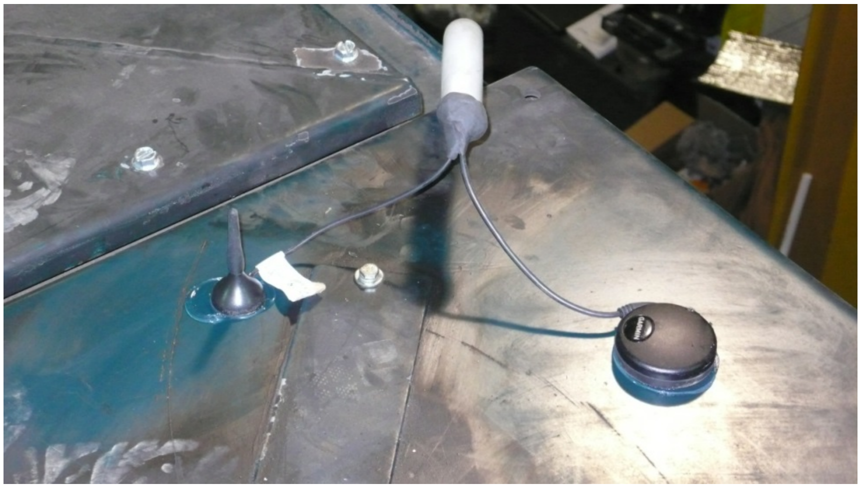


Figure 12. A GARMIN GPS and a GSM antenna installed on the roof of the locomotive

2.1.12 Locomotive with Installed DVRU

Following installation and components integration work of the DVRU, the QNA team performed a DVRU functionality testing and calibration of the CFMU system while BNSF9674 was still in the Topeka System Maintenance Terminal. Figure 13 shows a photograph of the DVRU installed on the locomotive in the yard.

Figure 13. BNSF SD70 MAC locomotive # 9674 with installed DVRU in Topeka yard

2.2 Test for System Functionality and Remote Data Monitoring

The BNSF9674 locomotive was not directed to resume freight service immediately, offering the opportunity for QNA team to verify the DVRU system functionality, check the calibration of the CFMU, and verify wireless data communication to QNA's FTP site. The DVRU system was fully powered ON and the sensor output data were monitored to indicate that the system indeed functioned as directed. For example, the thermocouples output showed the ambient temperature, the fuel temperature, the vapor inlet temperature to the condenser and the condenser outlet temperature was close to that of the closed loop circulating chiller fluid. The fan, chiller and the Data Taker functioned as expected.

To verify the functionality of the two fuel level sensors mounted within and the accuracy of condensed fuel measuring unit (CFMU), QNA team poured-in neat No. 2 diesel fuel into its small fuel container. When the poured diesel level reached the lower sensor, the LED lighted indicating the detection of diesel fuel in the container and when the fuel reached the upper sensor level, the pump started pumping out diesel fuel through the outlet tubing to the locomotive fuel tank, until the container fuel level dropped to the lower sensor – at which point the pump stopped. The flow meter counter reading was found to correlate well with the calibration data generated in the laboratory test at QNA earlier. Figure 14 shows the assembled system of the CFMU and Figure 15 shows the original calibration curve of the CFMU based on several sets of readings taken in terms of Counts/mL of diesel fuel pumped out by the unit.

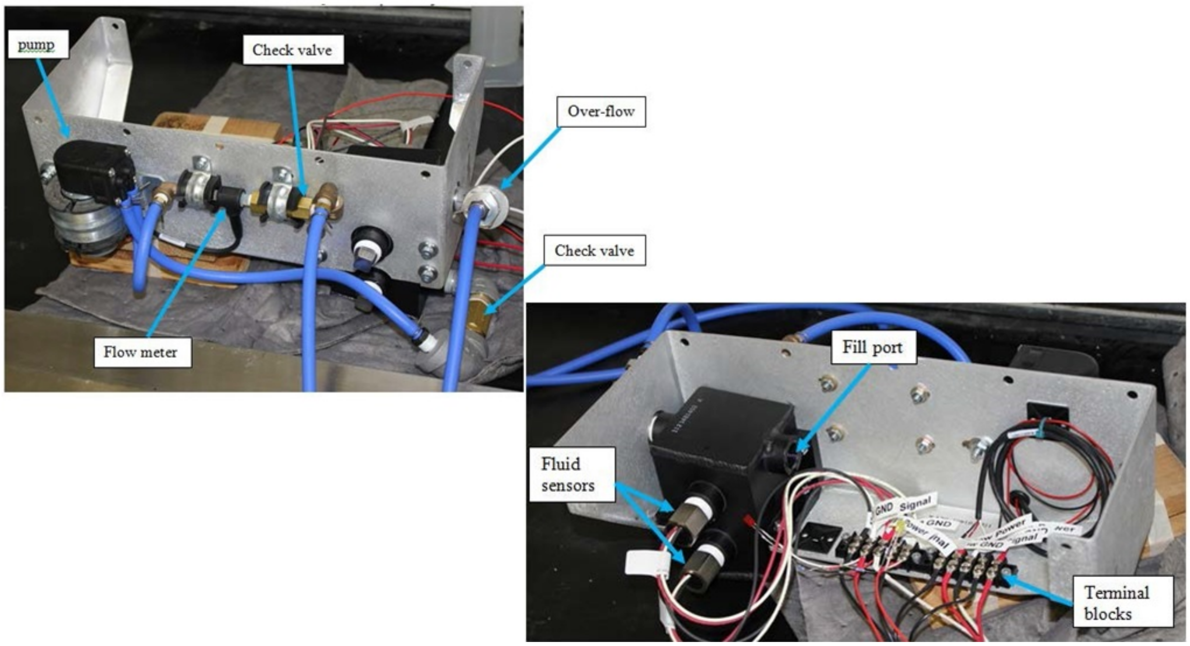


Figure 14. Calibrated condensed fuel measuring unit

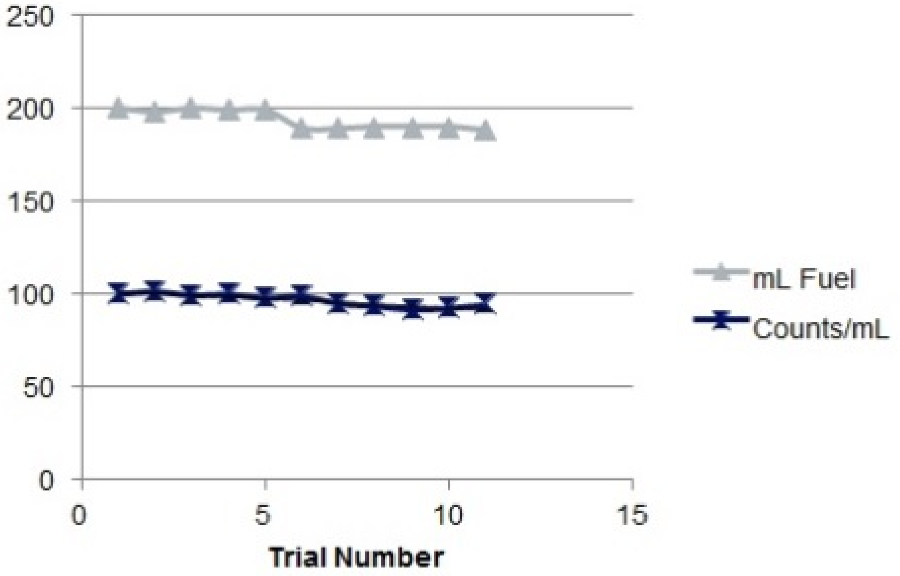
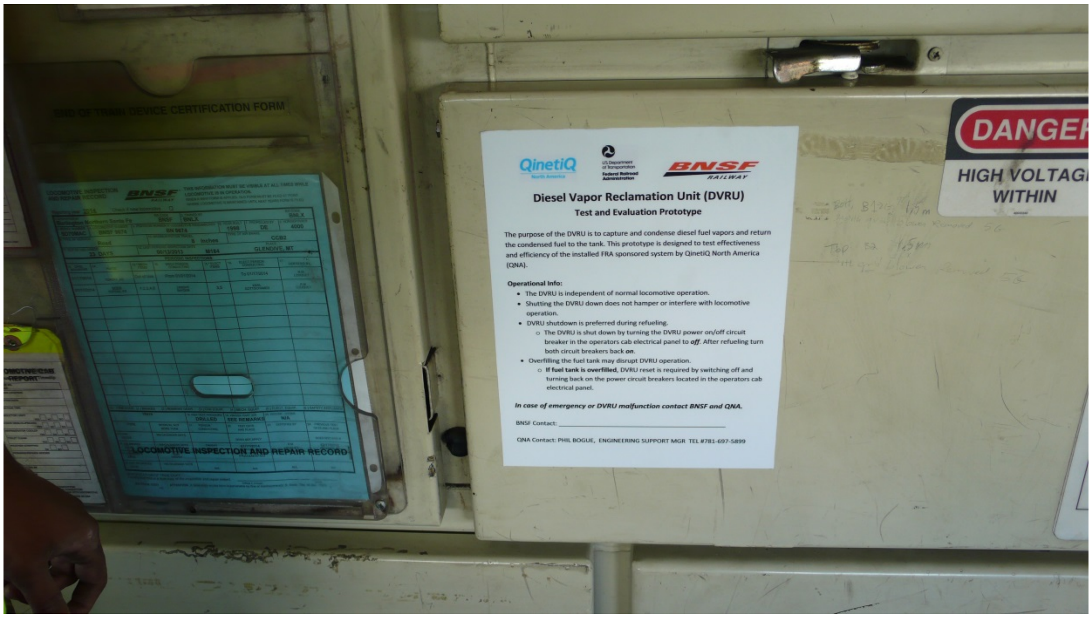


Figure 15. CFMU calibration curve representing counts per mL fuel pumped

The QNA team ascertained that the calibration spot check performed in the BNSF yard at Topeka, KS matched well with the data obtained during original laboratory calibration test data shown in Figure 15. Subsequently, on QNA's request, the engine of BNSF9674 was allowed to run at notch position 8, while remaining stationary in the yard for about 8 hours. QNA verified that the DVRU, including the Data Taker were all functional and performed as intended.

According to the prior arrangement with BNSF, two members of the QNA team rode a locomotive trailing behind BNSF9674 with a view to log the progress in freight railroad service including refueling for about a day, and to monitor the DVRU system health. BNSF decided not to release BNSF9674 for revenue service for the next several days when it was retained in the Topeka yard. Due to this change of plan, the QNA team had to return back to Waltham, MA. Prior to leaving Topeka, they strapped one "Placard" near the tank refueling point with instruction not to overfill the tank and another placard near the main switch board bus explaining conditions for switching 'ON' and 'OFF' the DVRU Inverter switch and the monitoring equipment switch of the DVRU system. Figure 16 shows the QinetiQ instructions not to overfill the tank strapped to the fuel tank surface near the DVRU installation and the fuel-fill port. DVRU prototype system testing and general operational information were placed prominently on a placard that was displayed near the main switch board as shown in Figure 17. Additionally, a copy of the PowerPoint presentation comprising of the complete circuit diagram of the DVRU and assembly, as well as functional details of all components was handed over to BNSF for appropriate dissemination of instructions to their operating crew and concerned personnel.

Figure 16. QNA's instruction sheet attached to the fuel tank



Diesel Vapor Reclamation Unit (DVRU)

Test and Evaluation Prototype

The purpose of the DVRU is to capture and condense diesel fuel vapors and return the condensed fuel to the tank. This prototype is designed to test effectiveness and efficiency of the installed FRA sponsored system by QinetiQ North America (QNA).

Operational Info:

- The DVRU is independent of normal locomotive operation.
- Shutting the DVRU down does not hamper or interfere with locomotive operation.
- DVRU shutdown is preferred during refueling.
  - The DVRU is shut down by turning the DVRU power on/off circuit breaker in the operators cab electrical panel to ***off***. After refueling turn both circuit breakers back ***on***.
- Overfilling the fuel tank may disrupt DVRU operation.
  - **If fuel tank is overfilled**, DVRU reset is required by switching off and turning back on the power circuit breakers located in the operators cab electrical panel.

In case of emergency or DVRU malfunction contact BNSF and QNA.

BNSF Contact: ______________________________

QNA Contact: PHIL BOGUE, ENGINEERING SUPPORT MGR TEL #781-697-5899

Figure 17. A placard displaying information on DVRU test and performance evaluation

2.3 DVRU Output Data Monitoring

The Data Taker (DAQ) and the data communication module were set to collect data with date and time stamp at preset intervals for all performance parameters such as (a) ambient temperature, (b) fuel temperature, (c) vapor inlet temperature, (d) vapor outlet temperature, (e) Fuel-vapor to Air Ratio (FAR) expressed in percent LEL, (f) CFMU-counts representing fuel pumped out to the tank by the CFMU. The GPS output data representing local longitude, latitude of the place and locomotive velocity at the time were also collected along with time stamp. All the collected data were preset to be transmitted at midnight through cell-phone network to the QNA's FTP site located in Waltham, MA. If there was lack of network connectivity at some location, then the data transmission would resume on the next night as the locomotive kept moving on its freight operational route. The GPS data indicating the longitude and latitude of the place at the time of data collection would indicate the location and the speed of the locomotive traveling on revenue service routes. The remotely transmitted data of the DVRU performance parameters, and the GPS output, was received at QNA’s FTP site in the format shown in Figure 18. The post-installation initial set of temperature and FAR data were analyzed and plotted for over one week period as shown in Figure 19.

Updated: 2014/01/29 12:36:41

Name	Value	Units	Timestamp
Fuel Temp	71.654256	degF	2014/01/29 12:35:00.757
Vapor Inlet Temp	60.311724	degF	2014/01/29 12:35:00.791
Vapor Outlet Temp	42.578376	degF	2014/01/29 12:35:00.825
Ambient Temp	38.50094	degF	2014/01/29 12:35:00.859
LEL	9.664434	LEL	2014/01/29 12:35:00.893
GPSTime	3		2014/01/29 12:30:01.244
LatD	3	Deg	2014/01/29 12:30:01.245
LatM	0	Min	2014/01/29 12:30:01.245
LonD	0	Deg	2014/01/29 12:30:01.245
LonM	0	Min	2014/01/29 12:30:01.245
Alt	0	m	2014/01/29 12:30:01.245
HErr	-1	m	2014/01/29 12:30:01.245
GPS State	0		2014/01/29 12:30:01.245
Head	0	deg	2014/01/29 12:30:01.249
Spd	0	kph	2014/01/29 12:30:01.249
Spd	0	mi/hr	2014/01/29 12:30:01.250
Spd	0	mps	2014/01/29 12:30:01.253
Trip	0	km	2014/01/29 12:30:01.254
1RELAY	---	State	1989/01/01 00:00:00.000
SetCV1on	---		1989/01/01 00:00:00.000
Counter	---	Counts	1989/01/01 00:00:00.000
1RELAY	---	State	1989/01/01 00:00:00.000
set1CVoff	---		1989/01/01 00:00:00.000
total	---		1989/01/01 00:00:00.000
Fuel Pumped	---	mL	1989/01/01 00:00:00.000
LowSwitch	0	State	2014/01/29 12:36:40.008

Figure 18. A sample set of DVRU system output remotely received at QNA

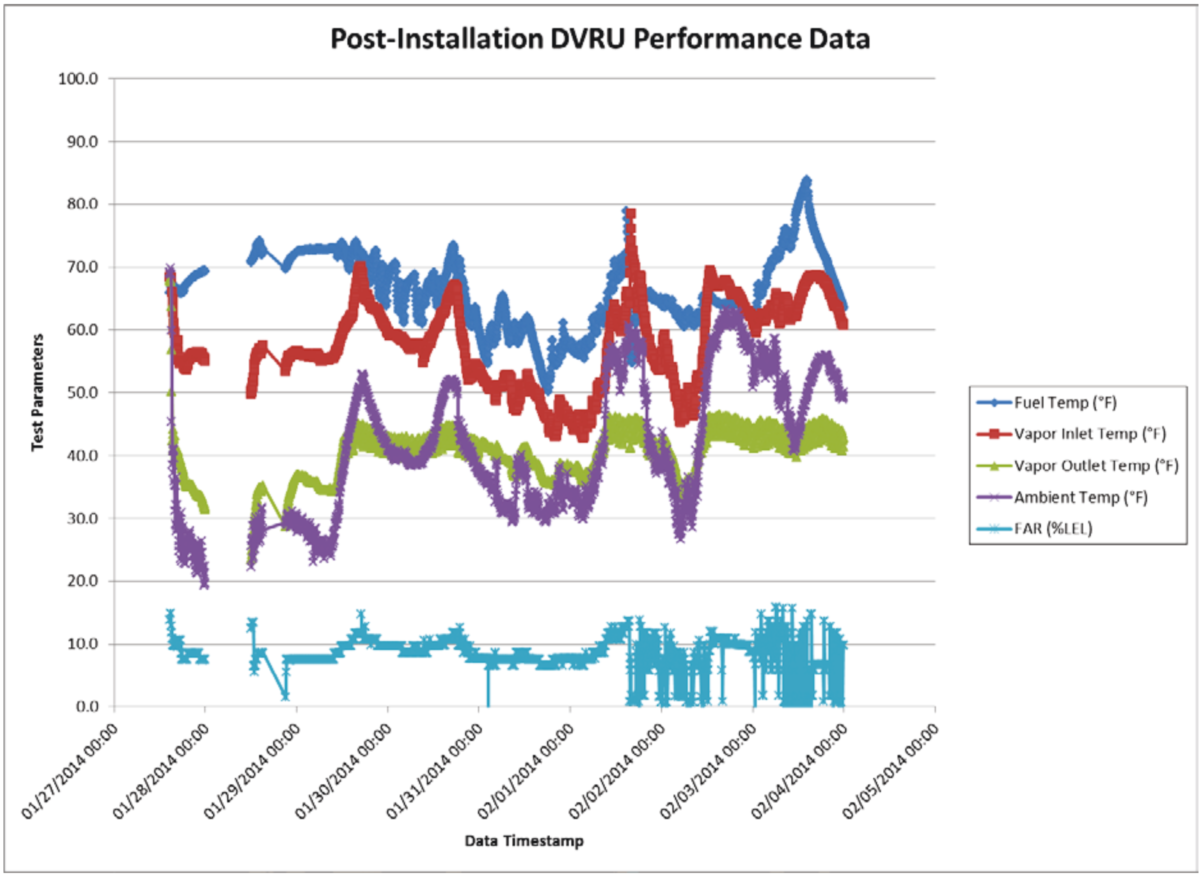


Figure 19. DVRU performance data plotted over one week

All the available data are plotted in Figure 19. The data from the test carried out by the QNA team in the yard when the stationary locomotive had its engine run at notch 8 for about 8 hours are on the left of the chart. The ambient temperature dropped from above 60 ºF to 20 ºF by midnight. The fuel temperature initially dropped a little below 70 ºF and then climbed back to 70 ºF as the warm return fuel from the fuel injectors warmed the fuel in the tank in the long run up to 8 hours. The vapor inlet temperature dropped from 70 ºF to about 55 ºF, with a sharp drop in ambient temperature. The vapor outlet temperature dropped close to 32 ºF, although the closed-loop circulating coolant with anti-freeze from the chiller was set at 40 ºF. The FAR, expressed as percent LEL, varied between about 16 and 8 percent as the vapor suction pump allowed the lean mixture of diesel vapor in air within the tank to dilute with ambient air inlet through two air-inlet pipes at the opposite end of the tank.

There is a gap in the plotted data set for a few hours when locomotive BNSF9674 was in the Topeka yard. It is possible that the locomotive main electrical bus knife switch might have been opened by a BNSF electrician to carry out maintenance work on the locomotive and that cut off power to the DVRU. Subsequently, with the power to DVRU restored, all the sensor output data were recorded and communicated, as seen in Figure 19. The plotted data for next several days show the diurnal variation of the ambient temperature, whose peaks and troughs nearly coincided with those of the vapor inlet temperature. The vapor outlet temperature was maintained close to 40 ºF as expected due to chiller preset temperature. The fuel temperature within the tank varied between 50 ºF and about 83 ºF depending on the locomotive engine running condition or notch position. Since the locomotive was in the yard for most of the time, it was under idling condition. There is hardly any noticeable variation of FAR over the plotted data set and the maximum value did not cross about 15 percent LEL.

2.4 Long Term DVRU Data Monitoring

During its post-installation and functionality test of the DVRU, QNA tested and ascertained long-term data acquisition and remote transmission to QNA server. The team took necessary precautions to place placards and markings including instructions at required locations on 9674 locomotive so that the BNSF staff would not inadvertently disrupt the DVRU system functionality during the locomotive's operational service. Several unforeseen things happened and there were many interruptions in remote data monitoring at QNA, which resulted in ultimately gathering a very limited amount of DVRU data between installation, trouble shoot and repairs lasting over one year. There were large time gaps between those events, primarily because of lack of accessibility for QNA personnel to BNSF9674, which BNSF operated mostly for coal-hauling operations in the north-west.

2.4.1 Remote Data Monitoring Problem and Trouble Shoot at Mandan, ND

After the initial few days of DVRU data analysis and monitoring at QNA, the remote data stopped becoming available at QNA FTP site. Over the phone inquiry with BNSF suggested that BNSF9674 was in freight-carrying operational service and that QNA will be informed when it would again report for the maintenance service at one of its depot four months later, QNA was informed that BNSF9674 was scheduled to be available for a day at Mandan, North Dakota and that QNA personnel may access the DVRU on the locomotive for troubleshooting and any necessary repair work. Accordingly, two QNA engineers went to Mandan, ND to trouble-shoot and repair the problem with the DVRU.

Upon examining the installed DVRU, QNA detected a lack of power inside the electronics control box. The inside of the box was flooded with water, which shorted the power supply, thus rendering the DAQ and the data communication module non-functional. The vapor suction fan and the chiller were in working condition which derived 110 V DC power separately through an inverter. The team observed liquid diesel fuel dripping out drop by drop from the CFMU collector tank overflow port. This could have happened due to the long term diesel vapor condensation by the condenser over the five months period when both the vapor suction fan and the chiller unit circulating the chilled coolant to and from the condenser were fully operational, but the fuel level sensors and the fuel pump within the CFMU were non-functional due to power supply cutoff within the electronics control box. A further reason could be due to the tank overfill under pressure that could push-up past the ball valve and accumulate some fuel in the fan and condenser manifolds.

Figure 20 shows the inside status of the DVRU electronics control box with all power indicators in the MSA vapor sampling pump, its display unit off, and the damp bottom inside wall of the box, including the evidence of rusting due to pressurized water ingress. It was believed that despite using an electronics box enclosure certified to meet NEMA-4X standard, water could have entered inside the box during the power wash that was given to the DVRU-installed BNSF9674 before it left the BNSF Topeka yard for revenue service. QNA was not made aware of the power wash procedure or schedule prior to or during the DVRU installation.

