STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR0003 (REV 10/98)

1. REPORT NUMBER	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
CA09-1099		

4. TITLE AND SUBTITLE

Compressed Natural Gas (CNG) Sweeper Operation Evaluaton

5. REPORT DATE

09-24-2009

6. PERFORMING ORGANIZATION CODE

7. AUTHOR

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8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

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10. WORK UNIT NUMBER

11. CONTRACT OR GRANT NUMBER

12. SPONSORING AGENCY AND ADDRESS

Caltrans – Division of Research and Innovation
1227 O st. 5th Floor
Sacramento, CA 95814

13. TYPE OF REPORT AND PERIOD COVERED

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Several counties across California have begun to switch from diesel-powered street sweepers to CNG (Compressed Natural Gas) street sweepers, in order to comply with Federal and State air quality regulations. In this report, we study the productivity and cost impact of using CNG sweepers as opposed to the diesel sweepers in Caltrans District 7. As part of this study, we reviewed the prior literature on the use of CNG vehicles, conducted crew site visits, and analyzed data from Caltrans' Integrated Maintenance Management System (IMMS) and maintenance cost records. Our findings on the productivity and cost of CNG sweeper operations are consistent with previous results found by researchers studying the use of CNG buses in mass transit and United Parcel Service (UPS) delivery. One key problem with the CNG sweepers is that the CNG fueling stations might be located far from the yard and the waiting time at the fueling station may be long. On balance, the move to CNG sweepers has resulted in a reduction in the productivity of sweeping operations. Consistent with other applications, there is no significant difference between the maintenance costs of the diesel and CNG sweepers. To offset this loss in productivity with CNG sweepers, we developed mathematical optimization models to make specific recommendations regarding (1) the locations where Caltrans should promote the use of CNG fueling stations, and (2) the rebalancing of the routes.

17. KEY WORDS

Productivity Analysis; Cost Analysis; Evaluation Techniques; Sweeper Operations

18. DISTRIBUTION STATEMENT

19. SECURITY CLASSIFICATION *(of this report)*	20. NUMBER OF PAGES	21. COST OF REPORT CHARGED
None	61	

DISCLAIMER STATEMENT

Compressed Natural Gas (CNG) Sweeper Operation Evaluation

Final Project Report

September 24, 2009

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Acknowledgements

The research team greatly appreciates the continuous support of the Caltrans Maintenance staff for providing the necessary data in this research.

Compressed Natural Gas (CNG) Sweeper Operation

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September 24, 2009

Abstract

Several counties across California have begun to switch from diesel-powered street sweepers to CNG (Compressed Natural Gas) street sweepers, in order to comply with Federal and State air quality regulations. In this report, we study the productivity and cost impact of using CNG sweepers as opposed to the diesel sweepers in Caltrans District 7. As part of this study, we reviewed the prior literature on the use of CNG vehicles, conducted crew site visits, and analyzed data from Caltrans' Integrated Maintenance Management System (IMMS) and maintenance cost records. Our findings on the productivity and cost of CNG sweeper operations are consistent with previous results found by researchers studying the use of CNG buses in mass transit and United Parcel Service (UPS) delivery. One key problem with the CNG sweepers is that the CNG fueling stations might be located far from the yard and the waiting time at the fueling station may be long. On balance, the move to CNG sweepers has resulted in a reduction in the productivity of sweeping operations. Consistent with other applications, there is no significant difference between the maintenance costs of the diesel and CNG sweepers. To offset this loss in productivity with CNG sweepers, we developed mathematical optimization models to make specific recommendations regarding (1) the locations where Caltrans should promote the use of CNG fueling stations, and (2) the rebalancing of the routes.

Keywords: Productivity Analysis; Cost Analysis; Evaluation Techniques; Sweeper Operations

Executive Summary

This report outlines our findings on the productivity and cost for CNG sweeper operations in District 7. We note that our findings are consistent with prior results found by researchers studying other CNG operations. Although there has been no published research on the usage of CNG vehicles on sweeping operations, there have been some studies outlining their use in mass transit and UPS delivery. A review of this literature shows that the critical factors that determine successful implementation of CNG vehicles are the size of the fleet, proper training of maintenance personnel, sufficient number of fueling stations and in particular access to an on-site fueling station, and a commitment to a natural gas program by the agency. Regarding the fleet size issue, the advantage of having more CNG vehicles is that the maintenance professionals are more familiar with the problems and the infrastructure supporting the CNG is used more often (e.g., justifying an on-site fueling station). From this perspective the CNG sweeper operations will always be behind the mass transit and delivery operations in this dimension since the fleet size for the former will always be smaller.

We visited two sweeping crews, one in the East Region and the other in the South Region. The two crews differed in their views of the CNG sweepers with the East Region crew having a strong negative opinion of these sweepers. Consistent with the literature, the problem with the fueling stations was listed as one of the primary problems with the CNG sweepers. The problems with the fueling station had to do primarily with (1) it takes time to drive to the fueling station, (2) the size of fueling station tank capacity which would frequently run out of CNG and the crew would have to wait extra time for it to refill, and (3) the Voyager payment cards are not accepted at all the stations and if they

are accepted sometimes card-rejection problems occur. Also, the crews outlined a number of design issues with the CNG sweepers, which if corrected, could significantly improve their productivity. The design issues with the CNG sweeper had to do with (1) its weight, making it difficult to pick up heavier items such as wood and requiring multiple runs to sweep the same location, (2) the trash bin for the CNG sweepers is smaller so a return trip to the yard to the dump the trash may be necessary, (3) capacity of the fuel tank for the CNG sweepers is smaller, and (4) the dust water control system does not shut down sometimes causing a waste of time to refill the tank. It is recommended that the complete list of design suggestions outlined in Section 3 be presented to CNG sweeper manufacturers to see if any of these problems can be corrected.

Our productivity comparison was based on lane miles (LAMI) data provided from IMMS. We analyzed resource usage data based on LAMI from 2002-2008 as recorded in IMMS. We focused on studying crews in which there was data for both diesel and CNG sweepers. After removing for outliers, five crews had over a 10% average reduction in their lane miles after switching to CNG sweepers, four crews had little change (within 10%), and one crew had over a 10% average increase in their lane miles. The crews which showed over a 10% reduction in lane miles had an average distance to the CNG fueling station of 4.7 miles as compared to the one crew which showed a significant increase in lane miles which had a distance of 3.9 miles to the fueling station. We qualify this comparison by first noting that we do not know for certain that these crews fill their tank at the closest CNG station and that the distance to the CNG station is only one factor that could affect the productivity of the sweepers. This analysis of the data was consistent with the anecdotal information that we received during our site visits.

On balance, the move to CNG sweepers has resulted in a reduction in the productivity of sweeping operations.

To offset the lost productivity, additional CNG sweepers will need to be purchased in District 7. For the five studied crews in the North Region where there existed pre- and post CNG sweeper usage data, the crews were 35% more productive in terms of LAMI when using diesel. Two additional sweepers will need to be purchased for the North Region to maintain the same productivity for these studied crews, assuming new routes can be created to better balance the workload of these crews. For the East region, the studied crews were 11.7% more productive in terms of LAMI when using diesel. One additional sweeper will need to be purchased for the East Region to maintain the same productivity for the studied crews, assuming new routes can be created to better balance the workload of these crews. We note that with additional equipment extra crews will need to be staffed. Since there was no pre- and post use data for the South and West Regions, no determination on the number of required CNG sweepers can be made at this time. We note that there can also be productivity improvements if some of the vehicle design suggestions outlined in Section 3 are made and the issues with the CNG fueling stations are resolved.

The cost analysis showed only significant differences in the purchase cost, with the CNG sweepers costing almost double than their diesel counterparts. Consistent with other applications, there is no significant difference between the maintenance costs of the diesel and CNG sweepers. They had equivalent maintenance costs despite the fact that the studied CNG sweepers had on average almost three times the monthly lane miles than the studied diesel sweepers. We note that no comparison on fuel costs was made since no data on fuel usage was provided.