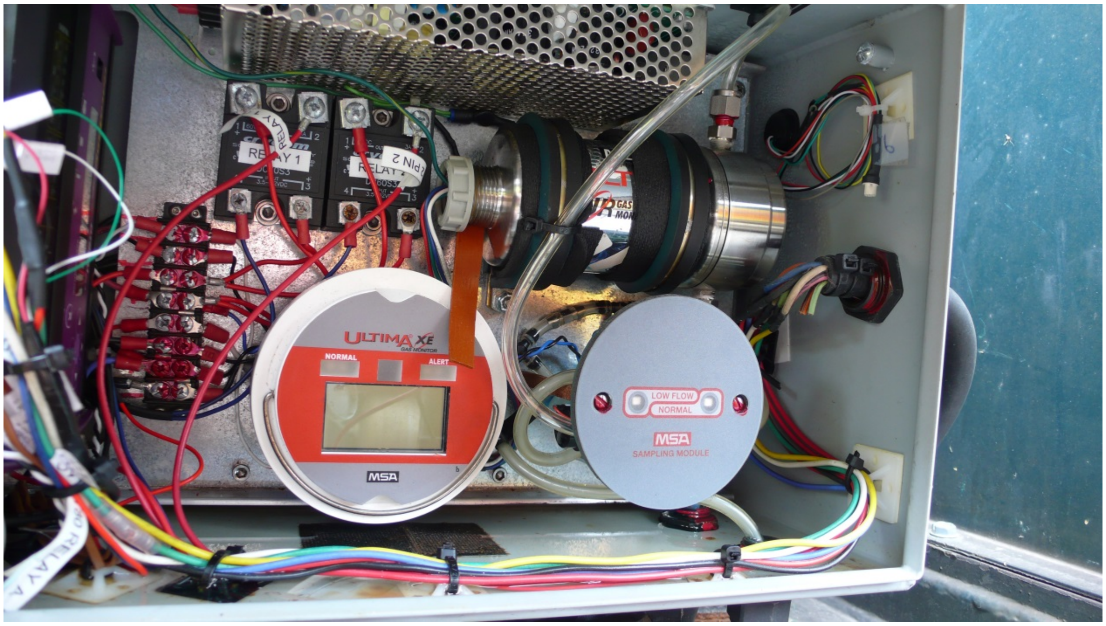


Figure 20. Inside view of the electronics control box with power cut off

The DVRU switches, both for the inverter and the monitoring equipment were found still 'ON' as shown in Figure 21, and the chiller unit was still functioning normally at its preset temperature of 40 ºF as shown in Figure 22.

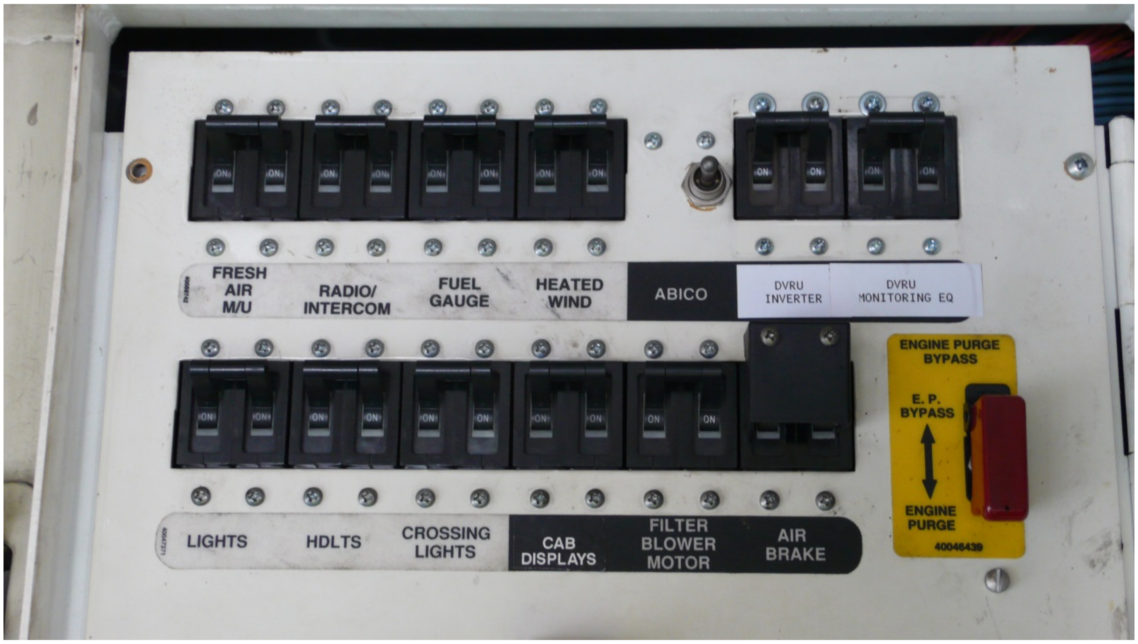


Figure 21. Main switch board showing status of DVRU-specific switches

Figure 22. Chiller display showing status of circulating coolant temperature

Because of the very little time available, it was not possible for the QNA engineers to repair, replace and test all components of the DVRU at Mandan to make it fully functional and to install an additional water-proof cover to effectively protect the electronics control box against future pressurized water ingress. To retrieve the residual recorded data from the Data Taker, QNA personnel brought the unit back to QNA. Further, the team switched off the inverter to shut down the fan and the chiller unit until the whole DVRU system could be checked and powered 'ON' at a BNSF Maintenance Depot.

2.4.2 DVRU Maintenance at Glendive, Montana

With prior notification from BNSF regarding the availability of SD70 BNSF9674, the QNA team check-listed all items necessary for repair or replacement in the DVRU to make it operational. QNA carried out the DVRU maintenance work at Glendive. On opening the cover of the electronics control box, the team found it contained water, which had to be removed using paper towels as shown in Figure 23. Because of the vulnerable location of the 74 V DC to 12 V DC converter within the electronics box, the QNA team shifted the new converter to a location at the back of the electrical panel inside the cab. They replaced the old Data Taker as well as a SIM card with a newer version supporting a more efficient data communication module connecting to a cellphone network (AT&T/Rodgers). The new version Data Taker installed inside the control box is shown in Figure 24. It was powered by a cable running from the converter which was shifted to the cab to avoid getting shorted by water spray.

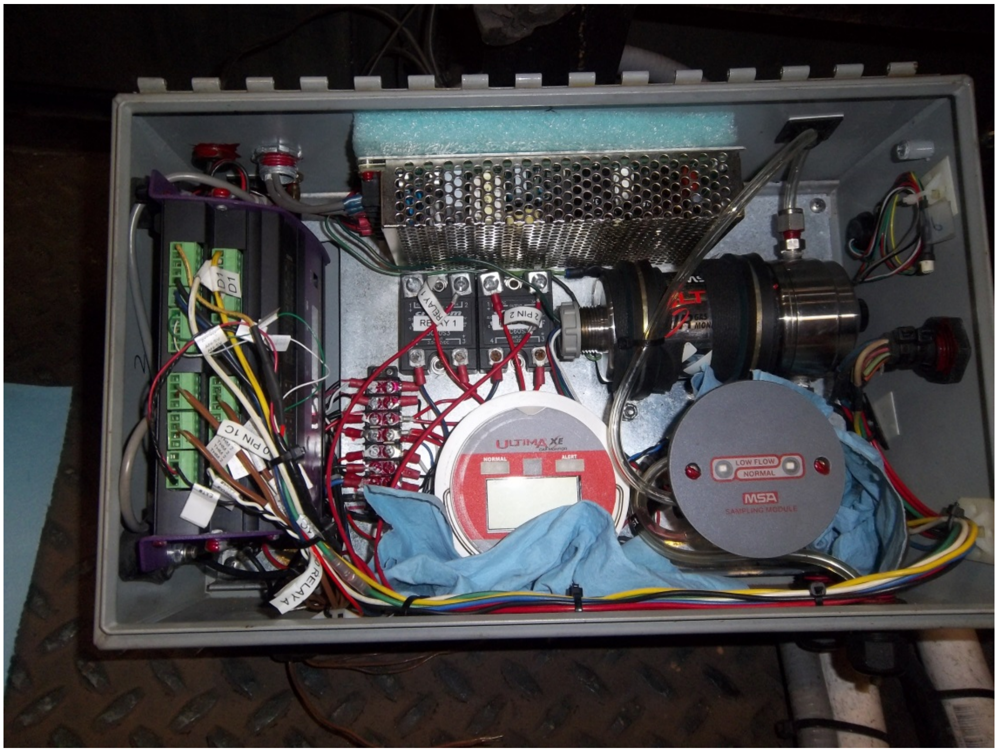


Figure 23. Water clean-up of the electronics control box at Glendive

Figure 24. New Data Taker module installed inside the electronics control box

The QNA team observed evidence of fuel overfilling during refueling despite clear instructions on the placard and decals to the contrary. The pressurized fuel overfill had likely caused the flooding of the tubing in MSA vapor sampling line. Figure 25 shows the fuel overflow marks on the tank sidewall and the diesel fuel inside the MSA tubing is shown in Figure 26.

Figure 25. Evidence of fuel overfill during tank refueling

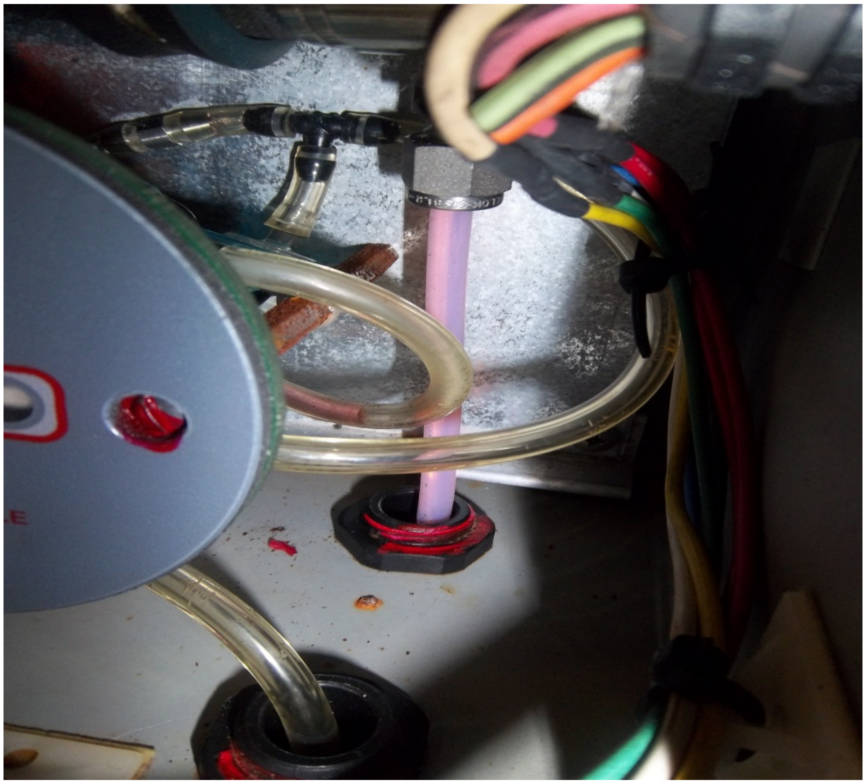


Figure 26. Overfilled diesel fuel in MSA vapor sampling tubing inside electronics box

On completion of the cleanup and maintenance of the electronics control box, as well as setting up the converter within the cab, the QNA team powered up the DVRU electronics control box and confirmed the sensors and display units were functional, as seen in Figure 27. They also watched the pump of the Condensed Fuel Measuring Unit (CFMU) start pumping fuel from its container with the Data Taker indicating 227 mL of fuel pumped out. Next, they cleaned up the collected dirt from the vapor suction fan and the chiller surfaces and tested their functionality by switching 'ON' the inverter located within the cab. The BNSF electrician who was present near the main switch board found the switchgear fittings were loose and tightened them prior to switching 'ON' the inverter. For some unknown reason, at powering 'ON', the inverter got instantly burnt. QNA team tried to locate a replacement inverter at Glendive, but in vain. Just to ascertain if the fan and the chiller got adversely affected during the inverter burning process, they isolated them from the inverter and then powered them separately from a different source to check their functionality. Figure 28 shows the power cables drawn from a different source to the chiller unit for its functional test. Fortunately, both the fan and the chiller were found to be fully functional. They installed an additional waterproof plastic cover to protect the electronics box against a power wash hazard in the absence of QNA team.

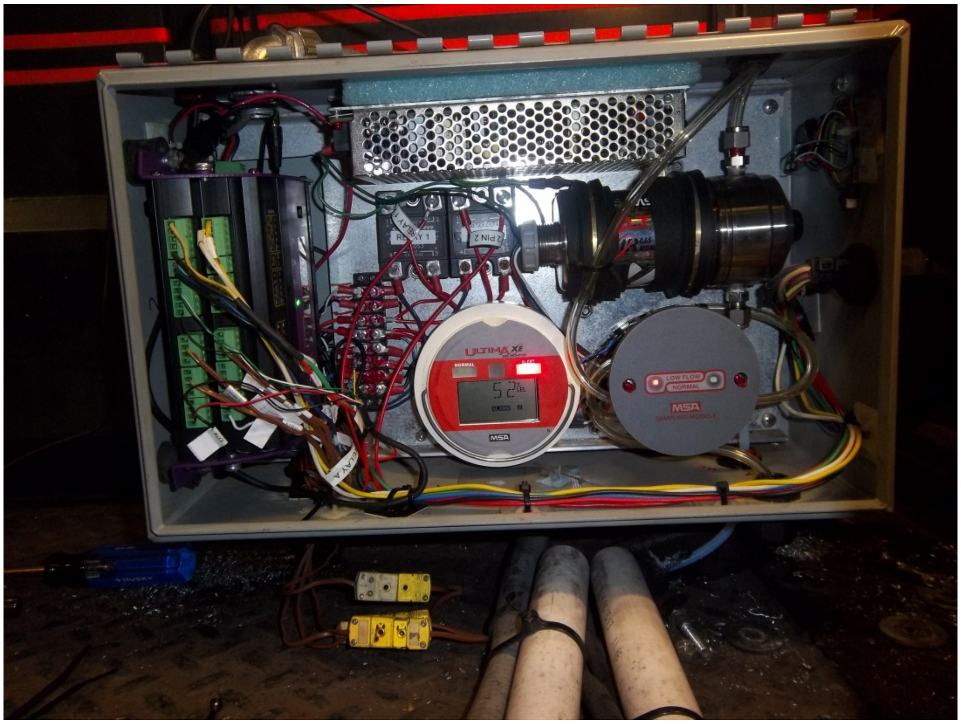


Figure 27. Powered electronics control box following maintenance at Glendive

In the absence of a replacement inverter, a warning placard was placed on the switch board not to attempt switching 'ON', while the switches for the DVRU equipment monitoring were left 'ON', as shown in Figure 29. Prior to departing the BNSF yard at Glendive, Montana, QNA team was informed that they will be contacted again with the schedule for the replacement of the inverter.

Figure 28. Power connection to the chiller from a separate source for functionality test

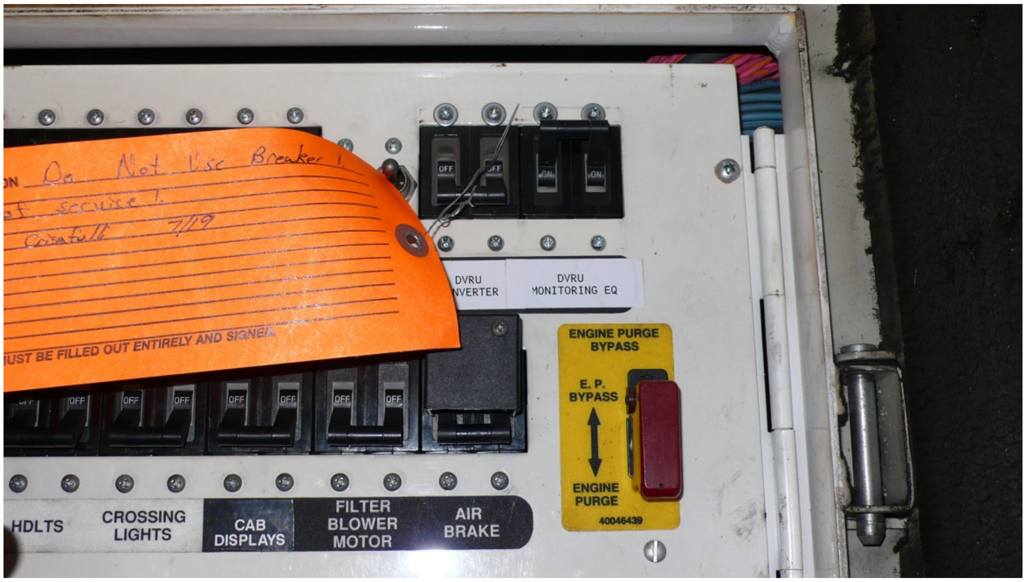


Figure 29. Switchboard display of placard not to switch on the inverter

Upon return to Waltham, the QNA team found DVRU system parametric data at its FTP site, which were wirelessly transmitted by the Data Taker module following its powering at Glendive. The data timestamp indicated the recording covered a period July 20 to 23, 2014 and then abruptly stopped. The acquired data were plotted and are shown in Figure 30.

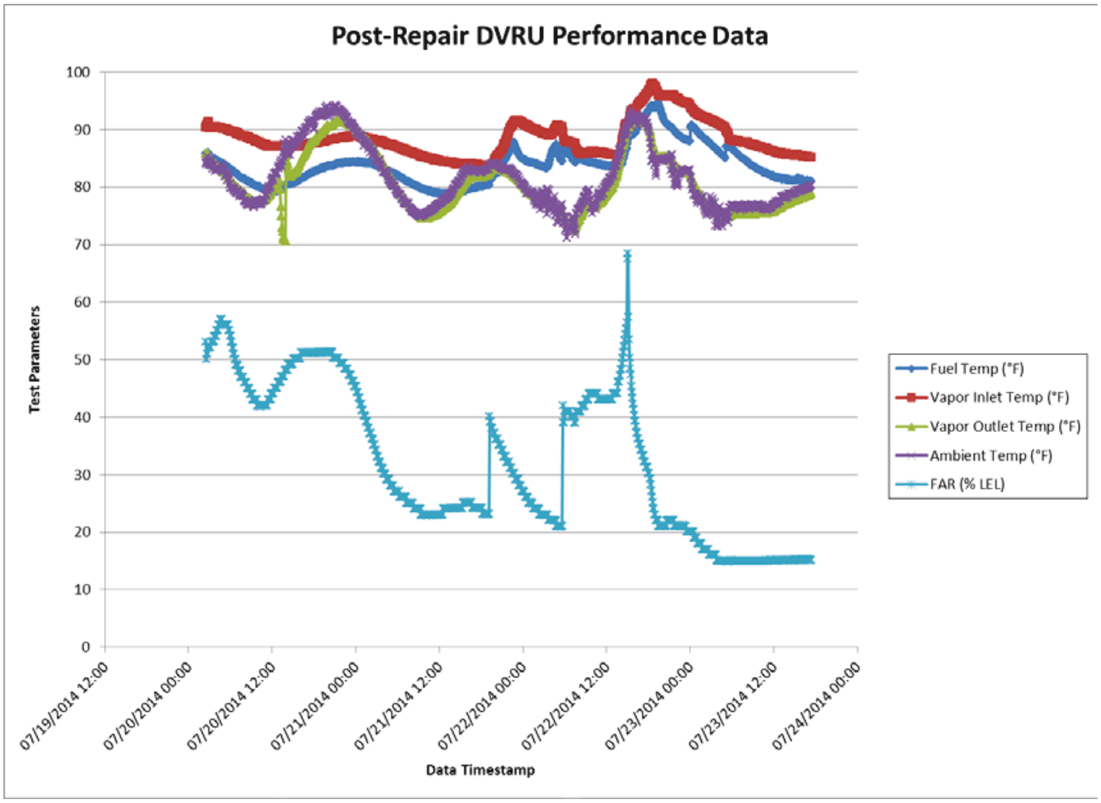


Figure 30. DVRU test parameter data following Glendive repair

The DVRU sensor output data in Figure 30 shows the variation of most parameters similar to the diurnal variation of ambient temperature, varying between 75 ºF and 95 ºF. Because of the shutdown of the chiller by the QNA team on July 20, the vapor outlet temperature did not drop below 70 ºF, in the absence of cooling of the condenser by the circulating coolant from the chiller. The fuel temperature had minimal variations possibly due to low speed operation of the freight train hauled by BNSF9674. However, the FAR variation in this figure shows several peaks and troughs and requires some interpretation based on observed facts and possible operational scenarios. On July 20, when QNA team was present at Glendive and photographed the MSA equipment, including the vapor suction tubing, they had observed the presence of some liquid fuel in the tubing and it is possible that the ULTIMA-XIR sensor had detected above 50 percent LEL vapor passing through the inline filter initially, which later dropped close to 20 percent as the filter got stripped-off the fuel particles. Next, there were two rapid rises in the FAR curve which correspond to rise in fuel temperature from 80 ºF to 95 ºF, as well as ambient temperature from 72 ºF to 94 ºF.

2.4.3 Maintenance Work and Locomotive Ride at Glendive, Montana

Following several interactions with BNSF management and engineering regarding the need to board BNSF9674 for the maintenance of DVRU with replacement of the burnt inverter and to investigate the reason for interruption of remote data communication, the QNA team of two engineers was permitted to do so at Glendive, Montana. Upon arrival at Glendive, the team removed the protective wrappings from the components, such as the condenser unit that was covered following the inverter breakdown during the previous visit. They found the electronics control box was powered ‘ON’, as shown in Figure 31 and manually downloaded the recorded data from the Data Taker for analysis. It was observed that DVRU system parameter data were stored in the Data Taker from March 5 to 9, 2015 and again from March 10 to 12, 2015, when the locomotive was reportedly engaged in freight operations hauling coal trains. Because of the inaccessibility to cell phone network due to the broken antenna cable joint found on top of the electronics box, as shown in Figure 32, the data remained recorded in the circular buffer of the Data Taker.

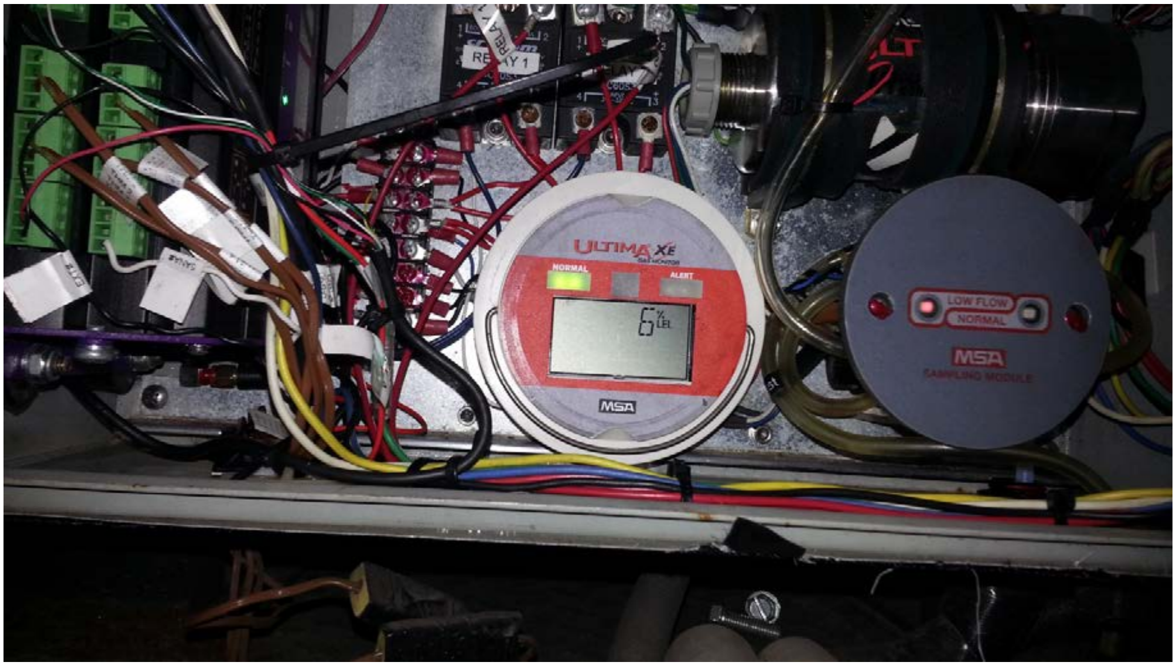


Figure 31. Powered ON electronics control box inside view at Glendive

Figure 32. Broken cell phone antenna cable joint found outside the electronics control box

Considering that no data were transmitted or recorded in the Data Taker from July 24, 2014 until March 4, 2015, it is believed that DVRU equipment monitoring switch was turned 'OFF' during that period by the BNSF staff, someone switched 'ON' the DVRU equipment monitoring system switch over a short period in March 2015 prior to QNA team arrival for maintenance. Figure 33 shows the above data plots along with data timestamp.