Since it is clear that there has been some productivity reduction with the implementation of CNG sweepers and that the fueling stations contributed to this reduction, we recommend that Caltrans promote the use of more fueling stations. Only twenty out of the possible sixty CNG fueling stations located in the Los Angeles Area are currently being used, whereby creating an opportunity to reduce the distance to the fueling stations by promoting the use of these additional stations, which are not currently being used for a number of reasons, including the fact that some of the stations do not accept the payment cards. A mathematical model was developed to identify which of these stations Caltrans should focus on promoting their use. The analysis was only from the perspective of reducing the distance traveled to these stations and did not consider the degree of difficulty for Caltrans to negotiate with the respective parties to accept payment of their cards. Considering only the public CNG fueling stations, the analysis showed that there is no benefit in promoting more than six additional stations since the improved distance measure was not significantly reduced when seven or more stations were considered. The use of these additional six stations will reduce the total distanced traveled to the fueling stations from the yards by 32.1 miles. Considering both the public and private CNG fueling stations, the analysis showed that there is no benefit in promoting more than fourteen additional stations since the improved distance measure was not significantly reduced when fifteen or more stations were considered. The use of these additional fourteen stations will reduce the total distanced traveled to the fueling stations from the yards by 92.0 miles.

The analysis showed the assigned road miles to the crews vary significantly from region to region and from crew to crew. A better balance of the assigned miles to the crews could significantly improve the productivity of the crews. We developed an optimization model that determined the assignment of road miles to crews that minimized the total deviation of the crew miles from the average miles of the region. To minimize the disruption to current operations, we only considered shifting road miles from one crew to another that are in the same region and cover adjacent areas. In comparison to the current crew to road miles assignment the recommended solution provides an assignment that provides a significantly better balance of the routes. The improvement in the balance of the routes is 15.15%, 57.72%, 47.32%, and 44.33% for the North, South, East, and West regions, respectively.

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Compressed Natural Gas (CNG) Sweeper Operation

1. Introduction

Several counties across California have begun to switch from diesel-powered street sweepers to CNG (Compressed Natural Gas) street sweepers, in order to comply with Federal and State air quality regulations. A diesel street sweeper generates large amounts of particulate matter both as a component of diesel exhaust and as dust that is produced during sweeping operations. Much of this particulate matter consists of particles less than 10 microns in size (PM10). PM10 can have serious health and environmental impacts. The measurement of atmospheric PM10 levels is used to determine whether regional air quality meets Federal and State standards. In addition to their CNG-powered engines, which are inherently low in PM emissions, the new street sweepers also include a dust-control system that significantly reduces the amount of PM10 that is generated during sweeping operations. These sweepers comply with South Coast Air Quality Management District (SCAQMD) Rule 1186, which is a stringent PM emissions testing and certification protocol that has been adopted by regulatory agencies throughout California.

A CNG street sweeper costs more than the equivalent diesel sweeper. However, the extra investment for a 1186- certified street sweeper is offset by the savings in emissions. For instance, for a distance of 10,000 miles swept annually, engine emissions from a CNG sweeper are lower by 458 lbs. of NO_x per annum and annual sweeping emissions are lower by 500 lbs. of PM10 per annum. Fuel for CNG sweepers costs significantly less than diesel. As of February 2009, CNG costs around $1.65 per gasoline gallon equivalent (GGE) around downtown Los Angeles, while diesel costs around $2.28 per gallon in California. The State has around 200 CNG fueling stations, of which a 100 are located in the Southern California region. However, Caltrans currently uses only 20 of these CNG fueling stations located across District 7 (Los Angeles and Ventura Counties).

Reports from the field indicate that the productivity of the CNG sweepers do not match the capabilities of the diesel-powered street sweepers. A number of reasons have been cited for this decrease in productivity. They include:

- Smaller tank size for the CNG sweepers requiring more frequent trips to the fueling stations
- Significantly less options for fueling for CNG sweepers as compared to diesel
- More down time due to maintenance for the CNG sweepers
- Long queuing time at the CNG fueling stations

The objective of this study is to assess the productivity (as measured in vehicle miles sweeping per vehicle) and cost of using the CNG sweepers with the diesel powered sweepers and to optimize operations of the CNG sweepers to improve their efficiency. The specific objectives of this study as listed from Caltrans' problem statement are:

1) Determine the production efficiency of Caltrans sweeping operations with CNG sweepers and compare that with the same sweeping operations using Diesel sweepers
2) Determine the lifecycle cost of operating CNG sweepers as compared to operating Diesel sweepers

3) Determine if Caltrans should purchase more CNG sweepers to offset lost production and how many are needed
4) Determine if Caltrans should establish or promote more fueling facilities and where
5) Determine how Caltrans can optimize the sweeping operations in the South Coast Air Quality Management District to maintain clean pavement surfaces
6) Determine if Caltrans should move sweepers to be based in different locations
7) Determine if Caltrans could route its CNG sweepers differently to maximize production

This document reports our findings for these seven objectives. We report our findings on the productivity and the cost of operating CNG sweepers. Our study is based on analyzing data collected from the Caltrans software system, IMMS, on the pre-use of the CNG sweepers with the post purchase of the equipment and on site visit interviews at the supervisor level in District 7. We partially report our findings on the number of needed CNG sweepers to offset lost productivity since we did not have pre and post-use data of CNG sweepers for all the regions in District 7. We developed mathematical models to make specific recommendations regarding (1) the locations where Caltrans should promote the use of CNG fueling stations, and (2) the rebalancing of the routes.

The remainder of this report is organized as follows. We first review the literature (Section 2) that documents CNG sweeper installations at any other agency within the United States. The purpose of this review is to understand the issues that other agencies may have experienced. Next, we summarize our observations at the two site visits that were conducted (Section 3). We then present the findings of our productivity analysis (Section 4) based on lane miles. The cost analysis, which is solely based on the purchase and maintenance cost, is presented next (Section 5). We note that no comparison of fuel costs was made since no data on fuel usage was provided. An associated analysis that gives the savings in travel distance if alternative CNG fueling stations are used is shown in Section 6 and in the same section we next present a mathematical model and the analysis for the determination of which additional CNG fueling stations should be promoted by Caltrans. Section 7 presents the model and the analysis for the rebalancing of the existing routes to improve overall system efficiency. We conclude this report with a summary of our findings to date and directions for future research and work.

2. Literature Review

This summary is based on a literature review on the implementation of CNG (Compressed Natural Gas) vehicles in the United States. This review is primarily based on three reports: one general report about the implementation of the CNG vehicles in the United States and two specific evaluations on the performance of CNG vehicles implemented by WMATA (Washington Metropolitan Area Transit Authority) and UPS. Although none of the studied reports focuses on street sweepers, their experience in using CNG vehicles provides useful insights in successful implementation of these types of vehicles.

Eudy (2002) in the report "Natural Gas in Transit Fleets: A Review of the Transit Experience" summarized survey findings and interviews of CNG implementations in transit agencies. Interviews of 53 agencies were conducted from April to June 2001. Forty-two of the agencies used CNG buses, comprising 19% of their fleet and another 2.5% consisted of LNG buses. Twenty-four of these 42 agencies stated that the use of CNG buses had been successful while the others stated it was still a challenge to use them.

Many factors such as fleet size, training, fueling infrastructure, public relations, and cost influenced the successful implementation of CNG buses. First, the size of the fleet played a major role. Eighty percent of the agencies that have fewer than 10 CNG buses reported challenges with their implementation. The reason for this outcome might be that the maintenance staff was not very familiar with the vehicles because of the fewer CNG vehicles. It is difficult for an agency with a small fleet size to justify an extensive training program.

An on-site fueling station is one critical component of successfully operating CNG buses. In fact most of the 42 agencies have an on-site fueling station with only seven not having this capability. Of these seven agencies, six reported challenges with using CNG buses and the one that reported successful implementation is adding an on-site fueling station. Generally, on-site fueling is significantly more convenient in operation than the off-site fueling.

From a cost perspective, most agencies reported that the CNG vehicles were more costly than their diesel counterpart in terms of both purchase and operating cost for both the success and challenge groups. The purchase cost of a CNG vehicle was typically on an average $46,000 more expensive. There was a wide variation in the reported operating cost due to the variation in fuel prices across the country. In a number of agencies that reported successful implementation of CNG buses, the savings in fuel costs compensated for the increase in maintenance costs. Due to extensive training programs, these agencies were able to identify effective strategies in reducing their maintenance costs (e.g., the CNG buses require less oil and filter changes) and develop effective diagnostic techniques for proper maintenance.

One reported side benefit of implementing CNG buses was the good public relations it provided to the agency. Most of the agencies that reported this benefit were from the successful implementation group.

In summary, the critical factors that determine successful implementation of CNG buses are proper training of maintenance personnel, sufficient number of fueling stations and in particular access to an on-site fueling station, and a commitment to a natural gas program by the agency. From the survey results, it is clear that CNG buses are here to stay as 69% of the survey agencies plan to purchase extra CNG buses. Both political and environment reasons impacted their decision to purchase additional CNG buses.

Chandler and Eberts (2006) in the report “Washington Metropolitan Area Transit Authority (WMATA): Compressed Natural Gas Transit Bus” made evaluations between diesel, CNG Cummins Westport, Inc. buses and CNG John Deere buses in WMATA’s Bladensburg depot. In 2002, WMATA had 164 CNG buses in operation in the Bladensburg depot with another 250 beginning operation in another depot. They randomly selected five buses from each group from the Bladensburg depot. Table 1 provides the details of the selected buses. Note that the evaluation period for CNG-Deere buses was only for six months because it had not been operational for a significant period of time at the time of this study and they did not want to consider the initial implementation period.

Table 1. WMATA Evaluation Information

Vehicle Information	Diesel	CNG-CWI	CNG-Deere
Number of buses in study	5	5	5
Model year	2000	2001	2002
Start date of operation	8/2000	8/2002	2/2003
Evaluation Period	9/01-8/02	6/03-5/04	4/04-9/04

The evaluation of the cost was only based on the operating cost of the vehicles which included the fuel and maintenance costs. The maintenance cost included the costs of preventive maintenance inspections (PMI), engine- and fuel-related cost, cab, body, accessories, hydraulics, brakes, etc. Table 2 shows the summary of the costs and the MPEG (miles per diesel gallon equivalent) of the three kinds of vehicles.

Table 2. WMATA Total Operating Cost

Study group	MPEG	Fuel cost ($/Mile)	Maintenance cost ($/Mile)	Total cost ($/Mile)
Diesel (Evaluation Period)	2.84	0.26	0.59	0.85
Diesel (Representative)	2.84	0.47	0.59	1.06
CNG-CWI	2.32	0.54	0.52	1.09
CNG-Deere	2.39	0.56	0.58	1.14

In Table 2, the difference between diesel (evaluation period) and diesel (representative) was the fuel cost. The diesel (evaluation period) used the actual diesel fuel cost during the evaluation period of the diesel buses, which was $0.75/gal. The diesel (representative) used the diesel fuel cost during the evaluation period of the CNG buses which was $1.33/gal. The CNG fuel cost also included the electricity cost for the CNG compressor station. Note that the maintenance cost for the CNG buses were typically less than the diesel and the difference in fuel cost would be significantly different in today's prices.

The study did not consider some of the fixed costs such as the $4 million spent for the CNG fueling facility and around $11.6 million used for modifications to the Bladensburg facility. Furthermore, CNG buses cost around $40,000 more to purchase. Overall, WMATA was pleased with their implementation of CNG buses. Their personnel were well trained and quickly became familiar with the CNG buses and there was good coordination and technical support with the manufacturers.

Chandler, Walkowicz, and Clark (2002) in the report "United Parcel Service (UPS) CNG Truck Fleet: Final Results" conducted an evaluation study between diesel and CNG delivery vehicles in three different facilities in Connecticut: Windsor, Hartford, and Waterbury. At the time of the study, the Windsor facility used only diesel vehicles, the Hartford facility had 34 diesel vehicles and 101 CNG vehicles, and the Waterbury facility had about 180 vehicles, 85 of which ran on CNG. The CNG vehicles were purchased from Cummins Westport, Inc. Table 3 shows the details of the evaluation data.

Table 3. UPS Evaluation Information

Vehicle Information	Diesel	CNG-CWI
Number of buses in study	3	13
Model year	1996	1997
Start date of operation	4/96	4/97
Fuel data period (different between vehicles)	12/98-6/99; 5/00-10/00	9/98-6/99; 5/00-10/00
Maintenance data period (different between vehicles)	1/97-7/99	1997-2000
Area of operation	Windsor, Connecticut	Hartford, Waterbury, Connecticut

Similar to the other study, the operating cost of the vehicles primarily consisted of the fueling and maintenance costs. Maintenance data included preventive maintenance inspections, unscheduled maintenance, and road calls. Table 4 shows the costs and the MPEG of the three kinds of vehicles. In Table 4, the diesel fuel cost reported during the data collection was $1.02/gal in 1998 to $1.25/gal in 2000 while the CNG fuel cost ranged from $0.39/standard cubic foot (scf) to $0.60/scf.

Table 4. UPS Total Operating Cost

	MPEG	Fuel cost ($/Mile)	Maintenance cost ($/Mile)	Total cost ($/Mile)
Windsor Diesel	11.22	0.107	0.167	0.274
Hartford CNG	8.14	0.111	0.215	0.326
Waterbury CNG	8.09	0.112	0.157	0.269

According to the data in Table 4, it can be seen that the maintenance cost of the CNG trucks at Hartford was 29% higher than that of diesel trucks while the CNG costs was 6% lower at Waterbury. The Waterbury facility had lower maintenance costs on a per mile basis for a number of reasons including the fact that they had more total vehicle usage. Because of the higher maintenance cost, Hartford also had the highest operating cost. It should be noted that UPS spent 500k each on two CNG fueling stations in Hartford and Waterbury. Although CNG vehicles generally cost more than the diesel vehicles, UPS plans to continue using CNG vehicles in delivery service with today operating more than 1,500 alternative fuel vehicles companywide.

In conclusion, the two specific cases cited above had reasonably successful implementations of CNG vehicles. One key ingredient to their success was developing an extensive training program for their personnel. The other common point of both cases is the number of CNG vehicles in the operating area. Both have about 100 CNG vehicles in operation. The advantage of having more CNG vehicles is that the maintenance professionals are more familiar with the problems and the infrastructure supporting the CNG is used more often (e.g. justifying an on-site fueling station). In both cases, the cost of the infrastructure is expensive and not included in the economy analysis. It should be noted that the operating costs would be significantly different today due to changes in fuel prices from the time of the study.

3. Site Visits

To date two site visits in District 7 were conducted. The details of these site visits are listed below.

Region	Location	Date
East	10903 Florence Avenue, Downey, CA 90241	10/30/08
South	11514 Felton St., Hawthorne, CA 90501	12/11/08

3.1 East Region

Our research team met with the supervisor and the crew at their site in Downey on 10/30/08. Characteristics of their work environment are listed below.

Work Environment

- 1 CNG sweeper
- Work 4-5 hours/day, 5 days/week, 3 weeks/month
- Sweep on freeways: 1 sweeper, 2 vehicles for protection and one for picking up trash. The vehicle for picking up trash contains two crew members, while all others contain one.
- They sweep 15 miles on freeway 5 and 5 miles on freeway 605.
- CNG vehicles are kept in operation for 5 years.
- They use the same routes as the previous routes with diesel.
- They typically fill up the fuel tank once at the end of the day.

The general consensus from our discussions is that this crew did not have a favorable opinion of the CNG sweepers for two primary reasons: problems with (1) the fueling station and (2) the design of the CNG sweepers. These two types of problems are further elaborated below.

Fueling Problems

- Fueling station is 5 miles away.
- The station may not have enough CNG to completely fill the sweeper tank. If fueling station was just recently used, it takes longer to fill since the crew has to wait for the station tank to refill.
- Not all CNG fueling stations accept the Voyager payment card.
- It takes a minimum of 5 to 10 minutes to fuel CNG and the wait may be longer.

Design and Quality Problems

- CNG sweeper is not designed for use on the freeway; sometimes it has difficulty reaching higher speed.
- The average speed on the freeway for CNG is 3-4 miles per hour while it was 4-5 miles per hour for diesel.
- Due to weight issues the durability of the CNG is poor and cannot pick up heavier material such as wood.
- Due to quality issues the crew may have to cover the same portion of the road multiple times.
- The trash bin for the CNG is of a smaller size than that of the diesel, so the CNG may have to make an additional return trip to the yard to dump trash.
- Fuel tank capacity is not large enough to contain more natural gas and is too heavy.

- Fuel system might leak.
- The front of the sweeper is longer than the diesel making it harder to turn around.

3.2 South Region

Our research team met with the supervisor and the crew at their site in Hawthorne on 12/11/08. Characteristics of their work environment are listed below.