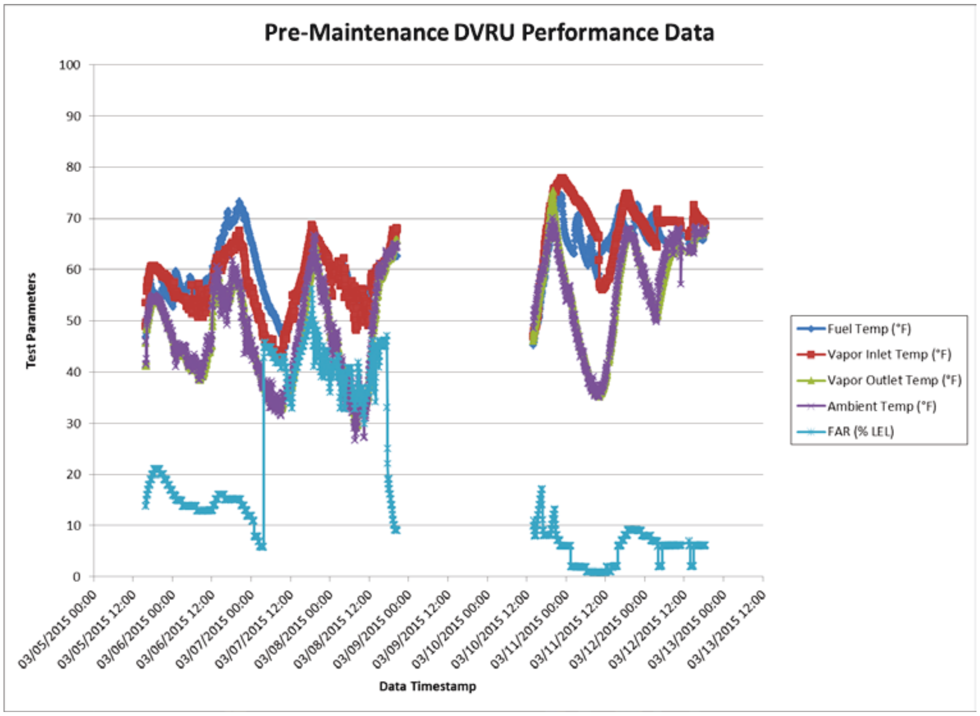


Figure 33. DVRU performance data prior to inverter replacement at Glendive

It is observed from Figure 33 that the vapor inlet and outlet temperatures, as well as the fuel temperature variations with time, show nearly identical trend as that of the ambient temperature. The FAR variation data show a nominal value of around 10 to 20 percent LEL for low speed operation of the locomotive. There is a sharp rise in FAR value to about 45 percent LEL, which is accompanied by a drop in ambient temperature from 62 to 32 ºF and the fuel temperature dropped from 73 to 45 ºF. Since FAR magnitude normally does not rise without rise in fuel temperature, this is suggestive of a refueling of the tank including an over-fill that could force some fuel into the tubing of MSA vapor sampling pump. The tank overfill may be substantiated by the fact that the QNA team found the tank fuel gage reading close to tank full (F) mark, as shown in Figure 34; although it is common practice of the railroads not to refuel a tank above 4,500 gallons to allow vapor space and venting.

Figure 34. Locomotive # 9674 tank fuel gage showing a nearly full tank

Following the sharp rise up to 45 percent LEL, the FAR value dropped gradually to 32 percent and rose rapidly in the afternoon up to about 60 percent LEL. This was accompanied by a rise in both ambient temperature and fuel temperature to above 65 ºF. Locomotive operation at higher notch settings may have contributed to the reading. The FAR values gradually dropped at the data discontinuation point in the afternoon (below 10 percent LEL). The break in the data plots between March 9 and 10, 2015 is indicative of either the locomotive engine shutdown for that period or someone among BNSF engineering personnel switching the 'OFF' and 'ON' switch on the main power bus during that period to carry out any maintenance work.

The resumed data plots to the right of Figure 33 show almost identical variation of the vapor outlet temperature with that of ambient. However, the fuel temperature and the FAR show very small variations at around 10 percent LEL, which are indicative of the locomotive's low speed operation or idling in the yard. When the QNA team arrived at Glendive in the afternoon, they found BNSF9674 idling in the yard. They also found the electronics control box undisturbed with its additional waterproof cover intact with instructions on it. After the data download, they again shut the electronics control box and reinstalled the additional waterproof cover over it as shown in Figure 35.

Figure 35. Waterproof cover reinstalled over the electronics control box

Following download of the recorded data in the Data Taker, the QNA team replaced the inverter and switched on the DVRU system, which was then fully operational except the broken cellphone antenna. This could not be replaced at Glendive as the team did not have a spare and they had to rely on a manual download from the Data Taker at a later date. The QNA team carried four thermocouples for deployment within the engine room of the locomotive to monitor the fuel inlet and outlet pipe temperatures to and from the engine, as well as the engine room and ambient temperatures. The placement of thermocouples on these pipes and the 4-channel Thermocouple Data Logger used for recording the data can be seen in Figure 36.

Figure 36. Thermocouple and data logger installation within engine compartment

With the consent of BNSF, two members of the QNA team boarded the trailing locomotive behind the lead locomotive BNSF9674 for a few hours ride from Glendive past Miles City for about 130 miles. They monitored the empty coal train travelling at times in notch position 5 to 7. On disembarking the train, they uninstalled the Thermocouple Data Logger and brought it back to Waltham to analyze the data. Figure 37 shows the plotted temperature data from the engine room thermocouples along with the ambient and the engine room temperatures as well as the tank fuel temperature. From this figure, it is observed that the outer wall temperature data of the fuel supply (inlet) line and the fuel return line from the engine are almost overlapping on one another. They also match with the engine compartment temperature in the later part of the test, which seem to imply that the thermocouples have essentially measured the pipe outer wall temperature. This coincided with the heated engine compartment temperature. It is also noted that during the winter-months, the fuel supply from the tank to the engine was pre-heated up to 90 ºF. Prior to starting the ride at Glendive, the engine was idling with the ambient at close to 50 ºF, the engine room temperature at 66 ºF, the fuel return line temperature at 73 ºF, and the fuel supply line temperature at 82 ºF. The fuel supply line and return line temperatures shot up well above 90 ºF and later reach over 115 ºF with the locomotive running. Since the temperature data recording interval was set constant at 3 minutes, it was easy to note when the locomotive was idling or running at low or high notch positions depending on the data point density or proximity (Figure 37). Based on the GPS data output, the BNSF train route was plotted as shown in Figure 38. Besides the positional information, the cumulative distance traveled from Glendive, MT and the train speed data were also available until the QNA team disembarked at Forsythe, MT and downloaded the recorded GPS data and the DVRU performance data from the Data Taker within the Electronic Control Box. The DVRU data recorded during the train ride by the QNA team from Glendive, MT to Forsythe, MT are plotted in Figure 39.

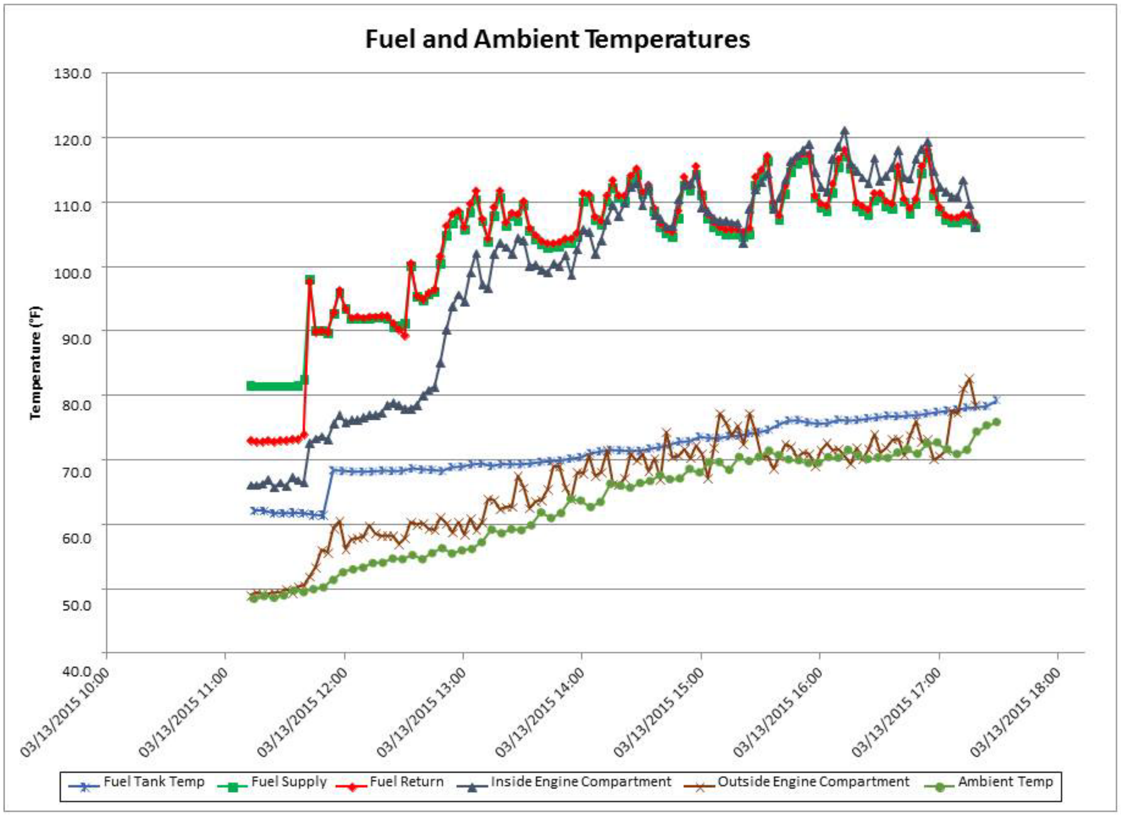


Figure 37. Engine room fuel line outer wall temperature variations

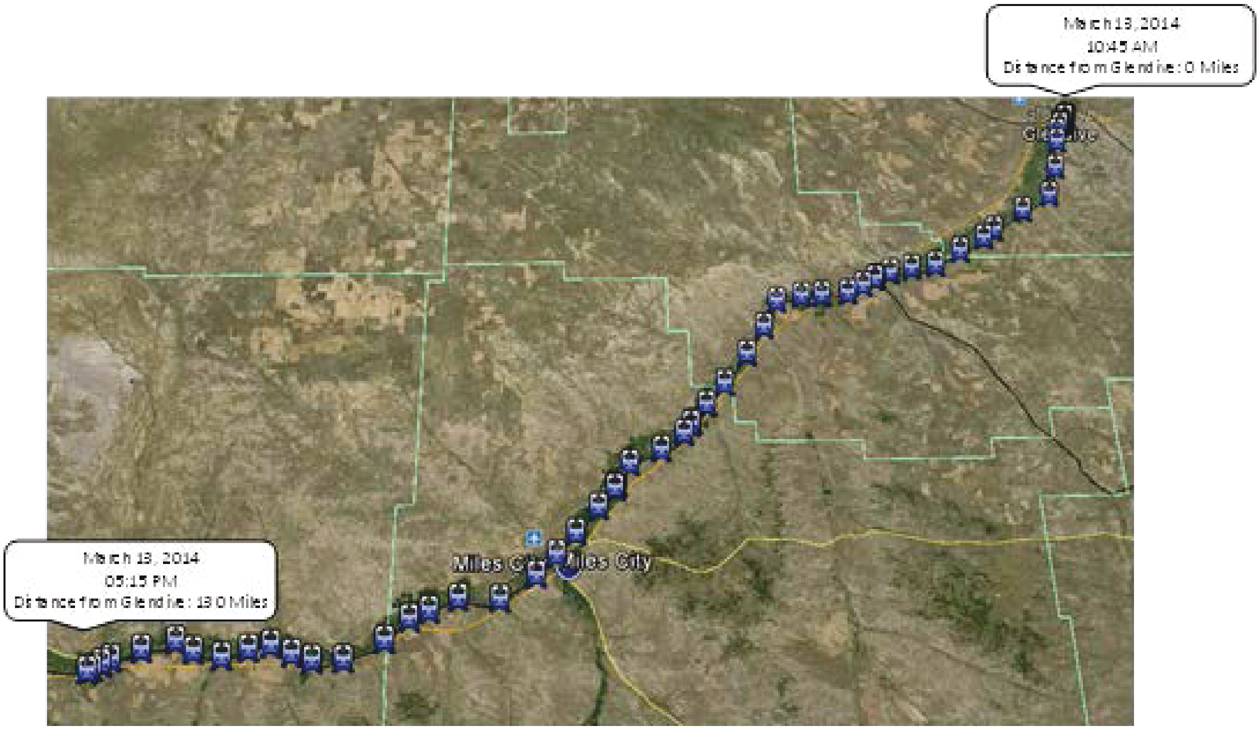


Figure 38. GPS plot of QNA team ride on a BNSF train from Glendive to Forsythe, MT

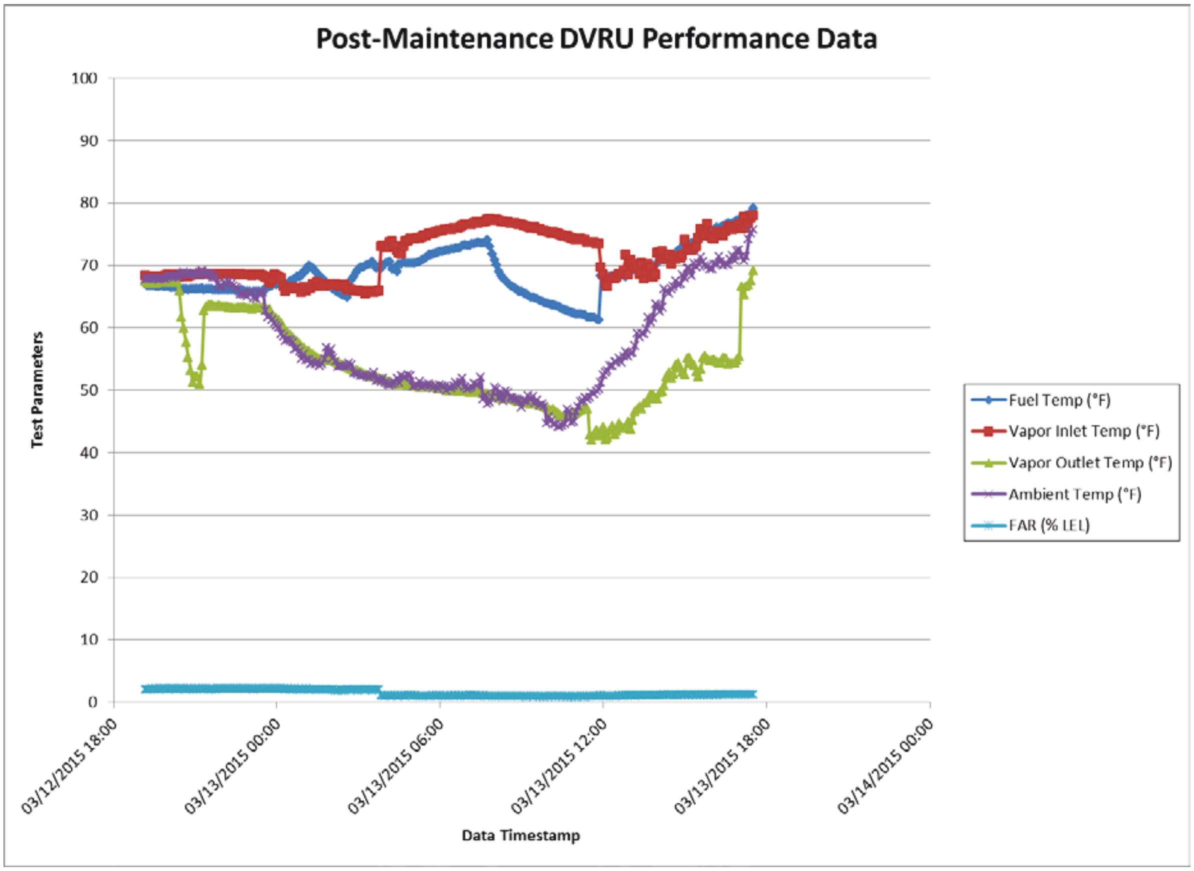


Figure 39. DVRU data recorded during the ride between Glendive and Forsythe, MT

From Figure 39 it is observed that the fuel temperature within the tank showed very little variation around 70 ºF during the period the locomotive was mostly idling in BNSF Glendive yard and then it showed steady rose to 80 ºF at the end of the 130 miles travel up to Forsythe, MT. The trend of variation of the vapor outlet temperature is similar to that of the ambient temperature, which is expected since the chiller and vapor suction fan were turned 'OFF' by the QNA team due to safety concerns. The vapor inlet temperature variation during the locomotive's 130 miles travel nearly coincided with the rise in fuel temperature up to 79 ºF. The FAR readings did not show any variation due to the choked condition for vapor flow through the fuel-soaked filters of the vapor sampling pump as indicated by the "Low Flow" LED glowing red. For lack of spare filters, the QNA team could not replace the filters at Glendive, which were soaked with fuel due to overfill under pressure; despite clear instructions written on decals strapped to the tank near the fuel fill ports.

2.4.4 Summary of Lessons Learned from the Long Term Performance Evaluation

The execution of this program involving the installation of the diesel vapor reclamation unit on a freight locomotive and subsequent performance evaluation of the system on the running locomotive required a great deal of support and cooperation of the BNSF Railways. BNSF authorities were very cooperative in agreeing to provide an EMD SD70 MAC locomotive BNSF9674 for the installation of the DVRU during its routine maintenance at BNSF Topeka Systems Maintenance Terminal, Kansas. QNA had prepared and sent to BNSF the CAD drawings of the DVRU components and the full assembly on the locomotive for ease of installation planning and execution. At the time of the actual installation of the unit during January 2014, several obstacles had to be overcome, such as blow-torch cutting a part of the flange on a catwalk to insert the condenser into position for assembly, replacement of a few existing welded brackets of running cables underneath the catwalk, reconfiguring some items and cables in the enclosure below the cab floor to install the chiller and route its coolant circulating tubing, etc. BNSF engineering personnel were very cooperative and allowed their contract staff to help complete the installation job well on time before the locomotive was due for resuming freight service. QNA took ample precautions to display placards inside the cab and near the main electrical bus explaining the purpose of the installed DVRU system, what not to do and whom to contact at QNA in the event something went wrong. Based on the suggestions of the BNSF staff, instructions were strapped onto the tank top surface near the fuel fill ports "Not to Overfill" the tank, which could otherwise adversely affect the DVRU performance evaluation process due to pressure-refueling performed on the locomotives. Unfortunately, the posted instructions were not always followed.

As it happened, the QNA team could not ride the train soon after the initial installation and successful testing of the DVRU due to unusual delay in BNSF9674 returning back to freight service. After the team returned to Waltham, MA the DVRU data communications, which were received successfully for a few days at QNA's FTP site stopped abruptly. The reason for this could not be found until BNSF permitted the QNA team to briefly board the locomotive at Mandan, ND on June 15, 2014. In the process of trouble shooting, the team found the electronics control box non-functional with a blown-out converter due to water flooding inside, possibly caused by a power-wash given to the locomotive at Topeka. This was corroborated from the downloaded data recorded by the Data Taker prior to its power failure in early February, 2014. The team had found the vapor suction fan and the chiller running all along with AC power drawn through the inverter and saw the liquid fuel dripping through the over flow port of the CFMU fuel collecting container located below the condenser. Due to the lack of power from the

Data Taker, the CFMU fuel pump was inactive and the fuel collected from the vapor condensation or fuel overfill of the tank had to escape to the ground through the overflow port of the container.

Through coordination with BNSF Operational staff, QNA seized an opportunity to carry out the maintenance of the electronics control unit and shifted the new converter location to within the cab at Glendive, MT. On powering the Data Taker, the QNA team confirmed the CFMU pump worked to pump out the fuel from its small container, which was previously calibrated to be 227 mL for emptying a full container. Unfortunately, no pumping data was available for the long term performance evaluation of the preceding period due to power cut off to the Data Taker. At Glendive, the team encountered another problem; the power inverter burnt-out on powering 'ON' which rendered the vapor suction fan and the chiller non-functional. QNA's FTP site received DVRU sensor output data until July 23, 2014. Data stopped after someone at BNSF switched off the power supply to the electronics control and data communication box. Later the cellphone antenna mounted to the top of the electronics control box was damaged. After downloading the data from the Data Taker, only sensor output data from March 5, 2015 to March 12, 2015 was available. This includes a break of one and one-half days, possibly due to engine shutdown. These data were plotted and shown in Figure 33. It is evident from this set of data that despite QNA's clear instructions posted at the main electrical switch board inside the cab not to operate the DVRU switches without contacting QNA's point of contact, switches were turned 'ON' and 'OFF'. Also, evidence of overfilling the fuel tank was found, as explained previously in Section 2.4.2, which resulted in messing up the fuel-vapor to air ratio (FAR) monitoring sensor performance. During the 14 month period of DVRU performance monitoring, following its installation on BNSF9674, components were disconnected from power supply or suffered functional problems, except for only one brief occasion when the entire DVRU system was fully functional on July 21, 2014. From the first week of February, 2014 until July 21, 2014 the fan and chiller/condenser were all working normally and QNA staff had visually seen and confirmed the flowing of condensed fuel from the condenser unit as well as the fuel overflowing out of the CFMU container. However, the power supply to the Data Taker was cut off during that entire period due to apparent power-wash induced flooding of the weatherproof NEMA-4 certified enclosure and, therefore, no condensed fuel could be measured or pumped out by the CFMU. It would be fair to say that under these circumstances, it is very difficult to make a realistic assessment of the DVRU performance, especially its vapor reclamation potential, based on the insufficient amount of test data available.

In summary, QNA gratefully acknowledges the trust and support offered by the BNSF Management during the execution of this program. In keeping with its commitment, BNSF provided the BNSF9674 for the installation of DVRU and its long term performance monitoring through wireless communications of the onboard recorded data. QNA installed and assembled all the components of the DVRU on BNSF9674 and had successfully carried out its functionality checks. However, during normal day-today revenue service operation, QNA could not get uninterrupted DVRU data wirelessly communicated to its FTP site for monitoring and record when the locomotive was returned to BNSF revenue service. Inspection, repair and maintenance of any failed component of the system was delayed until BNSF9674 was available at a specific BNSF yard. Consequently, QNA could only have access to the BNSF9674 for repair and maintenance works three times over a 14 month period. Unfortunately, every time within a week of QNA completing the DVRU maintenance, something went wrong or some component of DVRU could not function due to lack of compliance with the instructions provided on placards and decals. Despite QNA’s best efforts, the sustained fully functional status of the DVRU could not be maintained for long periods, which precluded acquiring enough performance data to determine the system’s long term characteristics and cost-effectiveness.

As a part of the ongoing research and development efforts, QNA had the support of FRA to develop units of the DVRU and install them on BNSF locomotives to extend the long term performance evaluation process further. This would facilitate the cost-benefit analysis. Based on the practical experience of the hardships encountered in the installation and maintenance of the single unit of DVRU, it was not considered worthwhile to proceed with the installation of more DVRU units. Our experience with failing to run a functional DVRU on a locomotive longer than a couple of weeks was a pointer to avoid further installation of DVRUs on more locomotives. Instead, it was considered prudent to proceed with a cost-benefit analysis considering two alternative approaches; one with the installed DVRU on all road locomotives of BNSF and the other without using a DVRU, but having the return fuel from the engine cooled down to 90 ºF or lower in a heat exchanger prior to returning the fuel back to the tank.