Work Environment

- Crew 690 is the cost center which takes care of the whole area.
- There are 6 CNG sweepers in the yard.
- Other yards in the area only have one sweeper for emergency use.
- There are 7 persons in the crew.
- Work hours from 5 am -1:30 pm, 5 days/week
- 1 lead vehicle, 2 sweepers (1 at the left side, 1 at the right side), and 2 back up
- Since there are enough backup CNG sweepers, when one goes down, they can use one of the backups so there is no downtime for maintenance.

The general consensus from our discussions is that this crew was much more favorable to CNG sweepers than their counterparts in the East Region. It could primarily be due to the fact that the CNG fueling station is closer (only 2 miles away as opposed to 5 miles for the East Region). Besides waiting time problems at the fueling station, this crew also mentioned issues with card rejection at the station. The design and quality problems listed here are directly taken from a list that was given to us during our site visit.

Fueling Problems

- CNG takes 15 minutes to fill up while diesel takes 5 minutes.
- Sometimes card-rejection problems do occur. (This might be due to the computer system being off-line)

Design and Quality Problems (these comments are directly taken from a sheet given to us by the crew)

- The rear engine exhaust pipe has come loose causing a fire and some heat damage.
- The flight belt material needs to be upgraded to the type that was previously used. The type that is used now has no steel reinforcement in it (like steel belted tires). This will help the belts last longer without breaking.
- The flights should be made of a stronger light weight material. Even when sweeping normal materials found on the freeway they bend easily.
- The sweepers using the natural gas seem to have low power issues.
- The cleanup water pressure for cleaning the flights does not have enough pressure to clean them properly.
- The 2 inch hose that is used for filling the dust control water reservoir should be larger to quicken the filling process.
- The steering shaft manually serviced "zert" fitting is located in a place that is difficult to reach.
- The dust control water system does not shut off when the brooms are raised. It

previously would shut off. This causes water to be wasted and un-necessary down time for refilling the tank. On previous units, the water would automatically shut off after raising the brooms.

- There is frequent down time due to flat tires and waiting for repairs. It is a safety issue as it might go down in a hazardous traffic situation. It would be good if use a better type tire that is less prone to have flats. For example, a fill material inside the tire that seals holes, or a solid rubber tires. It would also be good to have a magnetic type strip mounted in the front that would pick up sharp metal object to lessen the frequency of flat tires.
- The water control valves that are mounted inside of the cab do not adjust properly. The output is the same regardless of what position they are turned or set in. Water usage should be able to be adjusted depending on what is being swept. Using more water than needed increased the refilling frequency.

Noticed improvements

- There seems to be less hydraulic hose breakages.
- There are less hydraulic overheating problems.
- The air conditioning condenser is located in a better location. Previously it was mounted on top of the cab. When mounted there, a lot of debris would collect on it.

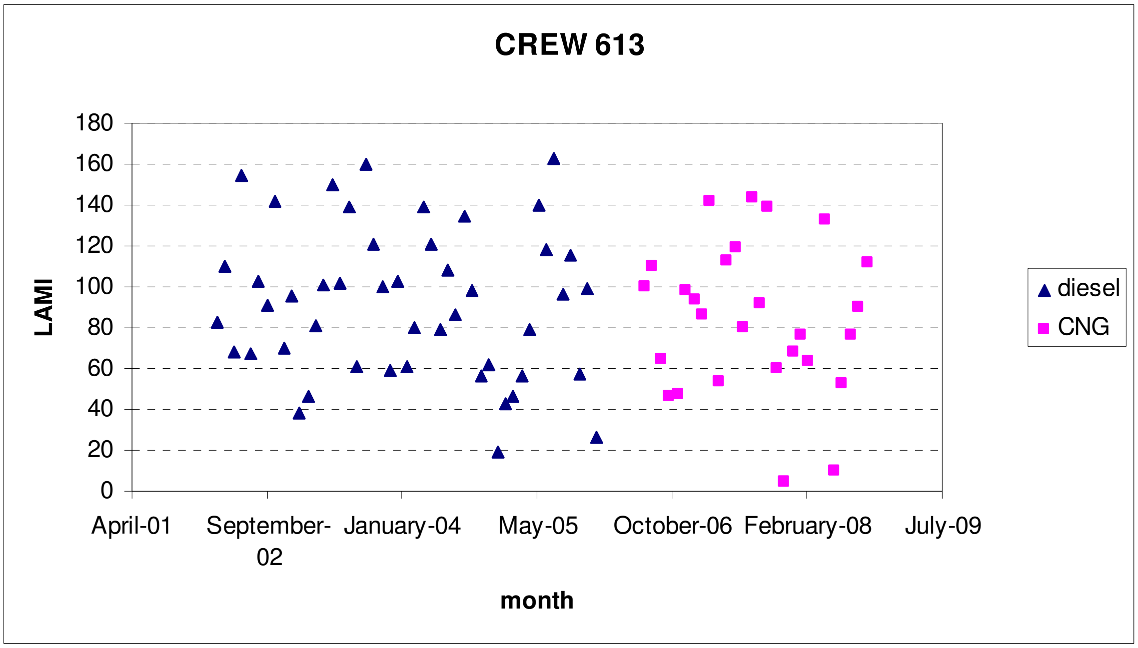
4. Productivity Analysis

Our productivity analysis is based on collected data from the Caltrans software system, IMMS, of pre-usage of the CNG sweepers with the post purchase of the vehicles and on site visit interviews at the supervisor level in District 7. We analyzed resource usage data based on LAMI (lane miles) from 2002-2008. We focused on studying crews for which there was data in both diesel and CNG sweeper LAMI data files, in order to compare the pre- and post-usage data of CNG sweepers. Table 5 lists the ten crews and their locations which satisfied this criterion. Of the four regions in District 7 (South, North, East, and West), we had pre- and post-usage data of CNG sweepers for only two of the regions. The last column shows the average monthly LAMI for the studied crews. We note that the total average monthly LAMI for each region as recorded in IMMS is 1685 (South), 751 (North), 1347 (East), and 636 (West). Hence, our pre- and post-data analysis from Table 5 represents 64.2% of the LAMI for the North Region and 63.4% of the LAMI for the East Region and no information on the South and West Regions.

Table 5. Studied Crews

Crew	Address	City	Code	Region	LAMI
613	2133 Riverside Drive	Los Angeles	90039	North	89.2
622	2133 Riverside Drive	Los Angeles	90039	North	47.2
626	11930 Blucher Street	Granada Hills	91344	North	155.1
633	23922 San Fernando Rd.	Newhall	91321	North	89.8
638	11210 Moorpark Street	North Hollywood	91602	North	101.2
645	10903 Florence Ave.	Downey	90241	East	111.1
652	4425 E. 3rd Street	Los Angeles	90022	East	115.3
657	1940 S. Workman Mill Rd.	Whittier	90601	East	148.9
663	2650 S. Garey Ave.	Pomona	91766	East	105.0
669	850 E. Huntington Drive	Monrovia	91016	East	231.1