3. Cost-benefit Analysis

The primary objectives of the present investigation included: (a) the feasibility assessment, installation, and performance evaluation of DVRU over long-term operation of freight locomotives, and (b) cost-benefit analysis of this approach to assess its industry wide implementation potential. Since insufficient performance data of the DVRU was collected during the 14 month operational period of the locomotive, an alternative approach to estimating the likely benefit of using a diesel vapor reclamation system was evaluated.

3.1 Estimation of the Diesel Vapor Recovery Potential

The block diagram of the fuel system of a diesel locomotive is illustrated in Figure 40. Fuel is pumped out of the tank by a delivery pump at a constant rate of 8gpm. The fuel is then passed through a filter to the pre-heater and delivered to the injectors under higher pressure. During the winter months, the preheater raises the fuel temperature to 90 ºF for a lower viscosity and smooth flow through the fuel injectors. During the rest of the year, the pre-heater is bypassed and the fuel is delivered directly to the injectors. A part of the delivered fuel is burned by the engine at different rates, depending on the notch position selected by the engineer, and the remaining fuel is returned back to the tank after it is used for cooling the injectors. The return fuel to the tank is generally hot and reaches a temperature range of 125 to 140 ºF. According to Electro-Motive Diesel [1], during a heavy freight train long-haul operation in a hot summer day, the maximum fuel temperature in a locomotive tank prior to refueling may reach a maximum of 145 ºF.

The tank is open to the ambient through a vent pipe. Headspace vapor escapes to the ambient in normal tank breathing due to diurnal temperature variations and also during refueling. The headspace within the tank reaches the diesel vapor equilibrium pressure and volume fraction depending on the fuel temperature. With high ambient and high return fuel temperatures and flow rates, the vapor volume fraction in air within the tank reaches 0.3 percent. This was the Lower Explosive Limit (LEL) for No. 2 diesel fuel specified by the Conoco-Phillips Petroleum Company [2]. Nearly the entire headspace of the tank is released to the ambient during refueling and a maximum of 4,500 gallons of diesel is refilled into a 5,000 gallon capacity tank.

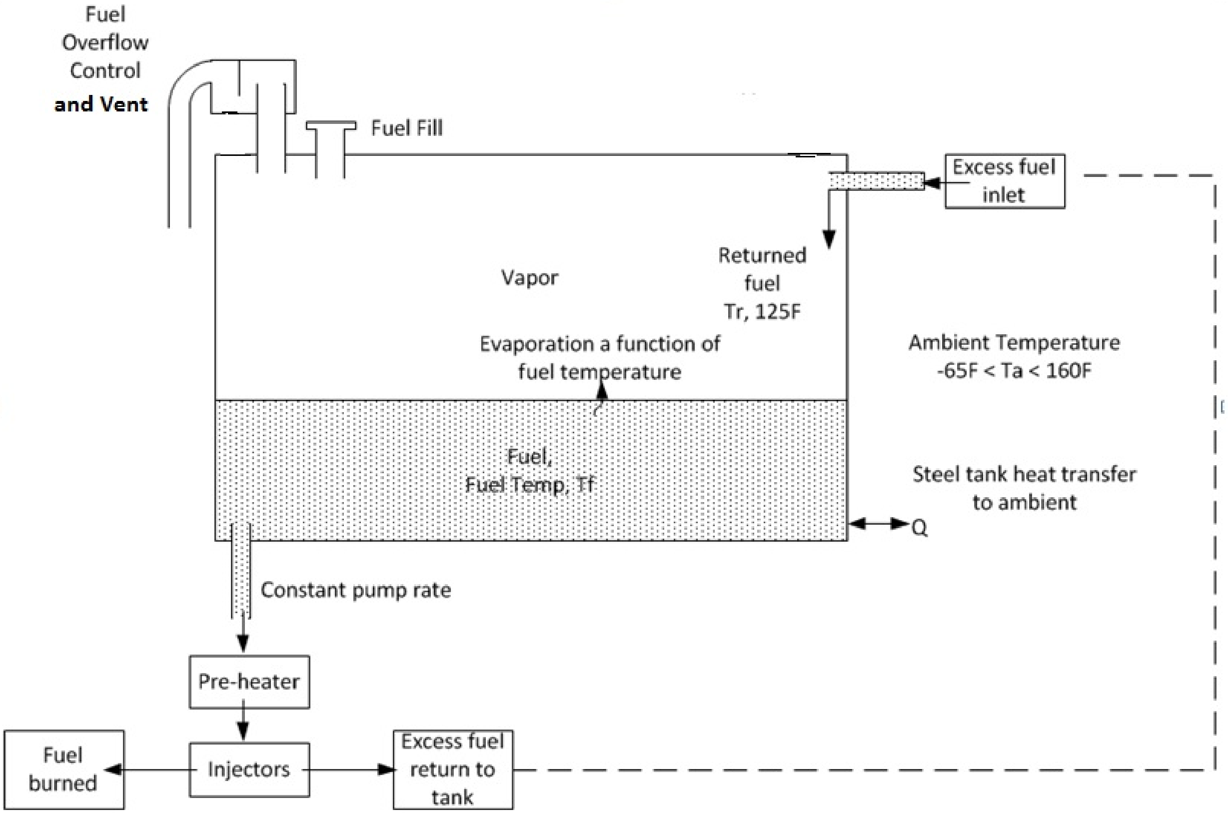


Figure 40. Baseline locomotive fuel system block diagram

3.1.1 Vapor Reclamation System Configuration Using DVRU

To reduce the risk of fire in an accident or a derailment of the locomotive, QNA developed a DVRU to reduce the fraction of diesel vapor in air within the fuel tank. The reduction in the amount of diesel vapor within the tank vapor space also served to potentially reduce the release of diesel vapor to the environment during refueling and save on fuel cost for the railroads. The first approach for diesel vapor reclamation is shown schematically in Figure 41. The fuel overfill control and vent box was modified to redirect the flow of the mixture of fuel vapor and air through a chilled condenser by an explosion proof vapor suction fan. The fan capacity drew off the diesel vapor and air in the tank rapidly enough to prevent the diesel vapor levels in air from reaching a saturation level or close to the LEL of the fuel used. The chilled condenser pumped the condensed fuel back to the tank and released the uncondensed part of the diesel vapor to the ambient. A modified approach to this scheme included a closed loop vapor circulation path that returned the uncondensed fuel vapor at the exit point of the condenser back to the tank again for recycling it through the condenser mixed with freshly evaporated diesel vapor. This modified approach required a separate vent pipe arrangement at the opposite end of the tank to allow fresh air inlet from the ambient into the tank for pressure equalization, shown in the schematic sketch of Figure 41.

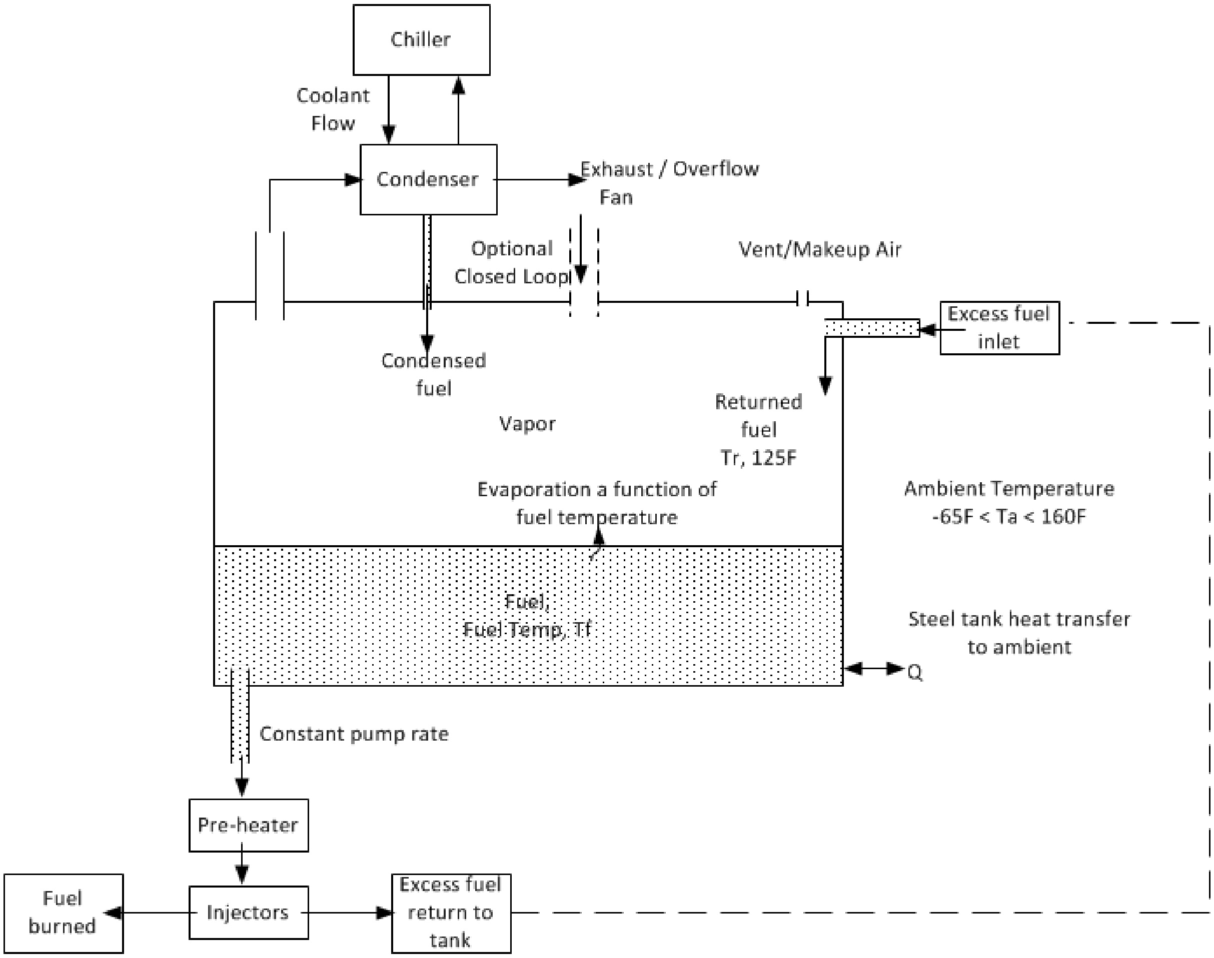


Figure 41. DVRU-integrated fuel tank system schematic

3.1.2 An Alternative System Configuration Using Return Fuel Cooling Alone

The alternative approach was investigated to simplify and lower the cost of the system. This concept dispenses with the complexity of using a DVRU and instead looks at cooling the return fuel from the engine. Figure 42 shows a schematic of this alternative system. After being heated in the process of cooling the fuel injectors, the excess fuel is passed through a heat exchanger. Using a closed-loop coolant circulation system, the heat exchanger continuously cools the fuel to a preset temperature between 70 and 90 ºF. The cooled down fuel is then returned to the tank for recirculation. The major advantages of this method include its simplicity for hardware modification and attainment of all the desired objectives through the lowering of tank fuel temperature. A conceptual sketch of a 'Brazed Plate Heat Exchanger' integrated with the return fuel line of a locomotive is shown in Figure 43. Because of the space constraint within the engine compartment, a relatively small size heat exchanger eased the connection with the return fuel pipe line, while the closed-loop coolant circulating longer pipes drew from a remotely located chiller unit as shown in Figure 43. Based on the No. 2 diesel data presented in Environmental Protection Agency publications, AP-42, chapter 7 [3], the diesel equilibrium vapor pressure and volume fraction in air versus temperature graph is presented in Figure 44 and observed that at cooler temperatures in the range of 70 to 90 ºF, the vapor pressure was <

0.02 PSIA and the corresponding vapor volume fraction in air was less than 0.101 percent. This was nearly one third of the lower explosive limit (LEL) of No. 2 diesel fuel [2].

By inhibiting the large scale formation of vapor within the tank vapor space through maintaining a cooler temperature of fuel in the tank, all the desired objectives are met:(a) no explosive vapor condition within tank to cause fire hazard in the event of a tank breach in an accident or derailment, (b) very insignificant release of diesel vapor from the tank to the ambient during refueling to warrant a concern for environmental pollution, and (c) improved fuel economy with almost entire fuel mass in the tank being used by the locomotive for revenue service and no appreciable loss in the form of fuel vapor.

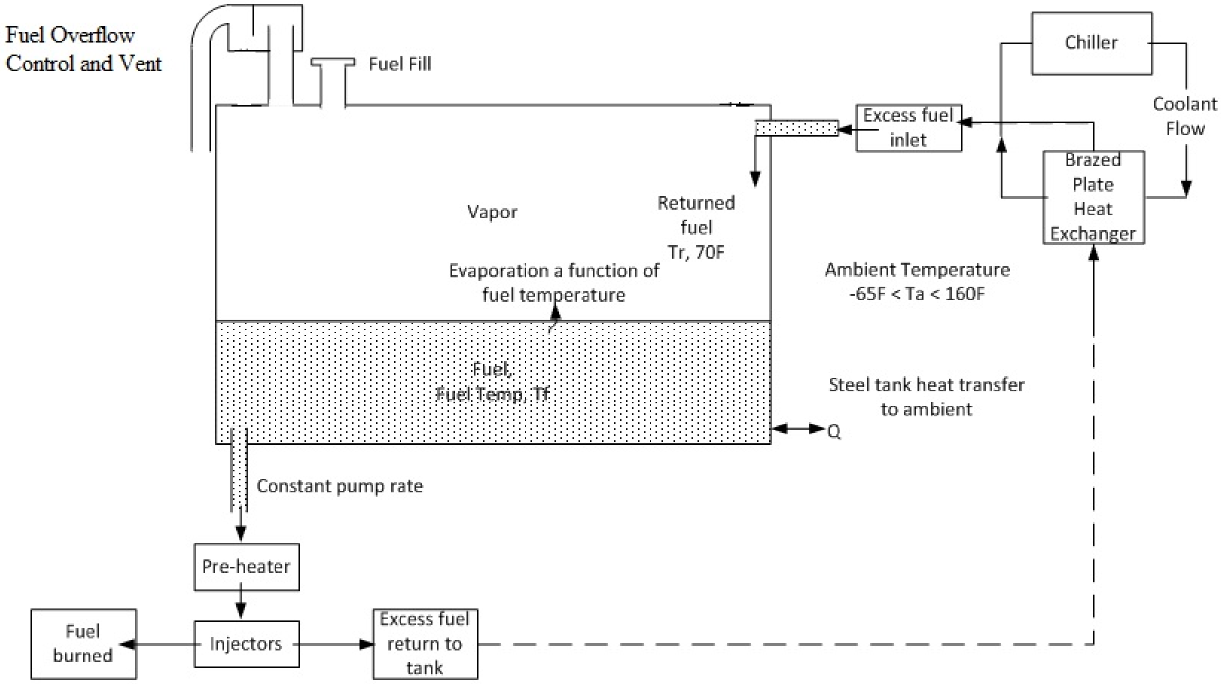


Figure 42. Schematic Fuel Tank System with Return Fuel Cooling

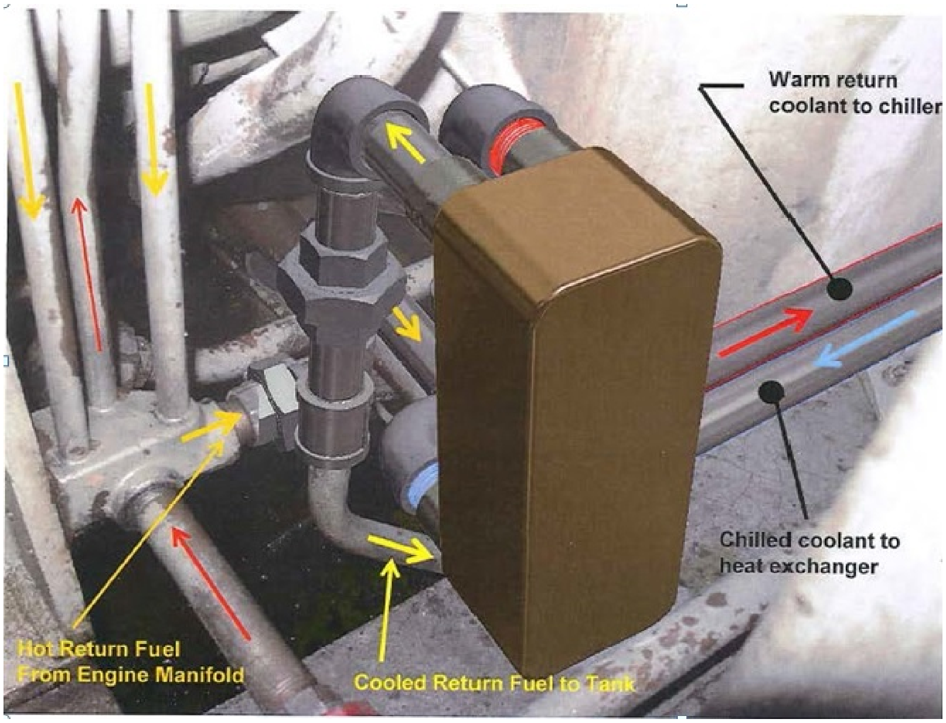


Figure 43. Schematic of a heat exchanger integrated with the return fuel line from engine

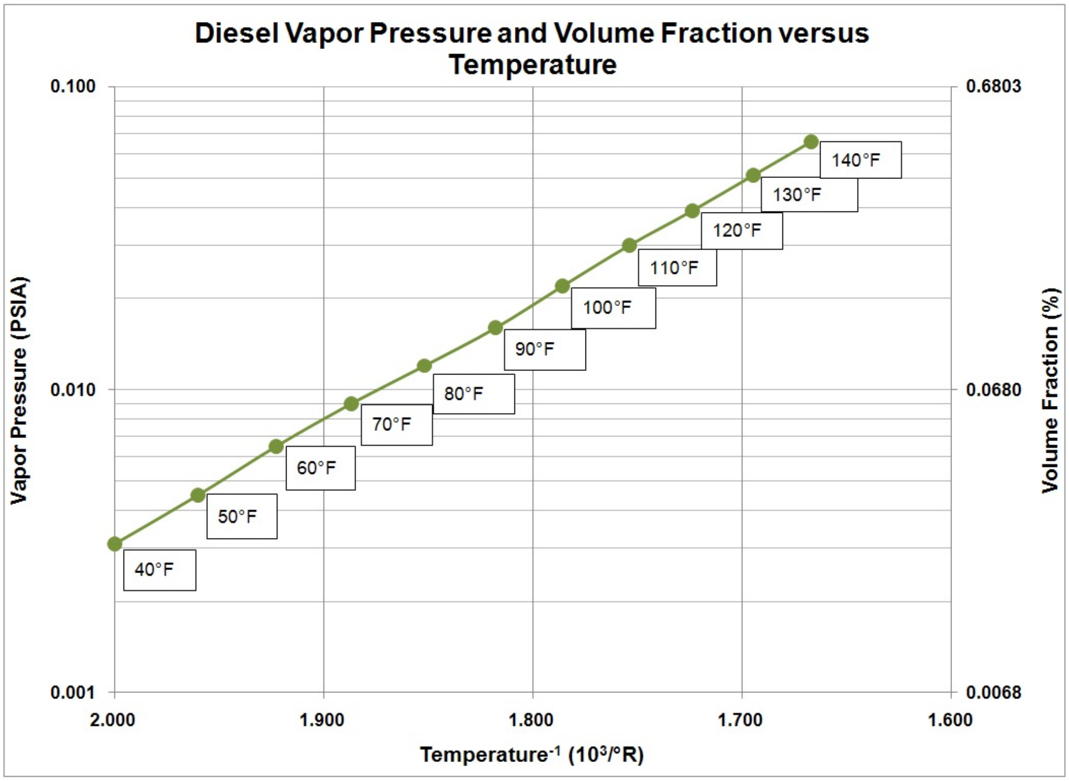
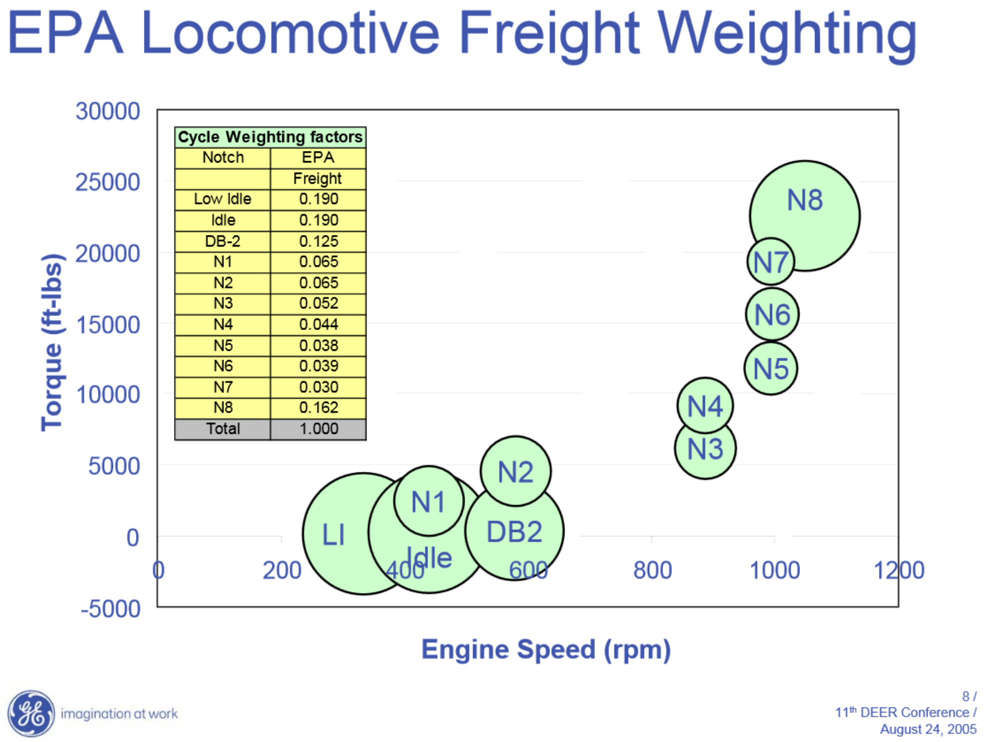


Figure 44. No. 2 diesel equilibrium vapor pressure and volume fraction variation with temperature

In the existing literature, limited data exists on fuel consumption in freight locomotives, in general and in particular, for different notch positions. A presentation by General Electric (GE) at the DEER conference in 2005 [4] showed the weighting the Environmental Protection Agency uses for freight locomotive notch positions, shown in Figure 45. A freight locomotive spent a majority of its time at the idle notch position. However, at idle and in lower notch positions, the locomotive consumed a very little fuel. Figure 46 shows the variation of fuel consumption with notch positions for a typical GE locomotive as presented in a South West Research Institute research report [5]. During revenue freight service, there are multiple locomotives jointly hauling the train and all locomotives are generally run at notch 8 for the majority of time with fuel consumption of about 220 gallons/hr or 3.7 gallons/minute. Using this data for the analysis, we can assume that 125 ºF return fuel was returned to the fuel tank at about 4 gallons/min, while the fuel was pumped out of the tank and circulated through the injectors at the rate of 8 gallons/min. The unburned part of the fuel picked up the heat in the process of cooling the fuel injectors and was returned back to the tank at about 125 ºF.