Figure 1. Plot of Total Lane Miles per Month



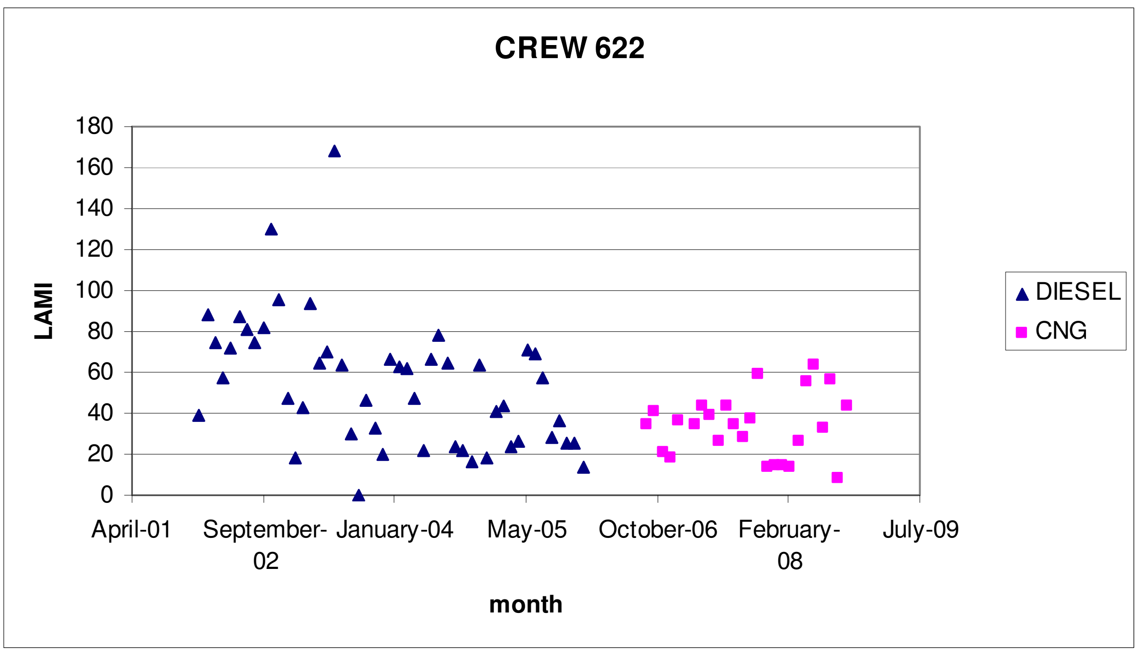
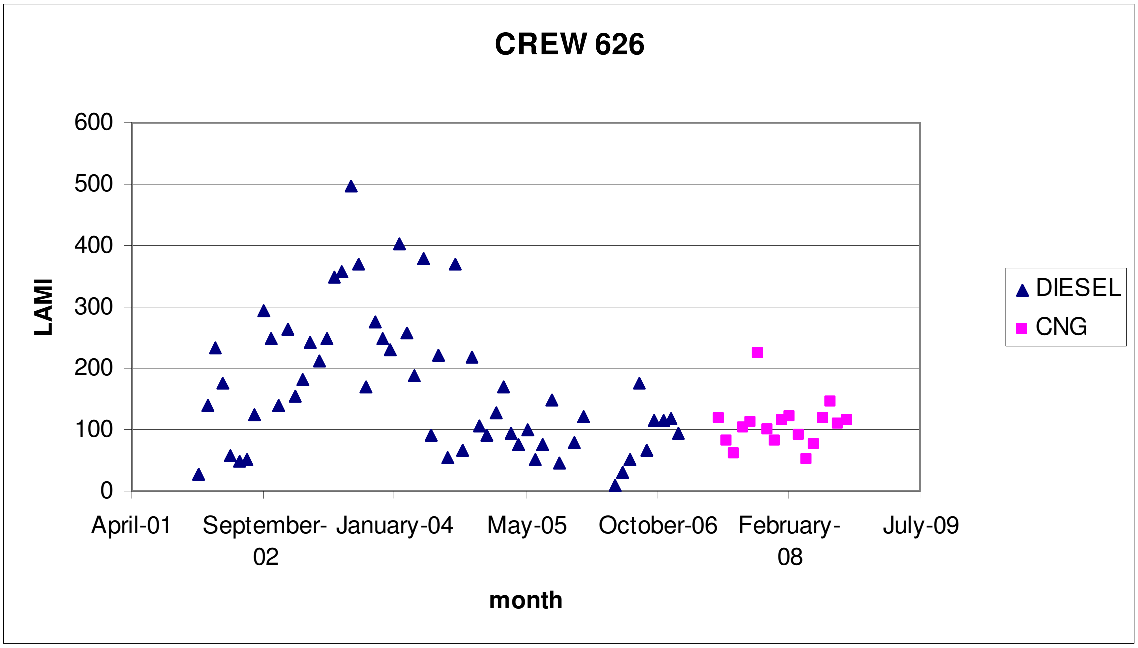


Figure 1. Plot of Total Lane Miles per Month



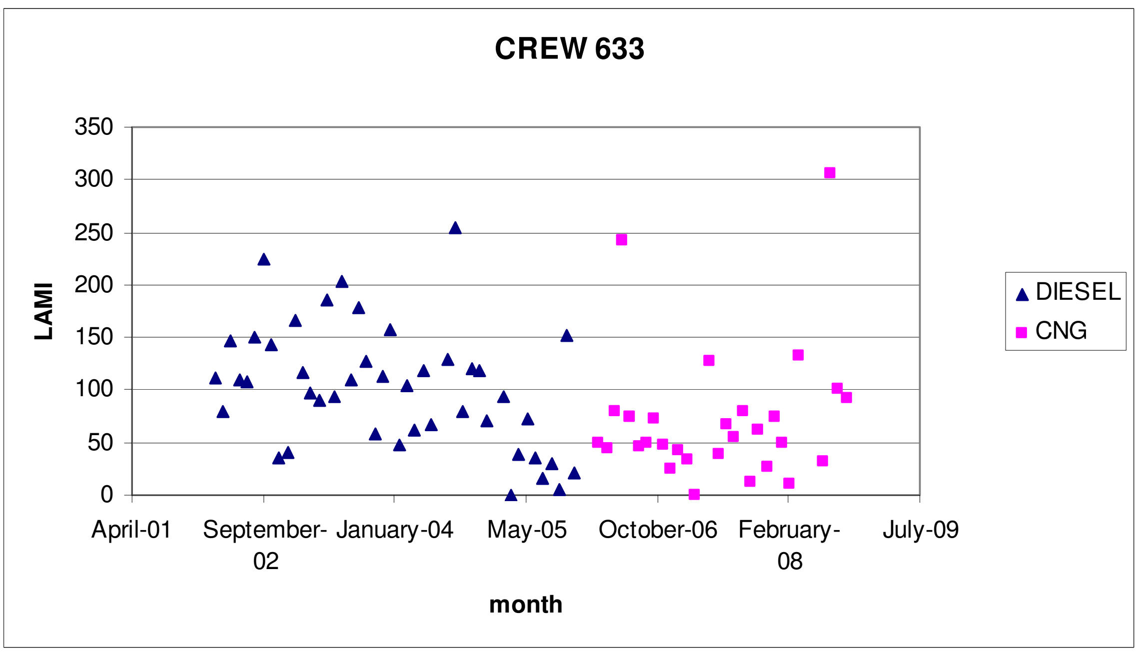
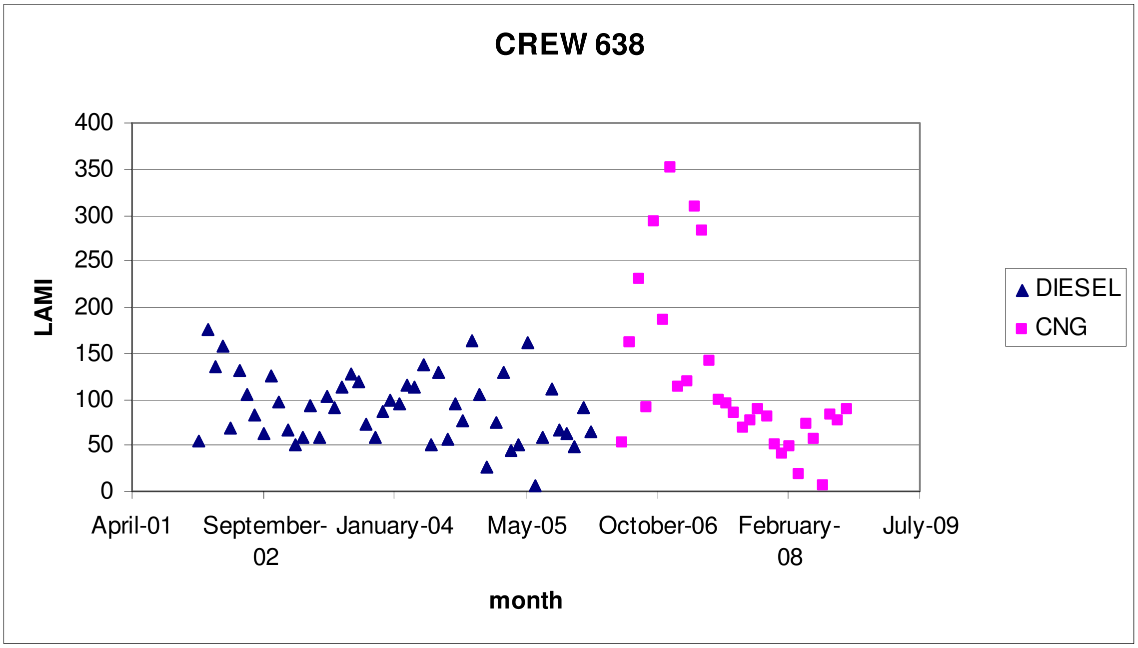


Figure 1. Plot of Total Lane Miles per Month



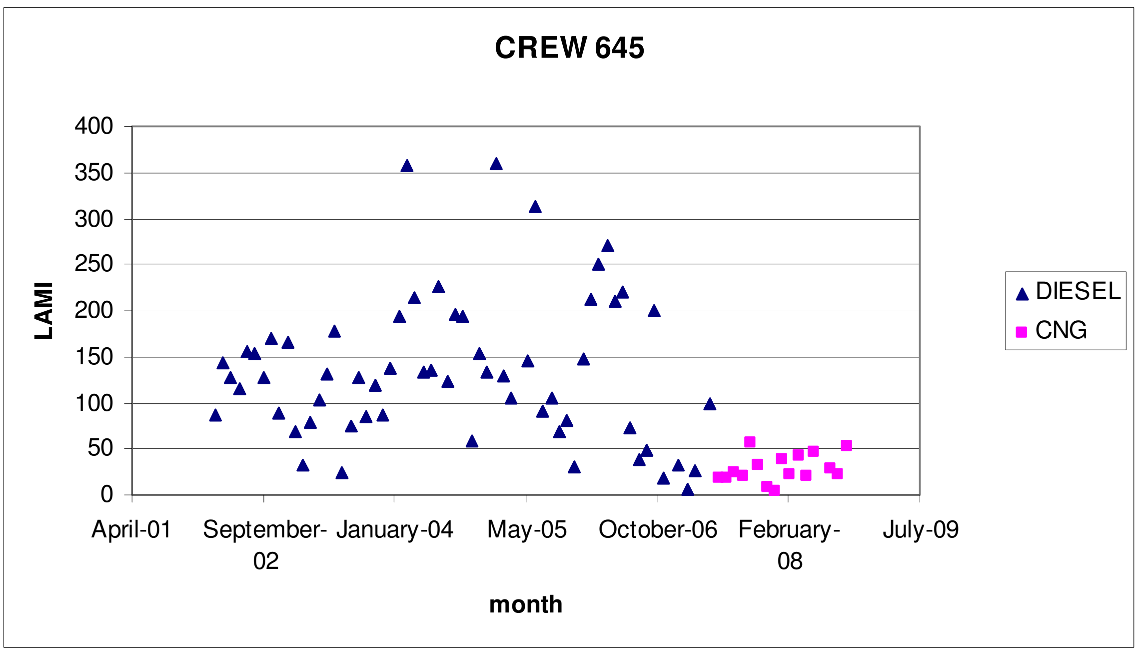
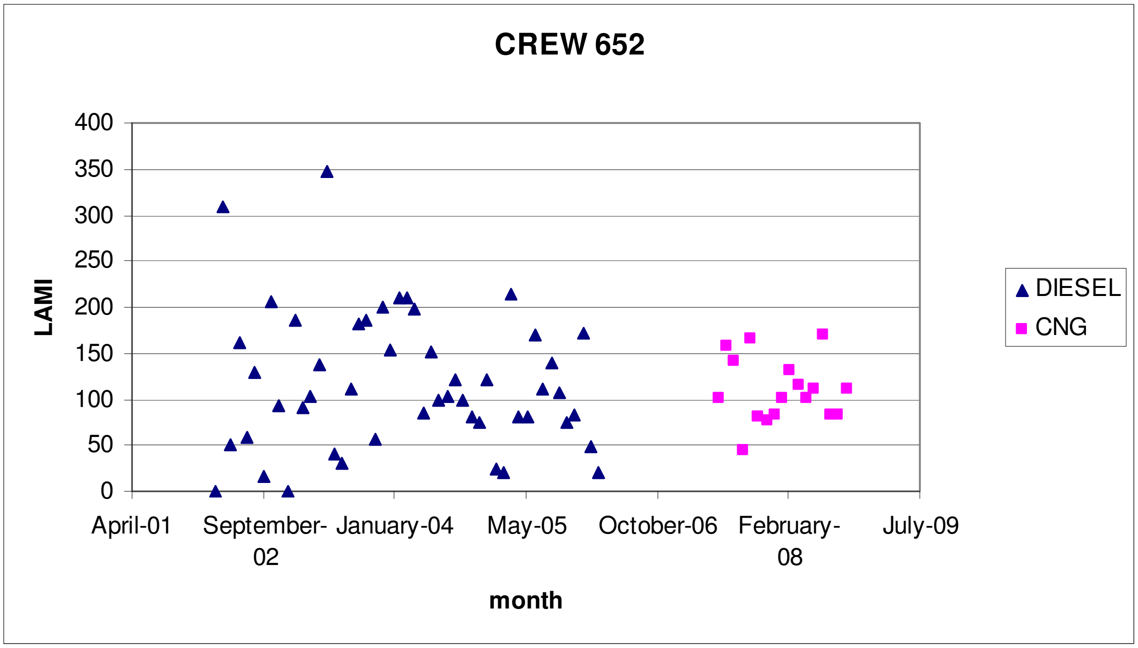


Figure 1. Plot of Total Lane Miles per Month



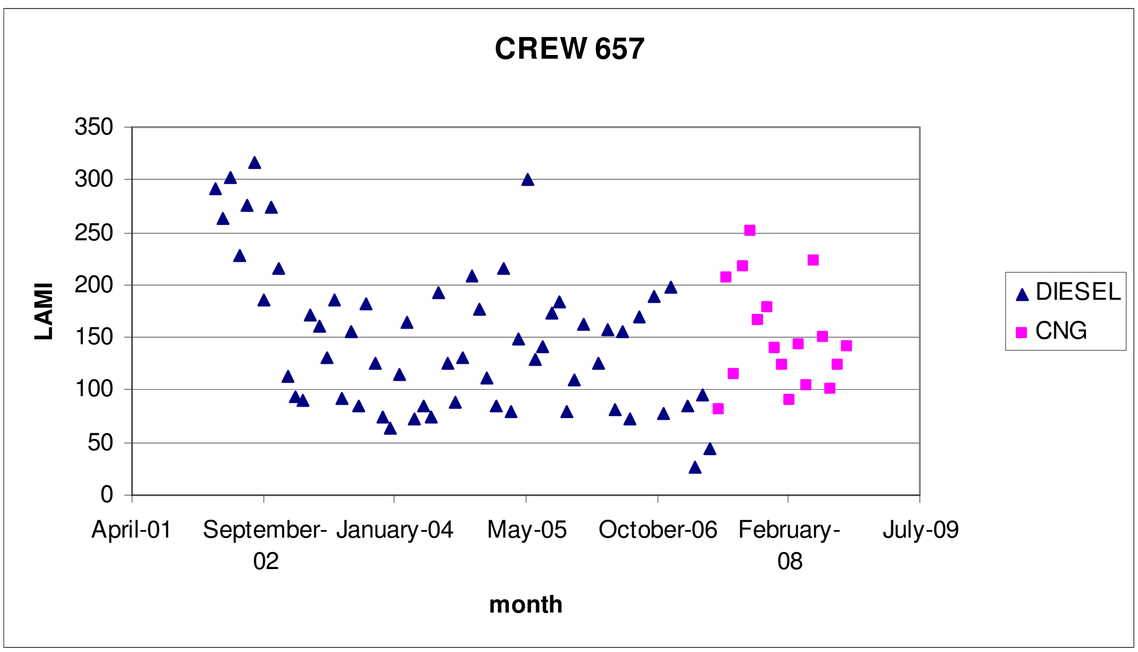
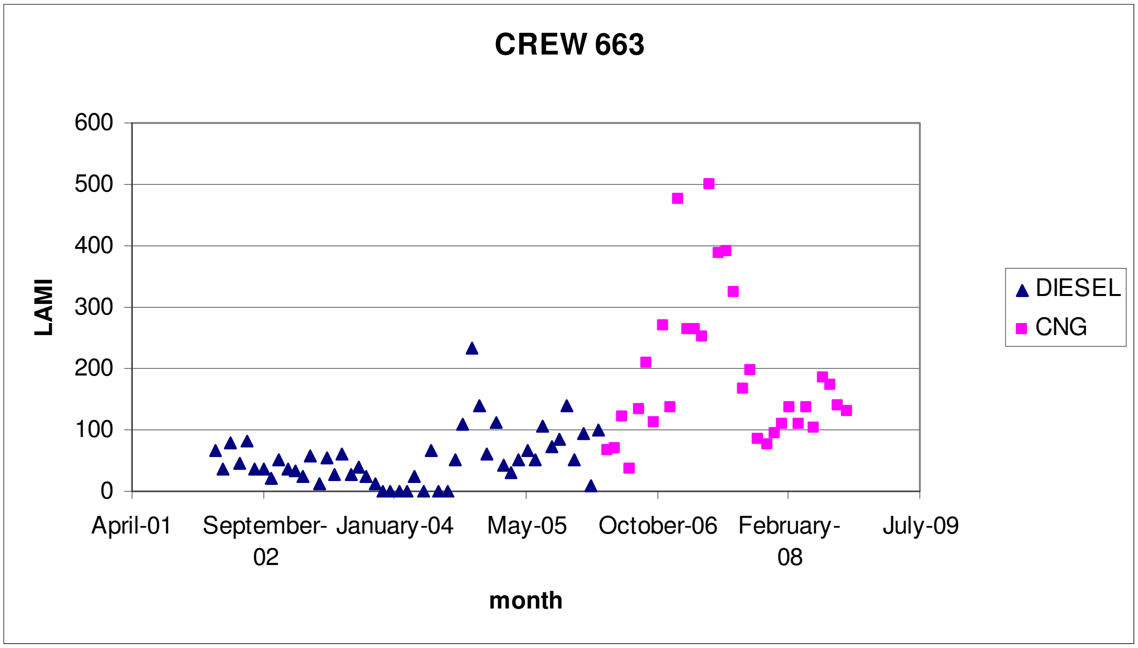