EPA Locomotive Freight Weighting

Cycle Weighting factors	
Notch	EPA Freight
Low Idle	0.190
Idle	0.190
DB-2	0.125
N1	0.065
N2	0.065
N3	0.052
N4	0.044
N5	0.038
N6	0.039
N7	0.030
N8	0.162
Total	1.000

8 /
11th DEER Conference /
August 24, 2005

Figure 45. EPA's typical freight locomotive notch setting fractional usage

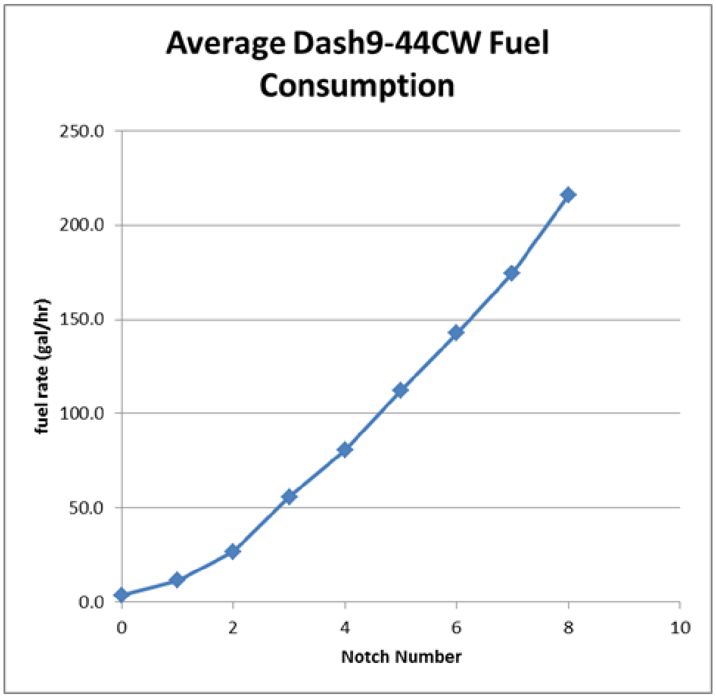


Figure 46. Variation of fuel consumption with notch positions for a typical GE locomotive

3.2 Estimation of Fuel Loss in Diesel Locomotives

For the cost-benefit analysis, we examined three sources of diesel vapor leaving the fuel tank. At refueling, practically the entire content of diesel vapor present in the headspace exited the tank rapidly as the tank was refueled up to about 90 percent of its capacity or a maximum of 4,500 gallons for a 5,000 gallons capacity tank. During normal diurnal cycles, the height of diesel in the tank changes through thermal expansion, causing a breathing effect in the tank. The diesel vapor is released through the vent pipe and the ambient air is returned. The last mode is a function of the DVRU design where some non-condensed diesel vapor is released to ambient in the open cycle used in tests. The following broad analysis quantified these effects and converted lost diesel vapor to a cost through a $4/gallon liquid diesel price.

3.2.1 Estimation of Lost Fuel Through Tank Breathing

The thermal expansion coefficient of diesel fuel measured 800 x 10^{-6} in^3/in^3K^{-1}. The thermal expansion coefficient of steel used in the tank was 12 x 10^{-6} in/inK^{-1}. Since the width and height growth of the steel tank was negligible compared to the diesel fuel expansion, the diesel thermal expansion was assumed to occur along its depth or along the height of the fuel tank.

The Midwest month-wise temperature variation data found in www.weather.com are shown in Figure 47, with an average of 30 ºF high-low daily temperature fluctuations. This caused the diesel fuel present in the tank to expand and contract, creating breathing and loss of diesel vapor to ambient. A 5,000 gallon tank typically carries fuel in the range of 4,500 to 1000 gallons. The average amount of fuel in a tank was assumed to be 3,000 gallons, used for the breathing vapor loss estimates.

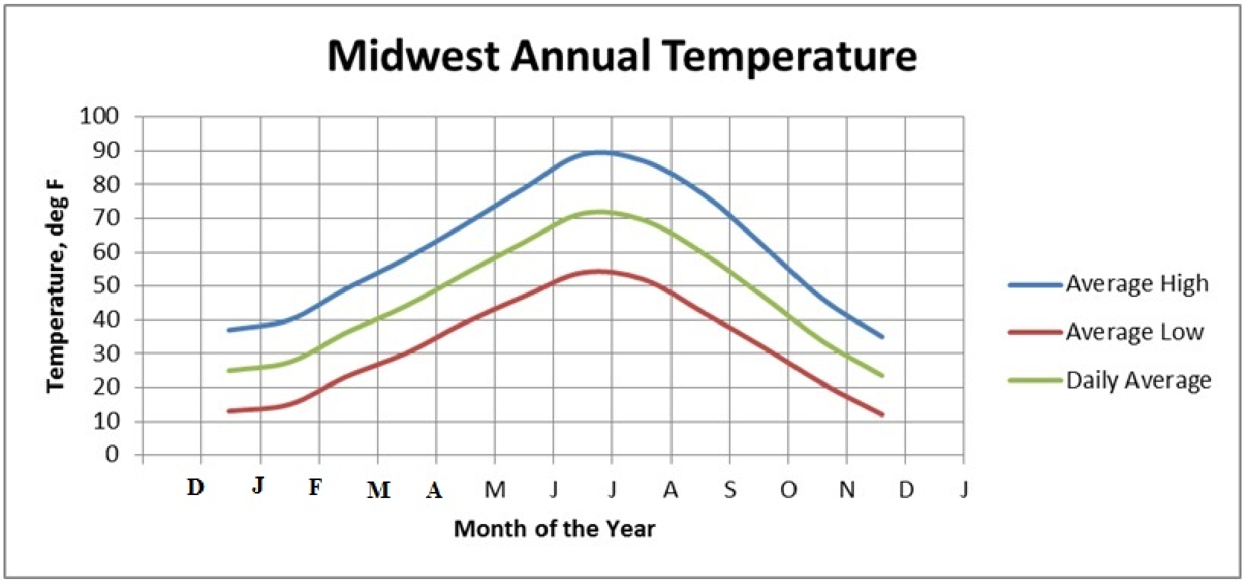


Figure 47. Midwest annual ambient temperature variation

From high to low temperature, fresh air mixed with the vapor in the tank. From low to high ambient temperature, the tank fuel temperature increased due to heat exchange and the diesel vapor was forced out through the vent. The fuel height change over 30 ºF for 3,000 gallons of fuel was based on the difference of the fuel and steel expansion coefficient, 788 x 10^{-6} in^3/in^3K^{-1}, or 4.378 x 10^{-4} $in^3/in^3/R$. At 3,000 gallons, the fuel height is 1.91 ft for a 10 x 21 ft tank. The change in height with a 30 ºF temperature change was 0.3 in. On average, the height of the fuel in the tank varied by 0.3 in peak-to-peak. This represents 39 gallons of headspace vapor exiting the tank every day. The amount of actual diesel vapor in those 39 gallons is found from the fuel-vapor to air ratio. The following analysis translates the 30 day ambient temperature variation to a fuel temperature fluctuation, depending on the time of year. That led to a different amount of breathing over the year. The analysis details are provided in the next section dealing with the refueling vapor loss estimation.

The US EPA lists distillate fuel oil #2 as having a vapor molecular weight of 130. The molecular weight of air is 29. Therefore, the vapor density of diesel is 4.48 times that of air. Air density is 0.01 lb/gal (0.001225 gm/cc at 15 ºC). Diesel vapor mass density is therefore 0.048 lb/gallon. The density of liquid diesel is 7.08 lb/gallon. The fuel-vapor to air ratios (FAR) in Table 1 are used to calculate the mass fraction of diesel vapor and the equivalent liquid diesel. The calculations shown in Table 1 show that a typical BNSF locomotive loses $0.18 per year per locomotive through the fuel tank breathing effects only.

The fuel temperature in the tank is estimated from the following model. The tank content in gallons is calculated from:

$$Tank\ Content = Initial\ Tank\ Content - [Flow_{out} - Flow_{in}] * time$$

The fuel temperature estimate assumes the tank is completely mixed. The energy equation for the fuel is given as:

$$Mass_{fuel} * C_p * \frac{dT_{fuel}}{dt} = Fuel_{in} * \left[T_{fuel_{in}} - T_{fuel}\right] - h * A_{tank} * [T_{fuel} - T_{amb}]$$

The procedure to estimate the tank fuel temperature consists of using the above equation at each time step to estimate the temperature derivative, and then to increment the fuel temperature from the previous time step.

$$T_{fuel_{n+1}} = T_{fuel_n} + \frac{dT_{fuel}}{dt} * \Delta t$$

An example of this model is shown in Figure 48 with the following parameters:

- Tank dimensions are 10 x 21 x 3.5ft for a 5,000 gallon fuel tank.
- Tank surface area = 637 ft^2
- Flow out = 8 gpm
- Flow in = 4 gpm
- Cp = 0.43 BTU/lb/F
- Tank surface heat transfer coefficient, h = 1.7 BTU/h/ft^2/F for low speed flow
- Ambient temperature = 37 ºF
- Fuel inlet temperature = 125 ºF

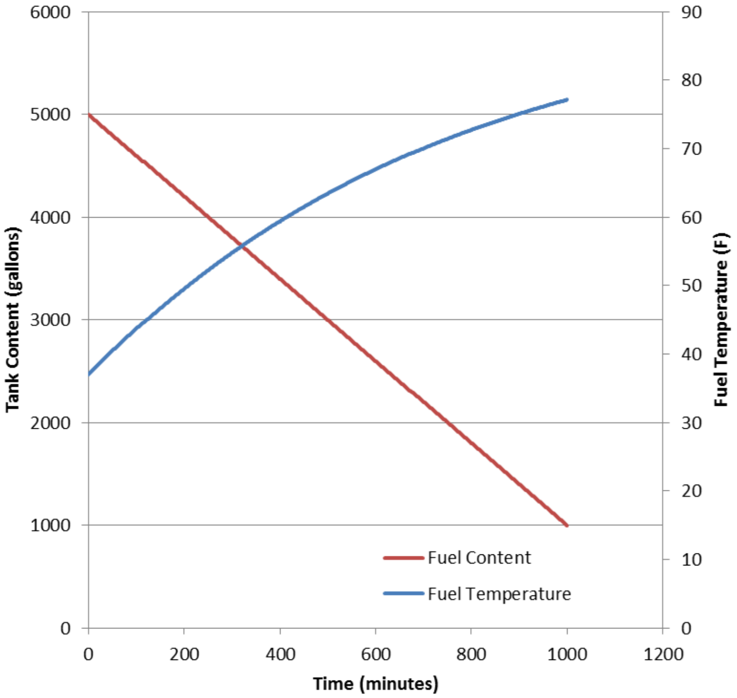


Figure 48. Tank Fuel Temperature Variation Over Time

The fuel tank temperature begins at the ambient temperature of 37 ºF in this example and increases to 77 ºF when the fuel content reduces to 1,000 gallons from the original 5,000 gallons. That value of 77 ºF is used in Table 1 for the fuel temperature for the 37 ºF ambient average high temperature case. This lowers the diurnal fuel temperature excursion from 30 ºF due to ambient to only 13 ºF from fuel temperature as calculated per the model above. So the fuel vapor lost due to diurnal temperature excursions are less than estimated earlier. The percent FAR is derived from Figure 44. Average fuel vapor content is generally much lower than the LEL of 0.3 percent. The diesel vapor lost per day is converted to the equivalent liquid diesel so that the

$4/gal diesel cost can be applied. This results in a loss of $0.18 per year, or 0.045 liquid gal and 7.08 vapor gal per year.

Table 1. Lost Diesel Fuel Cost Estimate Due to Tank Breathing Only

	Ambient Temperature			Fuel Temperature							
Month	Avg High, F	Avg Low, F	Avg Day, F	Avg High, F	Avg Low, F	Avg Day, F	Fuel Height Change, in.	FAR% with avg day F	Diesel Vapor Lost, (vapor gal/day)	Equivalent Liquid Diesel Loss (gal/day)	Diesel Cost per Month, $
1/15/2008	37	13	25	77.0	64.0	71.0	0.130	0.062%	0.011	6.69E-05	$ 0.01
2/15/2008	40	15	27.5	79.0	65.0	72.0	0.140	0.064%	0.012	7.44E-05	$ 0.01
3/15/2008	49	23	36	84.0	70.0	77.0	0.140	0.075%	0.014	8.74E-05	$ 0.01
4/15/2008	58	30	44	89.0	73.0	81.0	0.161	0.085%	0.018	1.13E-04	$ 0.01
5/15/2008	68	39	53.5	94.0	78.0	86.0	0.161	0.099%	0.021	1.32E-04	$ 0.02
6/15/2008	79	47	63	100.0	83.0	91.0	0.171	0.116%	0.026	1.64E-04	$ 0.02
7/15/2008	89	54	54	105.0	86.0	96.0	0.191	0.135%	0.034	2.13E-04	$ 0.03
8/15/2008	87	52	69.5	104.0	85.0	95.0	0.191	0.131%	0.033	2.07E-04	$ 0.02
9/15/2008	77	42	59.5	99.0	80.0	89.0	0.191	0.109%	0.027	1.72E-04	$ 0.02
10/15/2008	62	32	47	91.0	74.0	83.0	0.171	0.091%	0.020	1.28E-04	$ 0.02
11/15/2008	46	21	33.5	82.0	68.0	75.0	0.140	0.070%	0.013	8.20E-05	$ 0.01
12/15/2008	35	12	23.5	76.0	64.0	70.0	0.120	0.060%	0.009	5.98E-05	$ 0.01
						82.2				**Annual total**	$ 0.18
										per locomotive per year	

3.2.2 *Lost Diesel Vapor at Refueling*

According to a BNSF 2008 Annual Report, it achieved 470 revenue ton-miles/gallon in that year. Revenue ton-miles are the product of the number of loaded miles and the weight of the contents. BNSF had 6,510 locomotives in service at an average of 15 years old from date of manufacture. Approximately 4,600 of these were road locomotives and 1,415 million gallons of diesel fuel were used that year. The corresponding revenue ton-miles were 664,384 million and the average haul was 1,090 miles. Nearly all the fuel consumption was on loaded ton-miles. BNSF had 27,360 thousand gross ton miles per employee with 40,000 employees. The gross ton-miles equates to 1,094,400 million ton-miles. Gross ton-miles are the product of the loaded and empty miles and the combined weight of the car and contents.

Using the numbers above, the average road locomotive hauled 144 million ton-miles in 2008 and used 308,000 gals of fuel at 470 ton-miles/gallon. The average haul was 1,090 miles for 132,500 tons hauled for one road locomotive in that year. According to an AAR 2013 report containing Class I Railroad Statistics [6] in 2009 for all Class I railroads, the average load per carload was 64 ton, average load per train was 3,546 ton, and the average length of haul was 918 miles. The mileage was consistent with the BNSF 2008 report, so we use the average train haul weights listed by AAR for 2009. Referring to the 2008 BNSF data [7], at 3,546 ton per train, there was an average of 37.3 trains per locomotive that year considering that multiple road locomotives were used to haul a long freight train. At 3,546 tons, 1,090 miles and 470 ton-miles/gallon, there were 8,223 gallons of fuel used per haul. For a 5,000 gal capacity tank, the refueling occurs approximately after using 3,500 to 4,000 gallons. It was assumed an average of 2.1 refueling events per haul. For the BNSF entire fleet, there were 360,300 refueling events of about 4,000 gallons each in 2008.

Each refueling event loses the amount of diesel fuel equal to the diesel vapor content in the mixture of fuel-vapor and air (FAR) corresponding to the fuel temperature at the time of re-fueling. Figure 47 shows the annual variation of ambient temperature typically found in the

Midwest round the year from www.weather.com. An analysis was conducted that considered the effect of heated fuel returning to the fuel tank, while the fuel was being consumed at an average rate of 4 gallon/min. The analysis considered the resulting heating of the fuel within the tank and the heat transfer to and from the tank depending on the ambient temperature. The resulting fuel temperature variation at refueling is shown in Figure 49. Based on the fuel tank breathing analysis in Section 3.2.1, we assumed a 4 gallon/min hot fuel return rate from the locomotive engine at a temperature of 125 ºF.

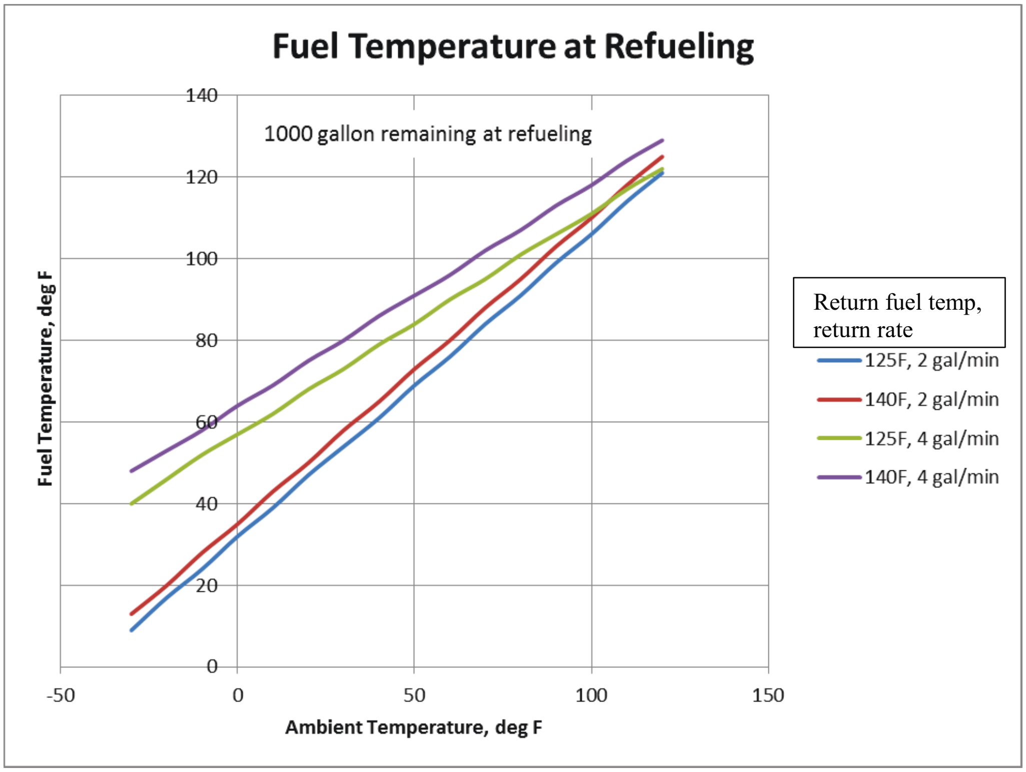


Figure 49. Variation of average tank fuel temperature with ambient at the time of refueling

The results of Figure 49 were used to determine the fuel temperature at refueling (1,000 gallons remaining in the tank) for different months of the year as shown in Figure 50. The resulting volume fraction of diesel fuel in the tank at refueling was derived from Figure 44 and Figure 50. This diesel vapor volume fraction (FAR) variation at the time of refueling over months of the year is shown in Figure 51. This analysis was extended to the equivalent gallons of diesel represented by that volume fraction in Figure 52. The data used in Figure 52 only considered the average high temperatures for all days in a particular month for the simplicity of presentation.

Figure 52 also shows what would happen if a cooling cycle was added to the system. Cooling the return fuel temperature had the effect of reducing the diesel vapor content in the tank headspace as shown in the figure. As discussed above, there was an estimated average of 360,300 refueling events for 2008 for the entire BNSF fleet of 4,600 road locomotives. Assuming these events were evenly distributed throughout the year, that was an average of 30,025 refueling events per month in 2008. This rate was used with the information presented in Figure 52 to estimate the yearly cost of the fuel lost to vapor on refueling.

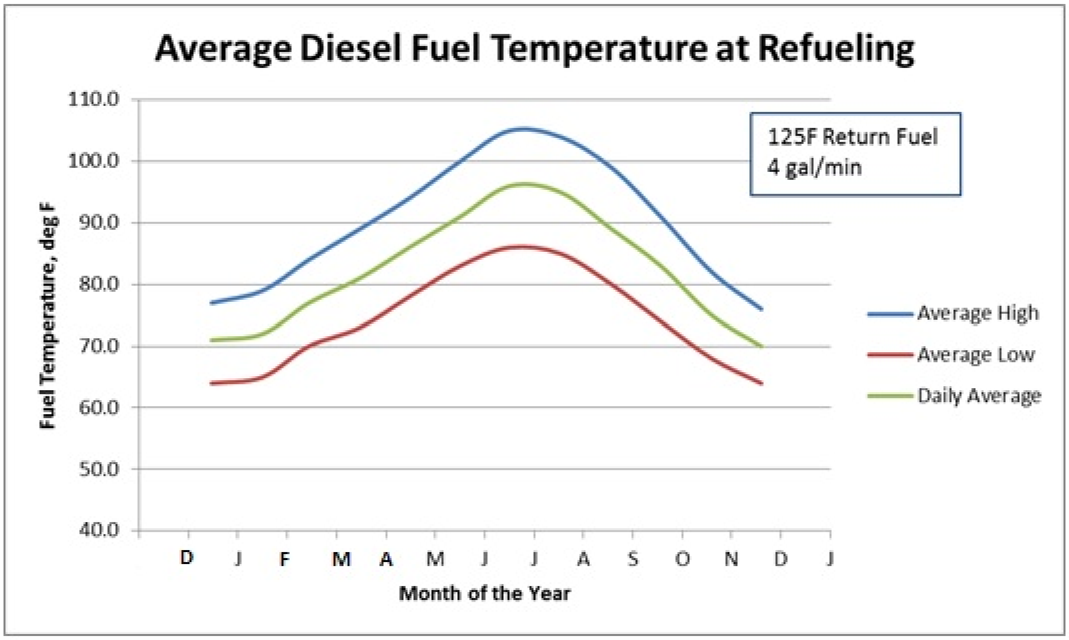


Figure 50. Average month-wise fuel temperature within tank at refueling

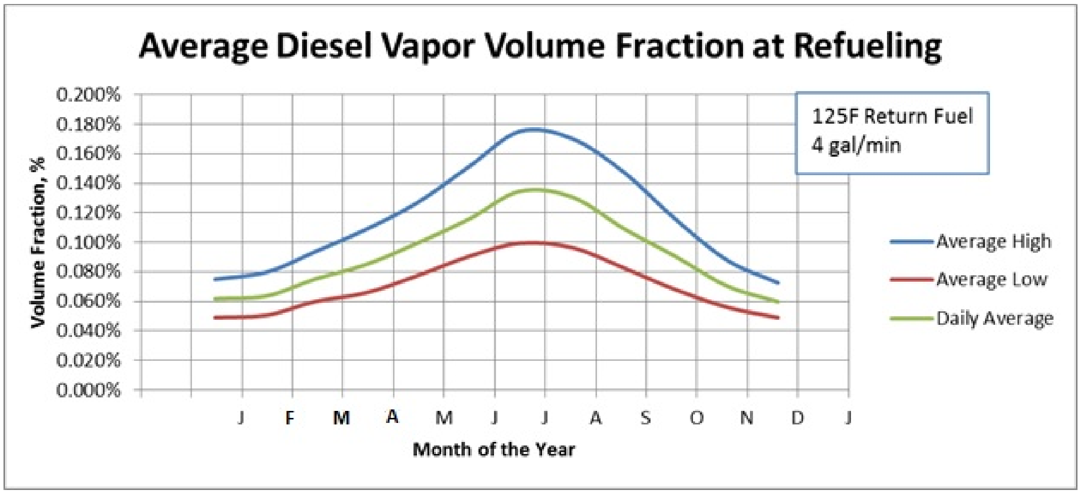


Figure 51. Month-wise average diesel vapor fraction in air within tank at refueling

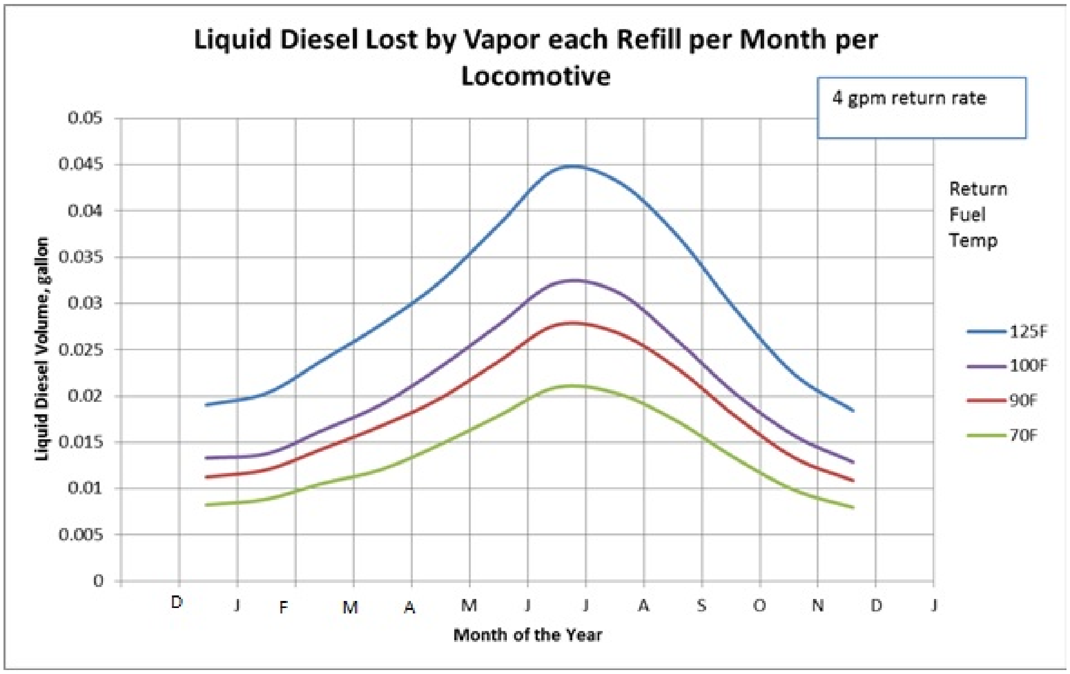


Figure 52. Diesel liquid volume lost per refueling by month

The railroad usage data for BNSF in 2008 were extracted from reference [7]. Assuming $4/gallon for the diesel fuel, the case of 125 ºF return fuel under current locomotive operational practice was the baseline at $43,000 lost from diesel vapor in the tank at refueling for all 4,600 road locomotives in 2008 in Table 2. Cooling the return fuel reduced the vapor content compared to the baseline case and saves money at each refueling. If all BNSF locomotives cooled the return fuel to 90 ºF, the total cost of lost fuel would have been $26,100, with a savings of $16,900 in that one year. That equates to a savings of $3.67 per locomotive per year of operation. Over a 30 year design life, the savings amounts to $110.20 per locomotive and a total saving of $506,920. The Table 2 below shows the savings that would be accrued with different levels of return fuel cooling. The estimated BNSF fleet-wide lost diesel fuel cost by month of the year, based on BNSF published data for 2008 and 2009, are shown in Figure 53.

Table 2. Estimated Cost Savings for BNSF in 2008 with Return Fuel Cooling

Return Fuel Temp, F	Total Fleet Annual Savings	Annual Savings per Road Locomotive	Total Lifetime Savings per Road Locomotive
125	Baseline	Baseline	Baseline
100	$12,650	$2.75	$82.54
90	$16,900	$3.67	$110.20
70	$23,420	$5.09	$152.73
50	$28,520	$6.20	$186.01

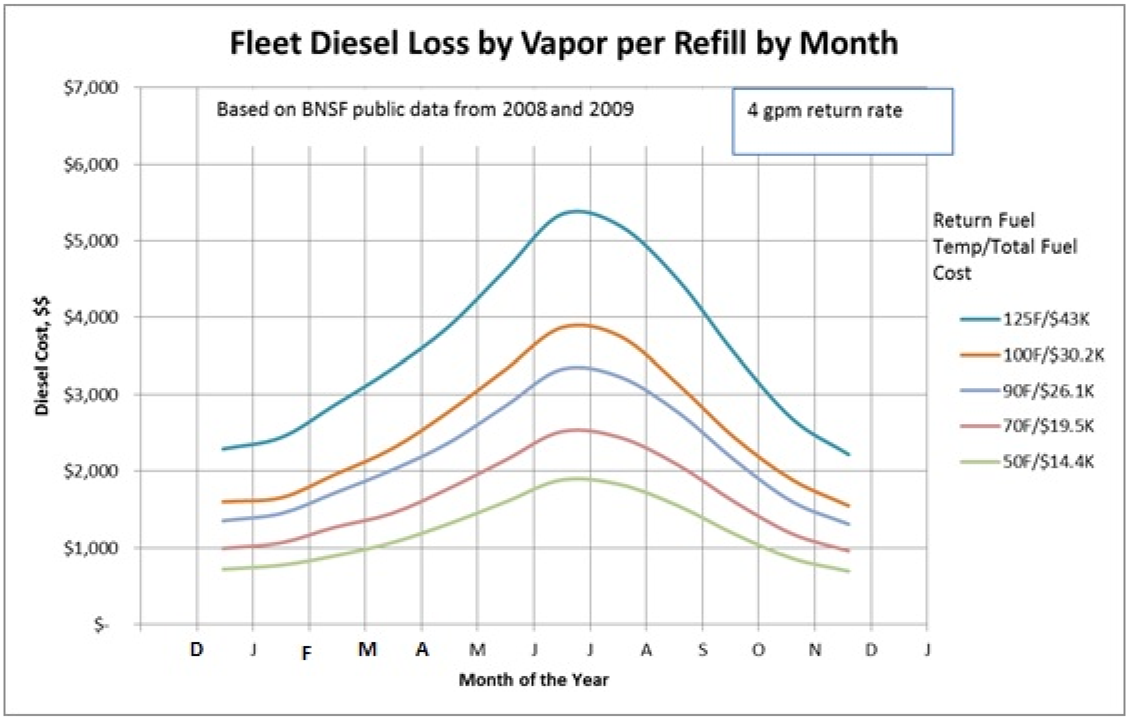


Figure 53. Estimated cost of lost diesel vapor per refill by month for all BNSF road locomotives

3.2.3 Estimation of Diesel Vapor Loss through DVRU Exhaust

The DVRU was designed to draw the diesel vapor out of the tank and condense it to liquid diesel and return it back to the fuel tank for reuse. Computational Fluid Dynamics (CFD) analyses using ANSYS-FLUENT commercial code [8] were developed for an EMD SD70 MAC fuel tank complete with the internal baffles and the vent pipe to properly scale the DVRU system parameters. The baffle system was found to offer a significant resistance to vapor flow within the tank. An estimated 40 CFM exiting mixture flow rate at the outlet of the condenser (Figure 41) was required to significantly reduce the vapor fraction in air to safe limits, well below the LEL of the fuel used. In a steady state condition, the DVRU device would ensure that newly evaporated diesel vapor was at least partially condensed to liquid by the condenser, while a fraction was exhausted to the environment.

The diesel evaporation rate curves in Figure 54 were developed based on data presented by Fingas [9] in the Journal of Petroleum Science Research. The curves show the rate of diesel vapor formation at different diesel fuel temperatures. The typical evaporation rate was 0.020 liquid gallons/minute (from 70 to 105 ºF) for the top 1.5 mm layer of the diesel fuel in the tank. This was equivalent to 3.15 gallons of diesel vapor/min by considering the 7.08 lb/gallon liquid density and 0.045 lb/gallon vapor density of diesel. The average of 82 ºF fuel temperature resulted in 0.088 percent vapor content at saturation, or 1.7 gallons of diesel vapor in a 2,000 gallon headspace within the tank. At this evaporation rate it would take 32.4 minutes to saturate the headspace. Based on the average fuel amount of 3,000 gallons in the tank and saturated diesel vapor in the 2,000 gallon headspace, Table 3 below shows the saturated diesel vapor variation with temperature and also an estimation of diesel lost through the DVRU working at 50 percent efficiency in a 1,090 miles freight haul at an average speed of 45 mph.

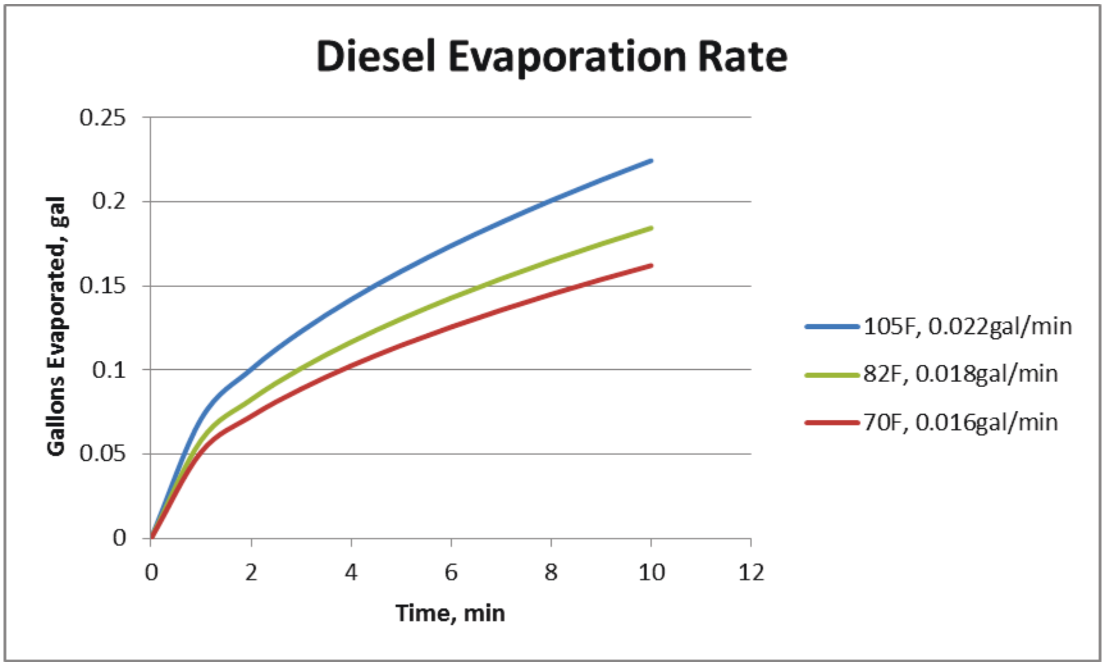


Figure 54. Variation of diesel fuel evaporation rate with temperature

Table 3. Estimated Diesel Vapor Evaporation and Loss through the DVRU

Fuel Temperature, (^{0}F)	Diesel Vapor Volume in 2000 gallon headspace, (gallons)	Evaporation Rate, (vapor gallons/min)	Time to Saturate 2,000 gallon headspace, (minutes)	Diesel vapor lost from DVRU in a 1090 mile haul at 45 mph at 50% efficiency, (vapor gallons)
105	3.5	3.46	2.65	16.0
82	1.76	2.83	1.63	13.1
70	1.2	2.52	1.25	11.6

The primary objective of using the DVRU was to remove diesel vapor faster than it was being generated within the tank to ensure that vapor buildup does not reach or exceed the LEL of the fuel used. In an ideal fuel tank without the presence of internal baffles, this objective can be reached with very little volume flow of the mixture of fuel vapor and air through the tank vapor space and the condenser. Diesel vapor was generated at about 0.020 gallon/min, or 0.0027 CFM. However, the fuel tank contains full-height longitudinal baffles with small holes in it; this divides the tank internal space into two halves. There are many sets of staggered baffles internally in both halves of the tank, to prevent fuel sloshing. These baffles highly restrict the free flow of the mixture of fuel vapor and air in the headspace above the fuel. Further, there were only a few small openings in the full-height central longitudinal baffle that allowed the fuel vapor to flow between the two halves of the tank for the SD70 MAC.

For the case of continuous fan operation of the DVRU, the rate of diesel fuel removal from the tank was equivalent to the rate of vapor generation. A typical freight locomotive haul had an average of 1,090 miles, as derived from BNSF data [7]. At a reasonable 45 mph average train speed and continuous operation with 50 percent of the vapor condensing and the condensed fuel flowing back into the locomotive tank, the amount of vapor lost to ambient with DVRU operation at an average 82 ºF fuel temperature was 13 gallon of diesel vapor per locomotive per haul. A typical BNSF locomotive performed 37 loaded hauls in 2008, for a total lost fuel potential with DVRU of 481 vapor gallons, which is equivalent to 3.05 liquid gallons at $12.23 per locomotive. This was offset by a near zero diesel vapor content in the area where the fan volume flow reaches a safe condition in the tank. Since the vapor was constantly removed, the diesel vapor lost at refueling was negligible if the DVRU kept up with the diesel vapor evaporation. In an internal vapor flow resistance-free tank, it would take very little fan draw in CFM to keep up with the diesel vapor formation. However, practical, existing fuel tank designs create significant vapor flow resistance due to the baffle structure, requiring a higher capacity fan to enable even a moderate vapor flow rate within the tank. In addition, it should be assumed that the fan is shut off during refueling, in which case the tank would reach saturation in about 30 minutes. So refueling loss is maintained in the following discussion.

3.2.4 Estimated Fuel Loss Summary

The results of the analyses conducted in the above subsections are summarized in Table 4. The tabulated results illustrate the baseline case of the current fleet with its fuel vapor loss from the tank breathing and refueling. The baseline assumes a 125 ºF return fuel at 4 gallon/min while the constant delivery pump supplied 8 gallon/min fuel to the fuel injectors of the engine. The numbers reflect the sum over the year (based on BNSF 2008 data) assuming annual Midwest weather data and heat transfer between the tank and the ambient. More fuel vapor was generated during the summer months and less in the winter months and this was reflected in these numbers.

The currently funded program developed a DVRU that partially recovered the fuel evaporated in the tank through condensation and returned back into the tank as liquid. The unit was approximately 50 percent efficient, with the balance of the diesel vapor exhausted out to the ambient. The size of the DVRU fan was not relevant to these numbers. The analysis assumed the fan was strong enough to keep up with the evaporation rate of the fuel. Assuming the entire BNSF fleet operates at 45 mph and the average 1,090 mile per haul experienced in 2008, the amount of fuel exhausted in the recovery process actually exceeds the amount that was lost from refueling in the baseline case. A more efficient condenser lowers these losses. We assumed that if the fan made up for all evaporated fuel vapor, there was negligible vapor in the headspace at the time of refueling. Design options for fuel cooling vs. fuel vapor evaporation are significantly more efficient.

We considered an option to provide a closed cycle DVRU system, where the exhaust of the condenser was returned to the tank instead of exiting to the ambient. This case was equivalent to an evaporation rate that was 50 percent greater than otherwise. The equivalent evaporation rate was 0.03 gallon/min for our baseline 0.02 gallon/min case. If the DVRU fan kept up with this higher equivalent evaporation rate, the vapor exiting to the ambient would be reduced to near zero. There would be very little to no diesel vapor in the headspace during refueling as long as the DVRU continued to operate and the continuous vapor loss due to the DVRU inefficiency would no longer be relevant. However the assumption must be made that the fans are turned off during refueling and the vapor content can saturate in 30 minutes. Tank breathing losses always occur since there is a vent to atmosphere.

The net result is that there is no cost savings with DVRU systems and the best option for reducing LEL in the fuel tank is with a system that cools the return fuel to a reasonable 90 ºF maximum. Both the DVRU and the return fuel cooling options will reduce the diesel vapor content in the tank headspace to much below the LEL.

Table 4. Summary of Fuel Loss from Vapor Escape and Annual BNSF Fleet Fuel Savings Potential Estimation

Mode	**Annual liquid gallons/ locomotive**	**Annual gallons/ BNSF Fleet**	**Annual $/locomotive**	**Annual $/BNSF Fleet**	**Annual BNSF Fleet Loss/Savings, $**
Baseline					
Tank Breathing	0.72	3,312	$0.18	$13,248	
Refueling	2.34	10,750	$9.35	$43,000	
Total	3.06	14,062	$9.53	$56,248	Baseline
DVRU (50% effective)					
Tank Breathing	0.72	3,312	$0.18	$13,248	
DVRU Exhaust	3.11	14,286	$12.44	$57,144	
Refueling	2.34	10,750	$9.35	$43,000	
Total	6.17	28,348	$21.97	$113,392	**$(57,144)**
DVRU (Closed Cycle)					
Tank Breathing	0.72	3,312	$0.18	$13,248	
DVRU Exhaust	0	0	0	0	
Refueling	2.34	10,750	$9.35	$43,000	Avoid over-pressure
	3.06	14,062	$9.53	$56,248	**$0**
Fuel Cooling (90^0F)					
Tank Breathing	0.027	124	$0.11	$497	
Refueling	0.92	4,220	$3.67	$16,882	
Total	0.95	4,344	$3.78	$17,379	**$38,869**

The next case of fuel cooling assumed that the return fuel was cooled down in a heat exchanger coupled to an air-cooled chiller from the usual 125 to 90 ºF without using any DVRU. The fuel cooling was very effective at drastically reducing the vapor formation within the tank. It resulted in a cumulative fuel savings of $38,869 for the 2008 BNSF fleet as a test case example both from tank breathing and at refueling. This is $3.78 per locomotive for that year.

3.2.5 Cost of Additional Hardware Items and DVRU Implementation Cost on a Locomotive

The cost of implementation, or the investment needed to effect the change, was examined in terms of the cost of equipment required per locomotive. It was assumed that an implemented diesel vapor reclamation system on a locomotive operating on routine revenue service would not require installation of the temperature and FAR sensors, condensed fuel measuring unit (CFMU), and the electronics controls and communication box, since the sensor data did not need to be monitored on a regular basis. This would minimize the DVRU installation cost.

(a) Estimated Hardware Component Cost of DVRU:

1. Suction Fan :	$ 2,070
2. Condenser:	$ 730
3. Chiller unit:	$ 2,750
4. Inverter (74VDC -110VAC):	$ 1,980
5. Pipes, Tubing, Fittings etc.:	$ 850
Estimated total hardware cost of the DVRU	$ 8,380

(b) Estimated Labor Cost for installation and annual maintenance/locomotive:

1. Installation (10 man-days):	$ 2,000
2. Annual Maintenance (4 man-days):	$ 800

(c) Estimated Hardware Component Cost of Heat Exchanger for Return Fuel Cooling Case:

1. Heat Exchanger of 52,000 BTU/Hour Capacity:	$ 636
2. Air-cooled Chiller unit of matching capacity:	$ 9,630
Total :	$10,266

The above cost estimate was based on single COTS unit procurement cost and for a large scale deployment scenario. These costs are likely to be somewhat lower. However, this approximate cost estimate shows a high cost of $8,380 for essential hardware components of a DVRU and an estimated installation cost on the order of $2,000 per locomotive. Further, an estimated Recurring Cost of about $800 for the annual maintenance of the installed DVRU system on a locomotive needs to be included, while considering the viability of additional investment. Similarly for the return fuel cooling case, the additional equipment cost would amount to $10,266 assuming that adequate space can be readily found on the locomotive for the installation of the heat exchanger and the air-cooled chiller unit.

Based on the savings estimated by installing a fuel cooling system, there is no justifiable return on investment based on fuel saved. The only justification for installing a return fuel cooling system is in the inherent improved safety and savings from fire incurred during an accident fuel breach.

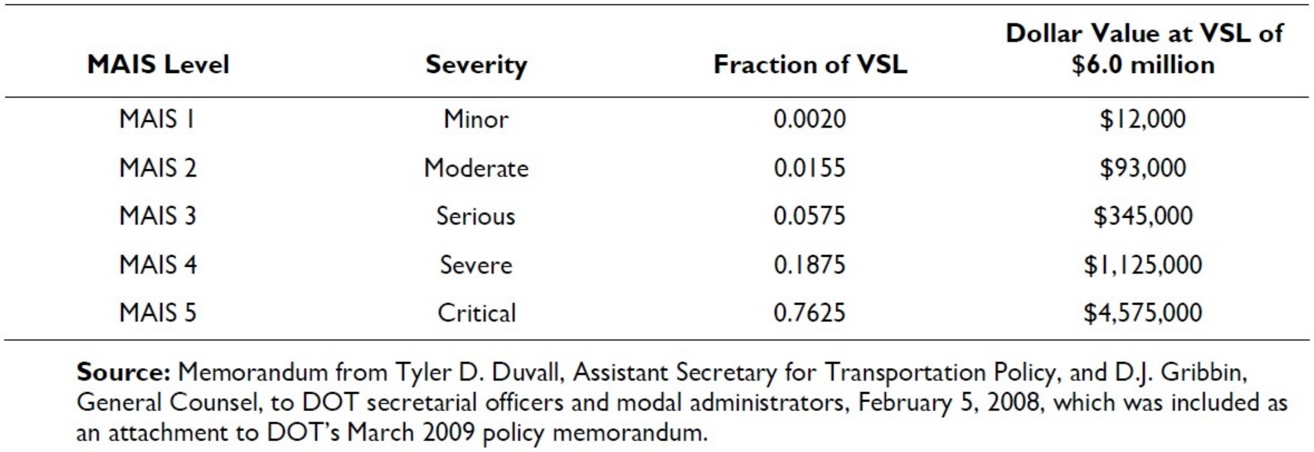
3.2.6 Cost Estimate of Freight Train Accident Damages due to Fuel Tank Breach and Fire

The above analyses revealed an insignificant cost saving due to lost fuel vapor during refueling and normal revenue service operations. However, the fuel vapor reclamation system concept was primarily driven by the concern for improved safety in the event of locomotive accidents and derailments that often lead to fuel tank breach and consequent fire hazard.

As a part of a previous FRA sponsored program related to railroad fire hazard mitigation, QNA investigated and submitted a report summarizing the accident information involving fuel leak and fire in Class I freight railroad locomotives during 1996 to 2004. Statistical data on fire related accidents of Canadian railroads and UK railroads were compiled in the original report for reference. The relevant part of that report is annexed to the end of the present final report as Appendix B. Table B.1 of Appendix B shows a list of U.S. Class I freight railroad accidents involving fuel tank breach and/or fire that happened during a period of nine years from 1996 to 2004. It summarizes information related to the location of accidents, date and time, speed of train at the time of accident, type of fuel tank breach, quantity of fuel spilled and if there was a fire, type of equipment involved, reported damage in $Million – due to property alone and including the Value of Statistical Life (VSL) – to account for the damage due to fatalities and injuries. The appendix shows number of death and injuries, source of accident information, remarks on the type of accident, and prevailing weather conditions.

The NTSB accident investigation reports generally reported damage data related to cost of repair and replacement of railroad properties, such as tracks and equipment. The monetization of human casualties including death and injury was rather difficult and was not included in the reported damage. The Department of Transportation (DOT) established guidelines for monetization of accident related deaths and injuries that are normally used for cost-benefit analysis of rulemaking and in the implementation of new safety measures. In March 2009, the Deputy Assistant Secretary for Transportation Policy and the Acting General Counsel issued a memorandum increasing the VSL from $5.8 million to $6.0 million [10]. Similarly, regarding the value of preventing injuries, DOT's 1993 January VSL guidance established the relative value of injuries of varying severity as a percentage of the economic value of a statistical life (VSL). DOT reasoned the willingness-to-pay estimates for a range of injuries were unavailable. The DOT used previously conducted research, which was based the percentages on the Maximum Abbreviated Injury Scale (MAIS), which categorizes non-fatal injuries into five levels ranging from minor to critical. The percentages used in the 1993 January guidance have not been updated, and are reflected in Table 5 below. The last column of this table shows the monetary value of those percentages using DOT's current $6.0 million VSL.