Figure 1. Plot of Total Lane Miles per Month



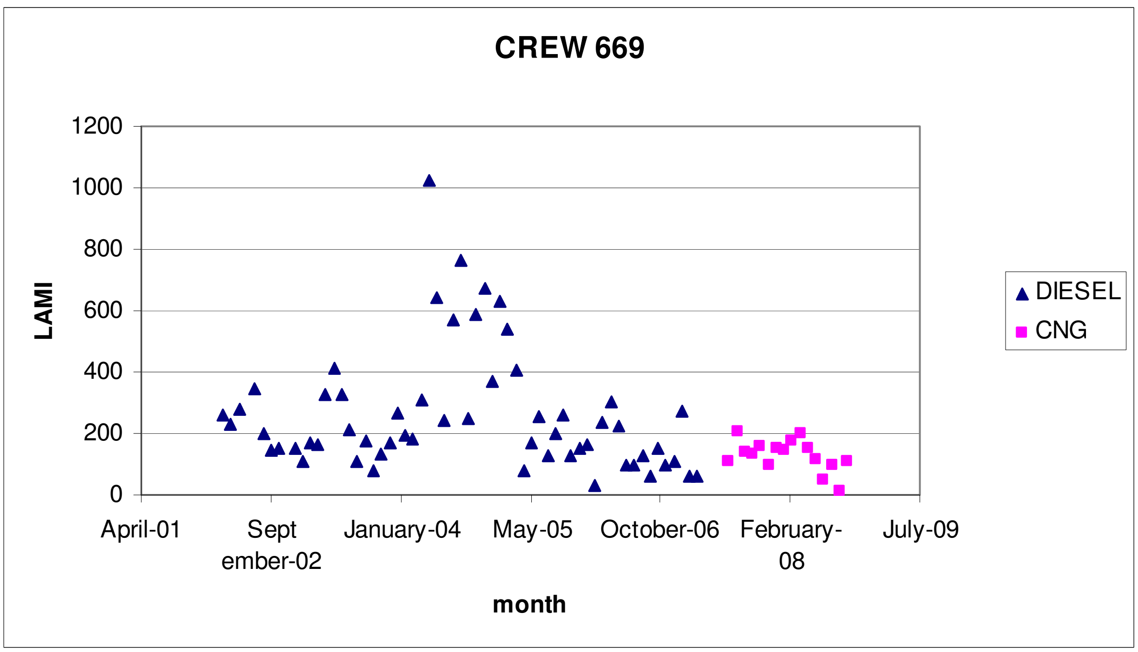


Figure 1 plots the total lane miles for each month for each crew. The data with triangle symbols are for diesel sweepers and with square symbols are for CNG sweepers. Most of the plots show a trend towards a reduced LAMI when switching to CNG sweepers except for crews 638 and 663. The average monthly LAMI for pre- and post-CNG usage for each crew is shown in Table 6. The results in the diesel column are the average for the diesel sweeper for a particular crew, while the next column is the average for the CNG sweepers. The percentage column represents the percentage change in LAMI from diesel when implementing CNG. In the "Regular" column in Table 6, the average is computed using all the LAMI data. When considering all the data, five crews (622, 626, 633, 645, and 669) had over a 10% average reduction in their lane miles, three crews had little change (within 10%), and two crews (638 and 663) had over a 10% average increase in their lane miles. However, a closer look at the plot for 638 shows that the increased lane miles is primarily due to a large spike in the lane miles in the October 2006 time period. This may suggest some outliers in the data so we conducted an Interval Quartiles Range (IQR) test which removes all data that is greater than the 75th Quartile + 1.5*(difference between the 75th Quartile and 25th Quartile). In the "IQR" column in Table 6, the averages are computed after removing the outliers. Note now that crew 638 no longer shows a significant improvement in lane miles when the outlier is removed. Crew 663 is the only crew that stills shows a significant increase in lane miles with CNG sweepers. With the removal of outliers, the same five crews (622, 626, 633, 645, and 669) still had an average reduction in lane miles of greater than 10%.

We note that one of the crews (645) that had a significant reduction in the lane miles when using CNG sweepers is the crew that we visited in the East Region. One of the biggest issues that they had with the CNG sweepers was the issues with the fueling station including distance to the station. We next examine this component. For crew 663 the distance to its closest CNG station is 3.9 miles while the average of this measure for the crews that showed a considerable reduction in their LAMI miles was 4.7 miles. We qualify this comparison by first noting that we do not know for certain that these crews fill their tank at the closest CNG station, and that the distance to the CNG station is only one factor that could affect the productivity of the sweepers. Other factors such as the utilization and reliability of the fueling station also play a major role in impacting the productivity of the CNG sweepers. In the next section, we show a complete comparison of the distances from the yard to the CNG fueling stations for all the crews in District 7.

Table 6. Summary of the Averages of the Lane Miles

Crew	REGULAR			IQR		
	DIESEL	CNG	percentage	DIESEL	CNG	percentage
613	92.1	84.3	-8.4	92.1	84.3	-8.4
622	54.1	33.7	-37.8	50.1	33.7	-32.8
626	169.2	107.6	-36.4	163.3	107.6	-34.1
633	101.9	71.4	-29.9	98.4	56.4	-42.6
638	90.6	119.5	32.0	90.6	83.3	-8.0
645	133.0	28.6	-78.5	125.1	28.6	-77.1
652	117.3	109.4	-6.7	108.3	109.4	1.0
657	148.4	150.5	1.4	147.7	150.5	1.9
663	52.3	188.4	260.2	52.3	144.7	176.7
669	258.9	128.3	-50.4	193.9	128.3	-33.8

Clearly to offset the lost productivity, additional CNG sweepers will need to be purchased in District 7. From Table 6, the total monthly LAMI for the five studied crews in the North region is 494.5 miles when using diesel sweepers and 365.3 when using CNG sweepers. Hence, for these crews, they were 35% more productive in terms of LAMI when using diesel. (We note this productivity value is determined after removing for outliers). Two additional sweepers will need to be purchased for the

North Region to maintain the same productivity for the studied crews, assuming new routes can be created to better balance the workload of these crews. If the routes stay the same, then it is recommended that these sweepers be added in the area processed by crews 626 and 633. We note that there can also be productivity improvements if some of the vehicle design suggestions outlined in Section 3 are made and the issues with the CNG fueling stations are resolved. The latter issue is the focus of Section 6.

With similar analysis, the total monthly LAMI for the five studied crews in the East region is 627.3 miles when using diesel sweepers and 561.5 when using CNG sweepers. Hence, for these crews, they were 11.7% more productive in terms of LAMI when using diesel. One additional sweeper will need to be purchased for the East Region to maintain the same productivity for the studied crews, assuming new routes can be created to better balance the workload of these crews. If the routes stay the same, then it is recommended that this sweeper be added in the area processed by crew 645. Since there was no pre- and post use data for the South and West Regions, no determination on the number of required CNG sweepers can be made at this time.