Table 5. Valuation of Accident Related Non-fatal Injuries According to DOT Guidelines



MAIS Level	Severity	Fraction of VSL	Dollar Value at VSL of $6.0 million
MAIS 1	Minor	0.0020	$12,000
MAIS 2	Moderate	0.0155	$93,000
MAIS 3	Serious	0.0575	$345,000
MAIS 4	Severe	0.1875	$1,125,000
MAIS 5	Critical	0.7625	$4,575,000

Source: Memorandum from Tyler D. Duvall, Assistant Secretary for Transportation Policy, and D.J. Gribbin, General Counsel, to DOT secretarial officers and modal administrators, February 5, 2008, which was included as an attachment to DOT's March 2009 policy memorandum.

In Appendix B, Table B.1 shows all freight train accidents involving fuel tank breach and fire. The reported data show the railroad property damage value and the total damage inclusive of damage due to fatalities and injuries. The damage computation was based on the VSL applied for both death and injuries as per the DOT guidelines indicated in Table 5. For the assessment of damage due to injury, MAIS 2 level representing moderate injury was used in the absence of any further classification of injuries in the reported freight train accidents.

The estimated total damage including all casualties for all freight train accidents involving fuel leak and fire over the 9 year period amounts to $138.49 million and 12 accidents involving approximately 39 locomotives. Therefore, the average damage from fuel leak and fire, related freight train accidents per year, amounted to $15.387 million annually and 4.3 locomotives per year on average. Based on the Class I freight railroad locomotive statistics compiled by AAR and shown in Figure 55, in 2005 there were 22,779 locomotives in revenue service. The estimated average fuel leak and fire related accident damage per locomotive per year was $675. Fuel breach and subsequent fire accidents affected approximately 0.019 percent of locomotives in revenue service. For the BNSF Railway currently operating 4,600 road locomotives, the estimated damage could be on the order of $3.105 million/year.

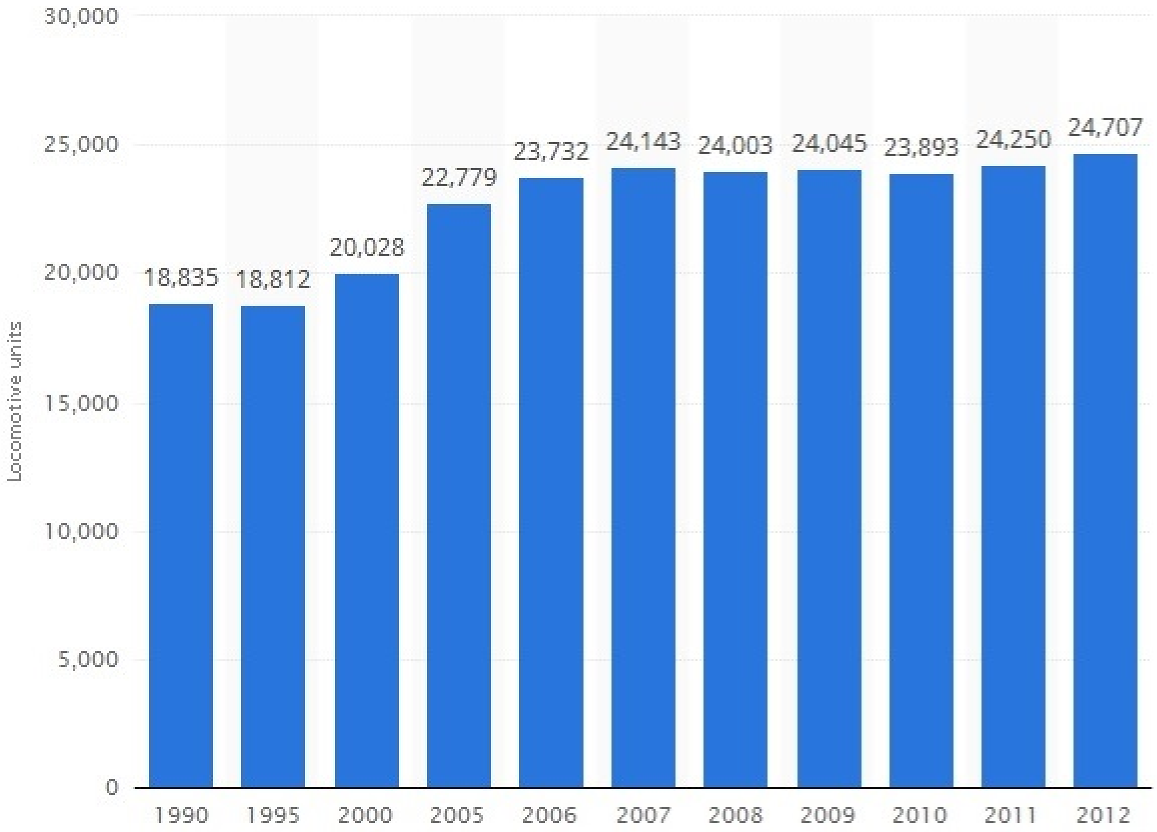


Figure 55. Number of US Class I freight railroad locomotives in service during 1990 - 2012

3.2.7 Summary of Cost–Benefit Analyses

The largest single cost-benefit is the assumption of elimination of damages due to fuel leaks and subsequent fires. That value was estimated at $675 per locomotive assuming all such damages are eliminated. The costs for implementing these changes are on the order of $10,000 per locomotive, or 15 years to recover the initial investment in the best case.

The potential for saving lives by preventing fires through reducing the diesel vapor in the tank headspace is also an important consideration beyond the monetary value of that implementation.

4. Conclusions

On average, every road locomotive deployed in revenue service may be losing about $9.53 per year toward the cost of diesel fuel lost to the environment in the form of diesel vapor, plus $675/year due to fires and injuries from fuel breach in accidents. This would amount to a total loss of approximately $684/year per locomotive or $3,150,000/year for a Class I railroad, such as BNSF operating a fleet of 4,600 road locomotives, mostly from accidents, subsequent fire, and injuries.

This program and the cost-benefit analysis concluded that the DVRU systems can be effective in reducing the fuel vapor content in the fuel tank headspace. However the cost of implementation is approximately $10,000 per locomotive. Cost savings are derived mostly from reducing the risk of fire in derailments due to fuel tank breaches. The cost savings from reducing fuel loss to the environment are negligible. The best case return on investment for this type of system is 15 years by eliminating the average costs of all fire-related accidents.

An alternative method for reducing diesel vapor content in the headspace is by cooling the return fuel into the tank. This can be accomplished with a brazed plate fuel-coolant heat exchanger and chiller system. Cost of implementation is approximately $12,000 mostly due to the high cost of a chiller at the required BTU. Cost savings rationale is the same as for the DVRU system.

The potential benefits of either a DVRU or return fuel cooling system include fire hazard mitigation (which saves properties and lives), preventing or minimizing of diesel vapor release to the environment, and improving fuel economy by reusing condensed fuel derived from diesel vapors or reducing diesel vapor formation.

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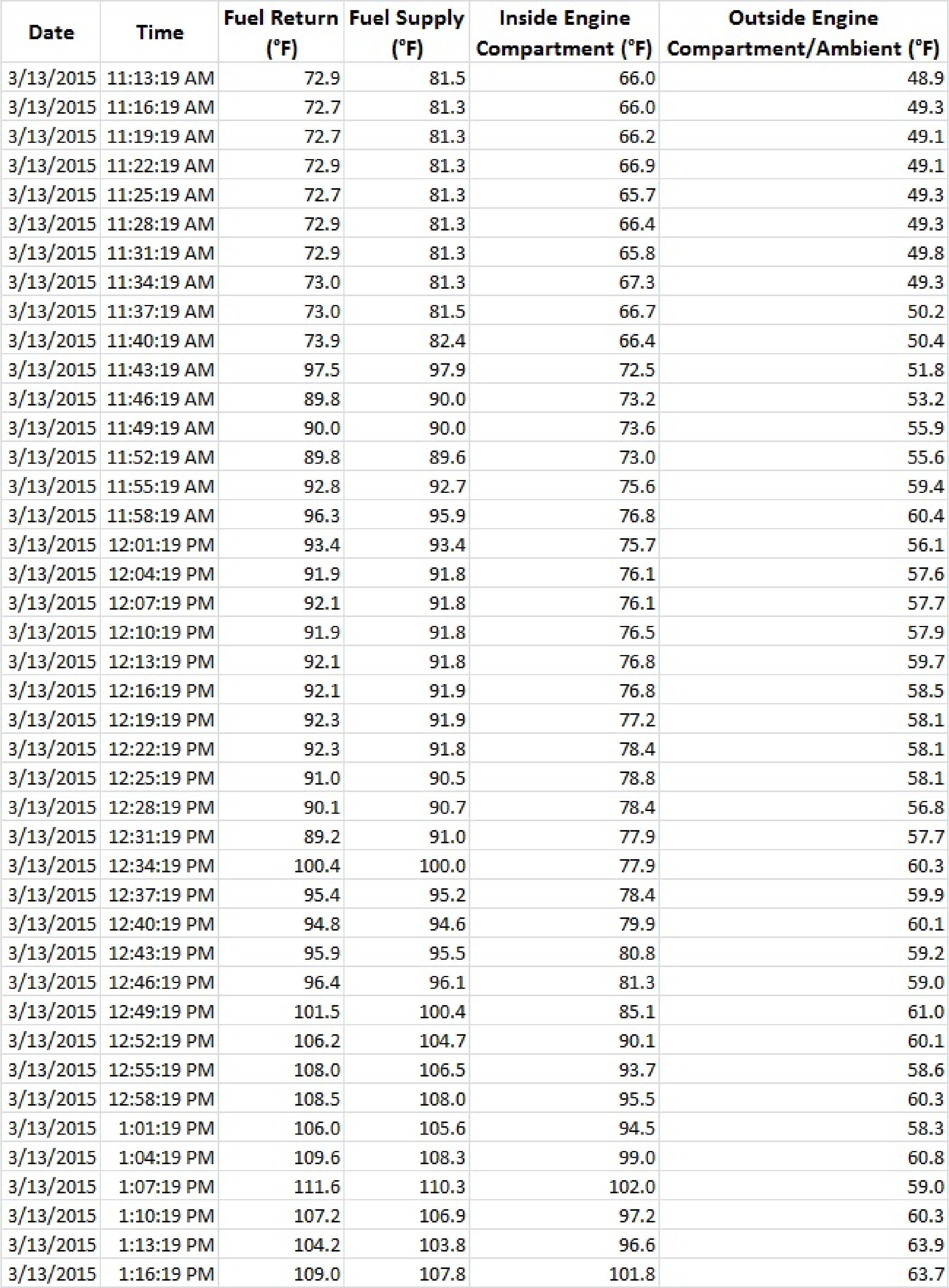
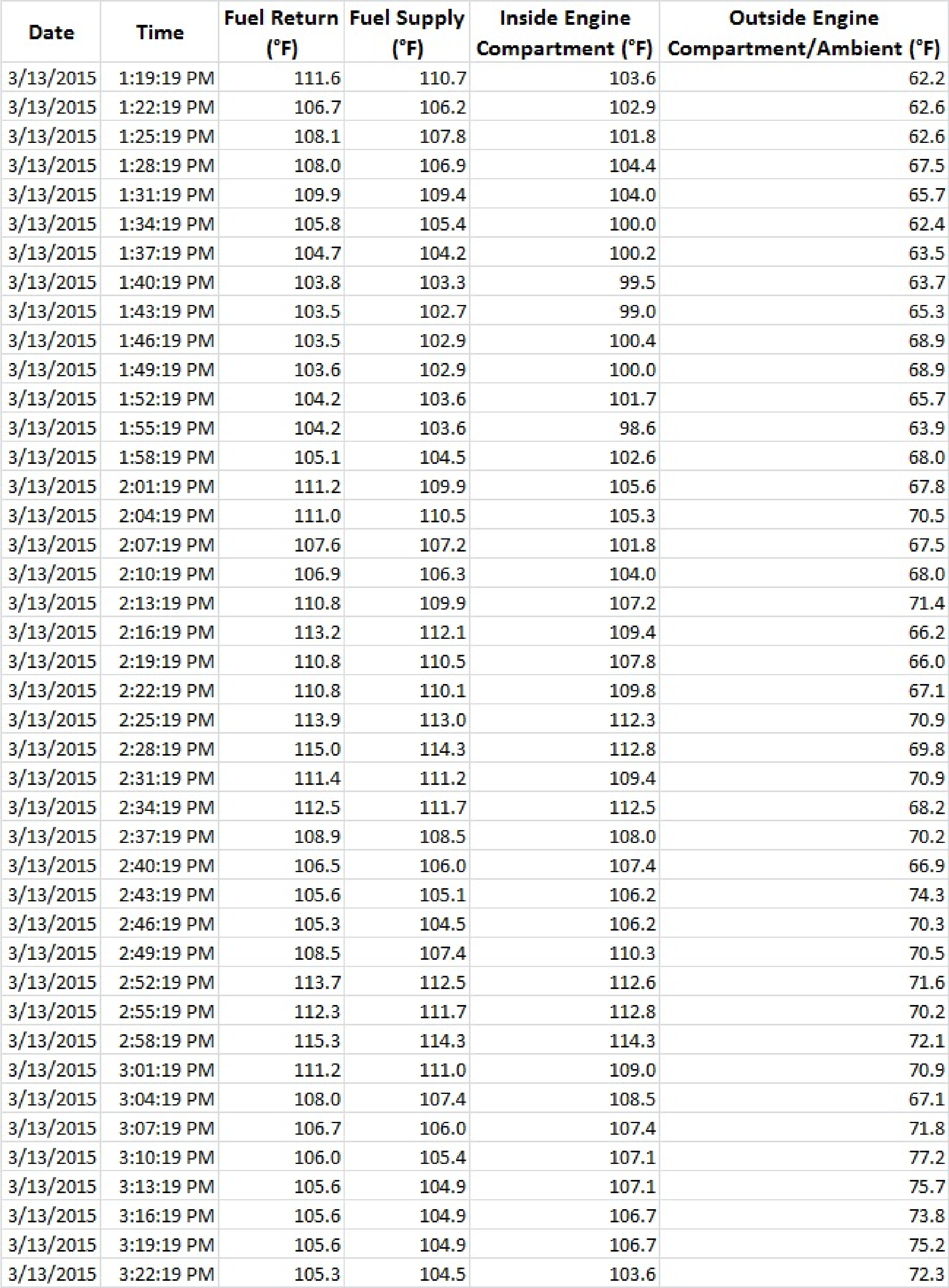
Abbreviations and Acronyms

BNSF	Burlington-Northern Santa Fe
CFD	Computational Fluid Dynamics
CFMU	Condensed Fuel Measuring Unit
GSM	Global System for Mobile Communications
COTS	Commercial Off-the-Shelf
CFR	Code of Federal Regulations
DAQ	Data Acquisition system
DVRU	Diesel Vapor Reclamation Unit
EMD	Electro-Motive Diesel
EPA	Environmental Protection Agency
FAR	Fuel-vapor to Air Ratio
FTP	File Transfer Protocol
GPS	Global Positioning System
LEL	Lower Explosive Limit
MAIS	Maximum Abbreviated Injury Scale
MSA	Mine Safety Appliances
POC	Point Of Contact
SIM	Subscriber Identity Module
VOC	Volatile Organic Compound
VSL	Value of a Statistical Life

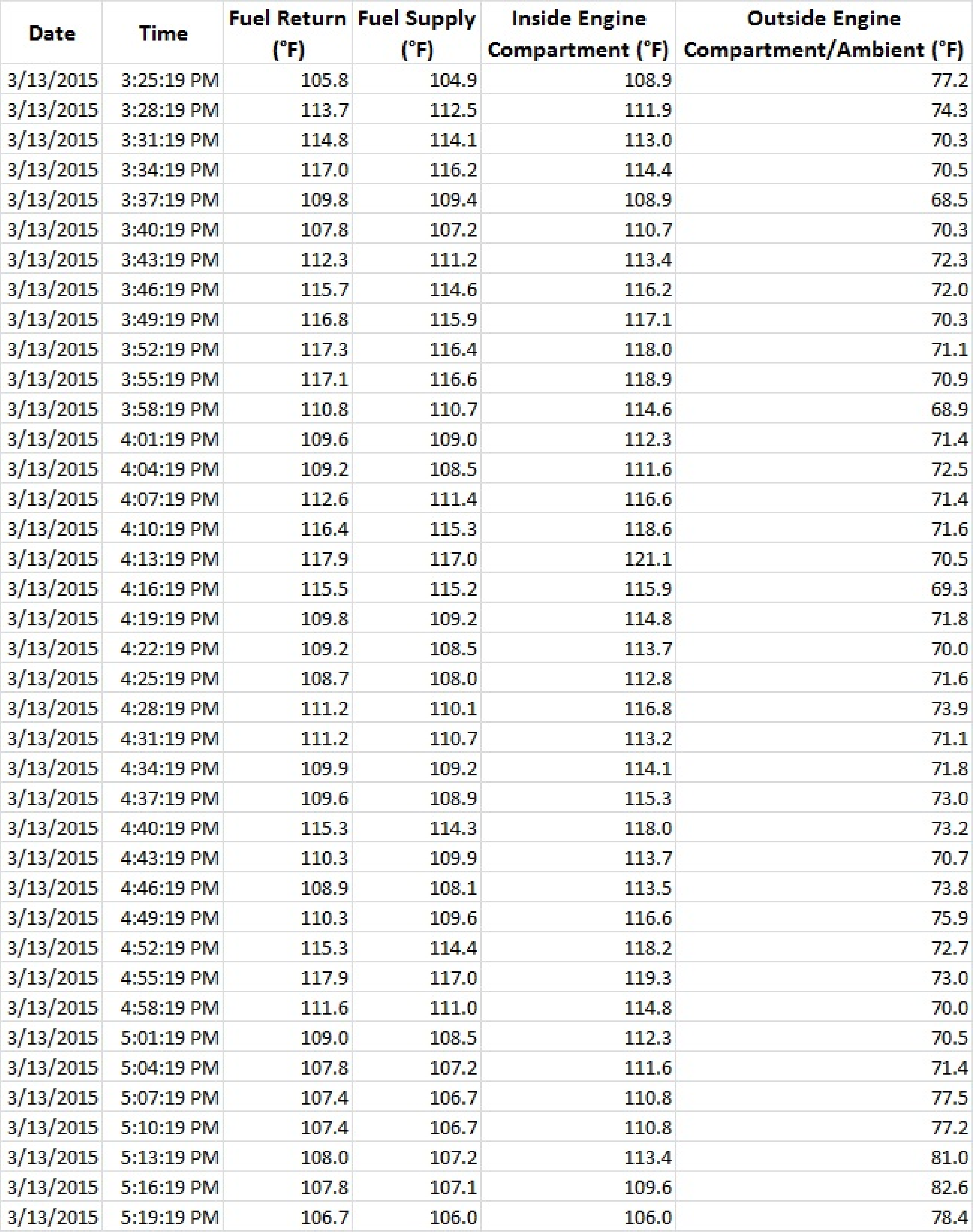
Appendix A. Locomotive BNSF9674 Fuel Line Temperature Data



Date	Time	Fuel Return (°F)	Fuel Supply (°F)	Inside Engine Compartment (°F)	Outside Engine Compartment/Ambient (°F)
3/13/2015	11:13:19 AM	72.9	81.5	66.0	48.9
3/13/2015	11:16:19 AM	72.7	81.3	66.0	49.3
3/13/2015	11:19:19 AM	72.7	81.3	66.2	49.1
3/13/2015	11:22:19 AM	72.9	81.3	66.9	49.1
3/13/2015	11:25:19 AM	72.7	81.3	65.7	49.3
3/13/2015	11:28:19 AM	72.9	81.3	66.4	49.3
3/13/2015	11:31:19 AM	72.9	81.3	65.8	49.8
3/13/2015	11:34:19 AM	73.0	81.3	67.3	49.3
3/13/2015	11:37:19 AM	73.0	81.5	66.7	50.2
3/13/2015	11:40:19 AM	73.9	82.4	66.4	50.4
3/13/2015	11:43:19 AM	97.5	97.9	72.5	51.8
3/13/2015	11:46:19 AM	89.8	90.0	73.2	53.2
3/13/2015	11:49:19 AM	90.0	90.0	73.6	55.9
3/13/2015	11:52:19 AM	89.8	89.6	73.0	55.6
3/13/2015	11:55:19 AM	92.8	92.7	75.6	59.4
3/13/2015	11:58:19 AM	96.3	95.9	76.8	60.4
3/13/2015	12:01:19 PM	93.4	93.4	75.7	56.1
3/13/2015	12:04:19 PM	91.9	91.8	76.1	57.6
3/13/2015	12:07:19 PM	92.1	91.8	76.1	57.7
3/13/2015	12:10:19 PM	91.9	91.8	76.5	57.9
3/13/2015	12:13:19 PM	92.1	91.8	76.8	59.7
3/13/2015	12:16:19 PM	92.1	91.9	76.8	58.5
3/13/2015	12:19:19 PM	92.3	91.9	77.2	58.1
3/13/2015	12:22:19 PM	92.3	91.8	78.4	58.1
3/13/2015	12:25:19 PM	91.0	90.5	78.8	58.1
3/13/2015	12:28:19 PM	90.1	90.7	78.4	56.8
3/13/2015	12:31:19 PM	89.2	91.0	77.9	57.7
3/13/2015	12:34:19 PM	100.4	100.0	77.9	60.3
3/13/2015	12:37:19 PM	95.4	95.2	78.4	59.9
3/13/2015	12:40:19 PM	94.8	94.6	79.9	60.1
3/13/2015	12:43:19 PM	95.9	95.5	80.8	59.2
3/13/2015	12:46:19 PM	96.4	96.1	81.3	59.0
3/13/2015	12:49:19 PM	101.5	100.4	85.1	61.0
3/13/2015	12:52:19 PM	106.2	104.7	90.1	60.1
3/13/2015	12:55:19 PM	108.0	106.5	93.7	58.6
3/13/2015	12:58:19 PM	108.5	108.0	95.5	60.3
3/13/2015	1:01:19 PM	106.0	105.6	94.5	58.3
3/13/2015	1:04:19 PM	109.6	108.3	99.0	60.8
3/13/2015	1:07:19 PM	111.6	110.3	102.0	59.0
3/13/2015	1:10:19 PM	107.2	106.9	97.2	60.3
3/13/2015	1:13:19 PM	104.2	103.8	96.6	63.9
3/13/2015	1:16:19 PM	109.0	107.8	101.8	63.7



Date	Time	Fuel Return (°F)	Fuel Supply (°F)	Inside Engine Compartment (°F)	Outside Engine Compartment/Ambient (°F)
3/13/2015	1:19:19 PM	111.6	110.7	103.6	62.2
3/13/2015	1:22:19 PM	106.7	106.2	102.9	62.6
3/13/2015	1:25:19 PM	108.1	107.8	101.8	62.6
3/13/2015	1:28:19 PM	108.0	106.9	104.4	67.5
3/13/2015	1:31:19 PM	109.9	109.4	104.0	65.7
3/13/2015	1:34:19 PM	105.8	105.4	100.0	62.4
3/13/2015	1:37:19 PM	104.7	104.2	100.2	63.5
3/13/2015	1:40:19 PM	103.8	103.3	99.5	63.7
3/13/2015	1:43:19 PM	103.5	102.7	99.0	65.3
3/13/2015	1:46:19 PM	103.5	102.9	100.4	68.9
3/13/2015	1:49:19 PM	103.6	102.9	100.0	68.9
3/13/2015	1:52:19 PM	104.2	103.6	101.7	65.7
3/13/2015	1:55:19 PM	104.2	103.6	98.6	63.9
3/13/2015	1:58:19 PM	105.1	104.5	102.6	68.0
3/13/2015	2:01:19 PM	111.2	109.9	105.6	67.8
3/13/2015	2:04:19 PM	111.0	110.5	105.3	70.5
3/13/2015	2:07:19 PM	107.6	107.2	101.8	67.5
3/13/2015	2:10:19 PM	106.9	106.3	104.0	68.0
3/13/2015	2:13:19 PM	110.8	109.9	107.2	71.4
3/13/2015	2:16:19 PM	113.2	112.1	109.4	66.2
3/13/2015	2:19:19 PM	110.8	110.5	107.8	66.0
3/13/2015	2:22:19 PM	110.8	110.1	109.8	67.1
3/13/2015	2:25:19 PM	113.9	113.0	112.3	70.9
3/13/2015	2:28:19 PM	115.0	114.3	112.8	69.8
3/13/2015	2:31:19 PM	111.4	111.2	109.4	70.9
3/13/2015	2:34:19 PM	112.5	111.7	112.5	68.2
3/13/2015	2:37:19 PM	108.9	108.5	108.0	70.2
3/13/2015	2:40:19 PM	106.5	106.0	107.4	66.9
3/13/2015	2:43:19 PM	105.6	105.1	106.2	74.3
3/13/2015	2:46:19 PM	105.3	104.5	106.2	70.3
3/13/2015	2:49:19 PM	108.5	107.4	110.3	70.5
3/13/2015	2:52:19 PM	113.7	112.5	112.6	71.6
3/13/2015	2:55:19 PM	112.3	111.7	112.8	70.2
3/13/2015	2:58:19 PM	115.3	114.3	114.3	72.1
3/13/2015	3:01:19 PM	111.2	111.0	109.0	70.9
3/13/2015	3:04:19 PM	108.0	107.4	108.5	67.1
3/13/2015	3:07:19 PM	106.7	106.0	107.4	71.8
3/13/2015	3:10:19 PM	106.0	105.4	107.1	77.2
3/13/2015	3:13:19 PM	105.6	104.9	107.1	75.7
3/13/2015	3:16:19 PM	105.6	104.9	106.7	73.8
3/13/2015	3:19:19 PM	105.6	104.9	106.7	75.2
3/13/2015	3:22:19 PM	105.3	104.5	103.6	72.3



Date	Time	Fuel Return (°F)	Fuel Supply (°F)	Inside Engine Compartment (°F)	Outside Engine Compartment/Ambient (°F)
3/13/2015	3:25:19 PM	105.8	104.9	108.9	77.2
3/13/2015	3:28:19 PM	113.7	112.5	111.9	74.3
3/13/2015	3:31:19 PM	114.8	114.1	113.0	70.3
3/13/2015	3:34:19 PM	117.0	116.2	114.4	70.5
3/13/2015	3:37:19 PM	109.8	109.4	108.9	68.5
3/13/2015	3:40:19 PM	107.8	107.2	110.7	70.3
3/13/2015	3:43:19 PM	112.3	111.2	113.4	72.3
3/13/2015	3:46:19 PM	115.7	114.6	116.2	72.0
3/13/2015	3:49:19 PM	116.8	115.9	117.1	70.3
3/13/2015	3:52:19 PM	117.3	116.4	118.0	71.1
3/13/2015	3:55:19 PM	117.1	116.6	118.9	70.9
3/13/2015	3:58:19 PM	110.8	110.7	114.6	68.9
3/13/2015	4:01:19 PM	109.6	109.0	112.3	71.4
3/13/2015	4:04:19 PM	109.2	108.5	111.6	72.5
3/13/2015	4:07:19 PM	112.6	111.4	116.6	71.4
3/13/2015	4:10:19 PM	116.4	115.3	118.6	71.6
3/13/2015	4:13:19 PM	117.9	117.0	121.1	70.5
3/13/2015	4:16:19 PM	115.5	115.2	115.9	69.3
3/13/2015	4:19:19 PM	109.8	109.2	114.8	71.8
3/13/2015	4:22:19 PM	109.2	108.5	113.7	70.0
3/13/2015	4:25:19 PM	108.7	108.0	112.8	71.6
3/13/2015	4:28:19 PM	111.2	110.1	116.8	73.9
3/13/2015	4:31:19 PM	111.2	110.7	113.2	71.1
3/13/2015	4:34:19 PM	109.9	109.2	114.1	71.8
3/13/2015	4:37:19 PM	109.6	108.9	115.3	73.0
3/13/2015	4:40:19 PM	115.3	114.3	118.0	73.2
3/13/2015	4:43:19 PM	110.3	109.9	113.7	70.7
3/13/2015	4:46:19 PM	108.9	108.1	113.5	73.8
3/13/2015	4:49:19 PM	110.3	109.6	116.6	75.9
3/13/2015	4:52:19 PM	115.3	114.4	118.2	72.7
3/13/2015	4:55:19 PM	117.9	117.0	119.3	73.0
3/13/2015	4:58:19 PM	111.6	111.0	114.8	70.0
3/13/2015	5:01:19 PM	109.0	108.5	112.3	70.5
3/13/2015	5:04:19 PM	107.8	107.2	111.6	71.4
3/13/2015	5:07:19 PM	107.4	106.7	110.8	77.5
3/13/2015	5:10:19 PM	107.4	106.7	110.8	77.2
3/13/2015	5:13:19 PM	108.0	107.2	113.4	81.0
3/13/2015	5:16:19 PM	107.8	107.1	109.6	82.6
3/13/2015	5:19:19 PM	106.7	106.0	106.0	78.4

Appendix B. Identification of Key Accident Parameters Involving Class 1 Railroad Fuel Tank Breach and Fire

This section describes the process used for identifying the key characteristics in post-accident fires from fuel spills. The objective of this task was to develop a means of quantifying the risk of a fuel spill and fire based on common factors in rail accidents where fires resulted. The overall approach included study of available data on rail accidents, quantification and correlation of the appropriate data, and definition of risk based on accident type. Development of mitigation solutions for fire hazards in locomotive fuel systems requires an understanding of the various accident conditions that might lead to a fuel spill and fire. The dynamics involved in many accidents may be similar in terms of speed, weather conditions, or accident type. Review of accident case histories provides a means of identifying key factors related to fuel spills and fires. Understanding the interactions between the various parameters allows for more effective evaluation of mitigation options. The case studies carried out under this program have facilitated evaluation of commonalities among various accident scenarios and identification of key factors contributing to fuel leak and fire in the post-accident condition. The study includes accidents involving freight and passenger locomotives.

B.1 Literature Search for Fuel and Fire-Related Railroad Accidents

The National Transportation Safety Board (NTSB) investigates most major rail accidents involving fatalities and/or release of hazardous materials in the United States. Accident reports prepared by NTSB cover both freight and passenger rail incidents and recommend changes to be adopted by the operating railroads and/or FRA to reduce the risk of future accidents. Unfortunately, no dedicated database was available that deals specifically with railroad accidents involving fuel leaks and fires in locomotives. The researchers used NTSB reports as the primary source for accidents within the United States so that incidents resulting in fuel spills and fires could lead to more in-depth investigations. They also studied supplemental information available from other government agencies that deal with fires and accidents, including the U.S. Fire Administration (USFA) and the National Fire Information Registry System.

In addition to accident information from the United States, the work conducted examined summaries and special reports of Canadian and British data. The data provides an understanding of the frequency and severity of the rail fires in these countries, and it allows for some statistical comparison with the U.S. data.

B.2 Organization of Data

The primary objective of surveying the past railroad accidents was to collect useful information on some of the basic characteristics of fire-related accidents and identify potential factors of interest. Factors isolated after the initial survey include the following:

- Type of fuel system breach (i.e., leak/rupture of fuel tank, leak from other fuel system components)
- Speed of the consist at the time of collision or derailment
- Volume of diesel fuel released following the accident
- Primary source of ignition of leaked diesel fuel or its vapor
- Local weather conditions, such as temperature, relative humidity (RH), and wind conditions, at the time of the accident

B.3 U.S. Railroad Accident Data Related to Fuel Leak and Fire

The accident reports covering both freight and passenger locomotives are available on the NTSB Web site, covering a 12 year period beginning in 1994. In addition, researchers searched the NTSB reports covering highway accidents specifically for grade crossing accidents. They also used NTIS to access older reports not yet available online and reviewed a special report from USFA pertaining specifically to rail accidents [1].

Of the 97 reviewed reports (96 from the NTSB and 1 from the USFA), 26 contained incidents that resulted in fuel spill and/or fire. Table B.1 provides a summary of accident information involving fuel leak and/or fire in freight locomotives covering a period from May 1996 to October 2004. Table B.2 provides similar information pertaining to passenger locomotives, covering a period from July 1984 to February 2001. In the older reports, some of the details, such as quantity of fuel released, are missing. Not all of the reports included specific weather- related information. Information available from the National Climatic Data Center (NCDC) was used for supplemented weather data, since ambient temperature and RH have important bearing on the formation of fuel vapors and on the ignition/spread of resulting fire. The recording meteorological station closest to the accident scene provided data in circumstances requiring NCDC information. NCDC data from most stations was available from 1995 on. Tables B.1 and B.2 report the available meteorological data.

After compiling the accident data presented in Table B.1 and Table B.2, researchers reviewed the data for trends or correlation between parameters. Each of the accidents noted in the tables falls into one of the following types of accident:

- Head-on collision between locomotives of two trains
- Rear end collision leading to derailment/rollover of locomotives
- Sideswipe accident between two trains leading to derailment
- High-speed derailment and/or rollover of locomotive caused by track defect
- Collision with road vehicle at grade crossing

Other accident data of relevance in Table B.1 and Table B.2 include the type of equipment involved, the resulting fatalities/injuries, and the reported damage in millions of dollars. The tables include the date and time of the accident, as well as the report number of the source for reference. The remarks column includes available climatic data at the accident site or at the closest recording station. As mentioned above, no available weather data existed for the older accidents.

Table B.1. Summary of Accident Information Involving Fuel Leak/Fire in Freight Locomotives (1996-2004)

Location	Date/Time	Speed (mph)	Fuel Leak (gal)	Type of Fuel Breach/Fire	Type of Equipment	Damage$^{@}$ ($M)	Death/ Injuries	Source	Remarks/Weather Conditions
Pico Rivera, CA	16 Oct 04 9:40 a.m.	57	5000	Tank Breach/ No Fire	3 Diesel-Electric Loco.	2.7	None	NTSB/ RAB-05/02	Derailment, 66º F, 70% RH
Kelso, WA	15 Nov 03 7:40 a.m.	49	2800	Tank Leak/ Minor Fire	6 Diesel-Electric Loco.	2.7/2.89	No Death/2 Injured	NTSB/ RAB-05/03	Side Collision/Rain, 45º F, 93% RH
Des Plaines, IL	21 Oct 02 10:38 p.m.	24	5000	Tank Breach/ No Fire	3 Diesel-Electric Loco	1.02/1.2	No Death/2 Injured	NTSB/ RAB-04/04	Sideswipe Collision and Derail, 49º F*, 59% RH
Clarendon, TX	28 May 02 8:57 a.m.	49	NR	NR/Fire	4 Diesel-Electric Loco.	8.0/14.3	1 Dead/3 Injured	NTSB/ RAR-03/01	Head-On Collision, 62º F*, 86% RH
Pacific, MO	13 Dec 01 5:46 a.m.	48 (Tr.#1) 17 (Tr#2)	10,000	Several Tanks Ruptured/ Small Fire	6 Diesel-Electric Loco.	10.0/10.37	No Death/4 Injured	NTSB/ RAB-04/06	Rear-End Collision/ Rain, 36º F, 88% RH
Clarkston, MI	15 Nov 01 5:54 a.m.	30	NR	Tank Leak/ Small Fire	Multiple Diesel-Electric Loco.	1.4/13.58	2 Dead/2 Injured	NTSB/ RAR-02/04	Head-On Collision, 52º F*, 97% RH
Momence, IL	23 Mar 99 7:02 a.m.	44	NR	Tank Breach/ Fire	Conrail Lead Loco. Derail	1.8	None	NTSB/ RAB-02/02	Side Collision of Two Trains, 32º F*, 75% RH
Bryan, OH	17 Jan 99 1:58 a.m.	58	NR	Tank Breach/ Fire	3 Diesel-Electric Loco.	5.3/17.3	2 Dead	NTSB/ RAR-01/01	Rear-End Collision in Thick Fog, 21º F*, 96% RH

Location	Date/Time	Speed (mph)	Fuel Leak (gal)	Type of Fuel Breach/Fire	Type of Equipment	Damage$^{@}$ ($M)	Death/ Injuries	Source	Remarks/Weather Conditions
Butler, IN	25 Mar 98 NR	30	7000	Two Tanks Ruptured/ No Fire	2 Diesel-Electric Loco. Derail	0.62/6.81	1 Dead/2 Injured	NTSB/ RAR-99/02	Side Collision of Two Trains, 44º F*, 73% RH
Grantsville, UT	3 Dec 97 5:30 p.m.	NR	NR	Tank Rupture/ Fire	2 Diesel-Electric Loco.	NR	No Death/1 Injured	NTSB/ HAB-02/12	Collision at Grade Crossing, 37º F*
Delia, KS	2 July 97 2:15 a.m.	70	Entire fuel spilled and burnt	Front Wall Crushed; Longitudinal Tearing & Holed/Fire	2 Diesel-Electric Loco. Derail; One Burnt	5.1/11.18	1 Dead/1 Injured	NTSB/ RAR-99/04	Side Collision, Partly Cloudy, 79º F*, 73% RH
Devine, TX	22 June 97 10:52 p.m.	NR	NR	Tank Rupture/ Fire	5 Diesel-Electric Loco. Derail	6.0/42	4 Crew Dead + 2 Unidentified Persons	NTSB/ RAR-98/02	Head-On Collision and Derailment, Clear Sky, 78º F, 90% RH, 11 Knots
Beaumont, CA	30 Aug 96 8:10 a.m.	20	NR	Tank Rupture/ No Fire	2 Diesel-Electric Loco.	0.18	None	NTSB/ RAB-98/14	Rear-End Collision and Derailment, 78º F
Smithfield, WV	20 Aug 96 5:22 a.m.	NR	NR	Tank Breached/Fire	3 Diesel-Electric Loco. Burnt	3.8/15.98	2 Dead/2 Injured	NTSB/ RAB-98/13	Head-On Collision and Derail, Foggy, 64º F
Pleasant Hill, IL	12 May 96 5:50 a.m.	NR	2500	Tank Breached/Fire	5 Diesel-Electric Loco. Derail	1.26	None	NTSB/ RAB-98/10	Side Collision and Derailment, 47º F*

Legend-NR: Not Reported; * Based on NCDC Data; @ Damage without/with Death and Injuries (VSL)

Table B.2. Summary of Accident Information Involving Fuel Leak/Fire in Passenger Train Locomotives (1993-2004)

Location	Date/Time	Speed (mph)	Fuel Leak (gal)	Type of Fuel Breach/Fire	Type of Equipment	Damage ($M)	Death/ Injuries	Source	Remarks/Weather Conditions
Syracuse, NY	5 Feb 01 11:40 a.m.	35	Small Qty	Fuel Tank/System Breached/No Fire	1 Diesel-Electric Loco. and 4 Cars Derail	NR	No Deaths/ 62 injured	NTSB/ RAB-01/04	Amtrak Collided with Rear of CSXT, 30º F, 88% RH
Intercession City, FL	17 Nov 00 4:35 p.m.	57	600	Fuel Tank Breach/No Fire	Amtrak Diesel-Electric Loco.	0.23	No Deaths/5 Injured	NTSB/ HAR-02/02	Amtrak Collision at Grade Crossing, 76º F, 72% RH
Bourbonnais, IL	19 Mar 99 9:47 p.m.	79	NR	Fuel Tank Breach/Fire	2 Amtrak Loco. and 11 Cars Derail	14.3	11 Dead/122 Injured	NTSB/ RAR-02/01	Amtrak Collision at Grade Crossing, 36º F*, 67% RH
Kingman, AZ	19 Aug 97 5:56 a.m.	89	NR	Broken Rail Penetrated Top of a Fuel Tank/No Fire	4 Diesel-Electric Loco.	7.2	No Deaths/183 Injured	NTSB/ RAR-98/03	Amtrak Derailed Over a Bridge, 68º F*, 53% RH
Branson, MO	14 May 97 9:46 p.m.	26	NR	Fuel Tank Breach/Fire	1 Diesel-Electric Loco.	0.41	No Deaths/2 Injured	NTSB/ RAB-98/03	Rear-End Collision Passenger into Freight Train, 51º F*, 71%RH
Silver Spring, MD	16 Feb 96 5:39 p.m.	Amtrak 38/ MARC 66	NR	Fuel Tank Breach/Fire	Amtrak–2 Diesel Electric Loco. MARC–1 loco.	7.5	11 Dead/11 Injured	NTSB/ RAR-97/02	Head-On Collision Amtrak and MARC trains, 45º F*
Intercession City, FL	30 Nov 93 12:40 p.m.	79	NR	Fuel Tank Breach/No Fire	Diesel Electric loco. and 4 Cars Derail	14.0	No Deaths/ 59 injured	NTSB/ HAR-95/01	Amtrak Collision at Grade Crossing, 73º F*

Location	Date/Time	Speed (mph)	Fuel Leak (gal)	Type of Fuel Breach/Fire	Type of Equipment	Damage ($M)	Death/ Injuries	Source	Remarks/Weather Conditions
Big Bayou Canot, Mobile, AL	22 Sep 93 2:53 a.m.	72	Entire Fuel Contents	Fuel Tank Ruptured by Bridge Girder/ Extensive Fire	3 Diesel Electric Loco. (F40-PH)	NR	47 Dead/103 Injured	NTSB/ RAR-94/01	Amtrak Train Derailed Over Bridge in Dense Fog
Stockton, CA	19 Dec 89 9:38 a.m.	NR	Large Pool Under Loco.	Fuel Tank Breached on Roll-over/Fire	Diesel Electric Loco.	NR	NR	USFA-TR-094/ Feb 2003 Special Report	Amtrak Collision at Grade Crossing
Chase, MD	4 Jan 87 NR	60	NR	Crushed Fuel Tank/Large Fire and Explosion	Amtrak Diesel Electric and 3 Conrail Loco.	NR	16 Dead/177 Injured	USFA-TR-094 / Feb 2003 Special Report	Amtrak Collision with Conrail, 33º F*
Essex Junction, VT	7 July 84 6:50 a.m.	NR	NR	Fuel System Breach/Small Fire	2 Diesel Electric Loco.	NR	5 Dead/29 Injured	USFA-TR-094 / Feb 2003 Special Report	Passenger Train Derailed Over Embankment, 68º

Legend-NR: Not Reported; * Based on NCDC Data

B.4 Canadian Railroad Accident Data

Table B.3 contains the statistical summary of railroad accidents with fires and explosions from the Canadian Transportation Safety Board (TSB). The TSB information [2] covers a period similar to the U.S. data previously summarized. The table includes the number and percentage of incidents of fires or explosions in collisions and derailments over the period. The data in Table B.3 indicate that, on average, 3.2 percent of the accidents over the reported 11-yr period resulted in fire or explosion. The limitation of the TSB data was that the report did not specifically separate the data for freight and passenger trains. In addition, it did not indicate how many fires or explosions were due primarily to fuel-related breaches following collision/derailment.

Table B.3. Canadian Train Accidents Involving Fires and Explosions (1994-2004)

Accidents*	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
No. of Fires/ Explosions	27	39	61	44	51	53	32	36	24	23	15
Total No. of Accidents	1213	1276	1304	1116	1075	1129	1063	1060	984	1030	1128
Percent Fires/ Explosions	2.2	3.0	4.6	3.9	4.7	4.7	3.0	3.4	2.4	2.2	1.3

* The accident data presented here include both passenger and freight trains. No separate data is available to account for fires/explosions caused only due to fuel-leak and fire in diesel locomotives.

B.5 British Railroad Accident Data

A major collision between a high-speed passenger train (HST) traveling at 130 mph and a diesel multiple unit (DMU) at Ladbroke Grove in 1999 produced a diesel fireball that resulted in a large number of fatalities. Following this accident, the British Rail Safety and Standards Board (RSSB) undertook an initiative to study effective measures for reducing the risk of fire from passenger train fuel tanks. RSSB published a special topic report on train fires [3] that includes elaborate compilations of various parameters and statistical tables involving Rail-Track programmable logic circuit-Controlled Infrastructure (RCI). Table B.4 presents the data for passenger train fires and all train fires, expressed in numbers of accidents, as well as normalized data in terms of million train miles (MTM) and million passenger train miles (MPTM). The data covers two periods: 1992 to 1993 and 1999 to 2000. The normalized data in Table B.4 indicates that the relative frequency of total train fires did not vary significantly with changes in train mileage. While the rate of all train fires per total MTM remained almost steady between 1.2 to 1.4, the rate of passenger train fires increased from 1996 to 1997 onwards. Table B.5 summarizes all RCI fires by cause/category over the eight year period indicated above. Among the 2911 total instances of train fires, only 29 cases of fire involved fuel leaks, which was about 1 percent of all cases of train fires in the United Kingdom.

Table B.4. Fires in Passenger and Freight Trains in RCI-U.K. 1992 to 2000

Year	No. of Passenger Train Fires*	No. of All Train Fires*	MPTM	MTM	Passenger Train Fires per MPTM	All Train Fires per Total MTM
1992-93	219	321	229.4	260	0.95	1.23
1993-94	241	339	228.8	254.8	1.05	1.33
1994-95	238	310	226.48	255.8	1.05	1.21
1995-96	279	346	240.02	265.05	1.16	1.31
1996-97	292	353	244.15	274.12	1.20	1.29
1997-98	334	412	255.21	292.37	1.31	1.41
1998-99	332	426	269.10	306.34	1.23	1.39
1999-2000	331	404	277.57	316.18	1.19	1.28

* The cause of fire is due to all sources, including fuel spill from fuel system of passenger and freight locomotives.

Table B.5. Assessment of All RCI–Fires in United Kingdom by Cause Category

Year	Fuel Leaks	Technical Causes Mechanical	Electrical	All Other Causes*	All Train Fires
1992-93	9	82	56	174	321
1993-94	8	68	66	197	339
1994-95	1	42	42	225	310
1995-96	0	37	41	268	346
1996-97	0	49	32	272	353
1997-98	3	37	53	319	412
1998-99	5	46	55	320	426
1999-2000	3	42	79	280	404
8-Year Total	29	403	424	2055	2911
Percent (%) of All Train Fires	1	13.8	14.6	70.6	100

* All other causes include other technical causes, such as brakes, technical causes not stated, and those due to arson, debris/litter/dirt, weather related, obstructions, and unknown causes.

The British report noted that while fires resulting from fuel leaks represented about 2.6 percent of all accident-related fires, DMUs experienced the highest number of the 29 fire cases during the eight year period—a total of 7. The report also notes that over the eight year period, locomotives accounted for 30 percent of fires, and the majority of these involved diesel locomotives. The study noted that trackside fires from leaked diesel fuel were usually short-lived and could be handled with relatively simple mitigation measures because diesel fuel does not readily burn in bulk liquid form. According to the RSSB report, the greatest danger of fire-related fatalities or damage to railroad properties lay in airborne fuel droplets or clouds of atomized diesel fuel and smoke produced during high-speed crushing and rupturing of a fuel tank. In the case of high energy impacts, it was probable that a source of ignition would be present to ignite the airborne diesel fuel vapor, producing a fireball. The British report recommended that effective fire mitigation measures should address inhibition or containment of airborne diesel fuel vapor in the event of an accident.