5. Cost Analysis

Of the roughly 35 sweepers in District 7, we received purchase cost and maintenance cost data for 10 of the sweepers, evenly divided between diesel and CNG. The data set did not include any fuel cost consumption data. Hence, no comparison based on this measure was made. Table 7 provides a summary of the purchase and the maintenance costs for each of the studied sweepers. All the studied sweepers were purchased between June 2003 and January 2006. As the table shows, the primary difference in the cost for these two types of sweepers is the purchase cost. The last column shows the monthly average LAMI for each piece of equipment. The maintenance costs are for incurred expenses that are not covered by the manufacturer's warranty. We note that despite the fact that the studied CNG sweepers had on average almost three times the monthly lane miles than the studied diesel sweepers, the CNG sweepers had a slightly lower maintenance cost. A particular crew may use more than one piece of equipment which helps explain the difference in lane miles for the different sweepers.

Table 7. Purchase and Maintenance Cost Summary

equip	type	crew	purchase date	date of latest maintenance record	purchase cost	monthly average maintenance cost	monthly average LAMI
7000356	diesel	632	28-Apr-04	8-Dec-08	162987.25	959.54	26.9
5689019	diesel	723	13-Jun-03	7-Nov-08	145835.79	1651.28	30.8
5689022	diesel	632	13-Jun-03	10-Dec-08	145911.51	910.46	35.6
7002040	diesel	620	15-Oct-05	20-Nov-08	178535.80	1220.76	91.1
5684102	diesel	735	14-Oct-03	21-Nov-08	146510.38	1086.07	42.8
average	**diesel**	**-**	**-**	**-**	**155956.15**	**1165.62**	**45.4**
7002020	CNG	642	21-Jan-06	5-Dec-08	311992.25	1462.14	292.0
7002021	CNG	613	21-Jan-06	19-Nov-08	312065.25	921.33	155.4
7002022	CNG	633	3-Jan-06	5-Dec-08	312209.55	1460.94	75.0
7002023	CNG	690	21-Jan-06	29-Oct-08	312047.00	672.40	56.2
7002027	CNG	690	21-Jan-06	16-Oct-08	312135.55	895.13	84.7
average	**CNG**	**-**	**-**	**-**	**312089.92**	**1082.39**	**132.7**

6. Location of CNG Fueling Stations

Since distance to the fueling station from the yard can play a major role in impacting the productivity of the CNG sweepers, we compare the distances to the CNG fueling stations for each of the crews in District 7. Table 8 shows the location of the 20 CNG fueling stations in the area that are used by Caltrans. Table 9 then shows the distance from the yard of each crew to each fueling station. We note that we only list the crews that primarily do the sweeping operations and do not list the other crews such as emergency crews.

The CNG fueling stations listed in Table 8 are not all the CNG fueling stations in the area. The U. S. Department of Energy lists additional CNG fueling stations. Table 10 lists these additional stations that could improve the closest distance measure to the sweeper yards. In Table 11, the columns under "Provided Stations" list the distances of the three nearest CNG fueling stations from the yard that were provided by Caltrans. The columns under "Public Stations" list the distances of the three nearest stations when the additional public CNG fueling stations listed on the U. S. Department of Energy website are added to the analysis. The columns under "All Stations" lists the distances of the three nearest stations when both the additional public and private CNG fueling stations are added to the analysis.

A superscript in Table 11 means that the distance from the corresponding crew to its nearest station could be improved by using fueling stations other than the ones currently used by Caltrans. The superscript number refers to the station number listed in Table 10 that would result in the reduction in travel distance if used. The improvement in the travel distances is summarized in Table 12. For example, adding just the public

CNG fueling stations listed in Table 10 reduces the total distance to the nearest CNG fueling station by 32.2 miles and the total distance to the second nearest station by 146.5 miles. This translates to a 9% reduction in travel distance to the nearest station when considering all crews. As a percentage of only the crews were an improvement in the travel distance is made, this percentage becomes 31%. When considering all the stations (both public and private), the total nearest distance reduces by 92.1 miles.

Table 8. CNG Fueling Station Information

NO.	Name	address	City	Zip
1	Bellflower-California Clean Fuels	153303 Woodruff Avenue	Bellflower	90706
2	City of Burbank (Clean Energy)	810 N. Lake Street	Burbank	91502
3	Canoga Park (Clean Energy)	7711 N. Canoga Avenue	Canoga Park	91304
4	Sanitation Districts of Los Angeles County's	23924 Figueroa Street	Carson	90745
5	The Gas Company	701 N. Bullis Road	Compton	90221
6	Covina Department of Public Works	534 N. Barranca Avenue	Covina	91723
7	Energy Resource Center (The Gas Co)	9240 Firestone Boulevard	Downey	90241
8	Energy Resource Center (SoCalGas Base)	12631 Monarch Street	Garden Grove	92841
9	Antelope Valley Unified School District	670 West Avenue L-8	Lancaster	93534
10	Long Beach Airport (Clean Energy)	2400 E. Spring Street	Long Beach	90806
11	Downtown L.A. County Garage (Clean Energy)	1055 N. Alameda	Los Angeles	90012
12	Los Angeles International Airport (Clean Energy)	10400 Aviation Blvd	Los Angeles	90045
13	MacValley Oil Company	100 Del Norte Boulevard	Oxnard	93030
14	SoCalGas Base (Clean Energy)	3530 East Foothill Boulevard	Pasadena	91107
15	The Gas Company	8191 Rosemead Boulevard	Pico Rivera	90660
16	Foothill Transit (Clean Energy)	200 E. End Avenue	Pomona	91767
17	CNG Fast Fill	120 Macneil Street	San Fernando	91340
18	The Gas Company	755 W. Captiol Drive	San Pedro	90731
19	Clean Energy	28273 Alta Vista Avenue	Santa Clarita	91355
20	SoCalGas Base (Clean Energy)	1701 Stewart Street	Santa Monica	90404

Table 9. Distance between Crews and CNG Fueling Station (miles)

crew	1	2	3	4	5	6	7	8	9	10
613	20.1	8.2	25.7	22.4	18.4	25.2	16.2	30.3	64.3	25.6
638	27.6	4.8	16.2	28.7	25.9	31.8	23.7	37.8	57.4	33.4
620	34.9	14.5	31.9	30.6	30.2	21.1	28	47.6	65.4	35.2
621	36.3	15.9	33.3	32	27.6	22.5	25.5	49	64	36.6
622	20.1	8.2	25.7	22.4	18.4	25.2	16.2	30.3	64.3	25.6
626	39.9	13	13.6	39	38.4	41.9	36	54.2	46.6	43.6
630	55.3	28.4	29.9	55.4	53.6	57.1	51.4	70.6	53.6	60
631	91.5	64.6	66.1	91.5	89.8	93.2	87.6	107	57.4	96.2
632	86.9	60	61.5	87	85.2	88.7	83	102	2.3	91.6
633	46.4	19.4	21	46.4	44.6	48.1	42.5	61.6	40.4	51
681	15.8	15.4	32.8	19	14.1	24.1	11.9	26	71.5	21.3
701	18.5	27.6	29.5	12.2	11.6	36.9	16.2	27.4	73.2	16.8
703	18.5	27.6	29.5	12.2	11.6	36.9	16.2	27.4	73.2	16.8
683	20.7	10.1	23.5	21.8	19	26.6	16.8	30.9	63.9	26.5
691	17.7	38.3	48.6	8.2	15.9	40.1	19.4	22.2	91.9	11.6
705	9.7	31.4	42.2	4.7	7.9	32	11.3	14.3	85.5	3.7
707	9.7	31.4	42.2	4.7	7.9	32	11.3	14.3	85.5	3.7
642	0.6	29.2	44.5	14.8	6.9	24.3	4.2	14.8	84.8	7.8
645	4.8	24.3	39.7	20	10.3	20.1	2.4	17.5	80	16.2
651	18.1	21.8	38	30.6	19.9	14.2	16.3	30.8	77.4	27.1
652	13	17.3	32.3	21.8	11.2	20.2	9	23.1	72.9	18.4
657	54.8	28.1	43.4	15.9	6	23.2	4	14.7	83.7	13.4
662	25	37.8	58.5	42	30.5	11.2	23.2	26.3	96.4	35.8
663	30.2	40.3	57.8	46.2	38.3	10.6	28.4	30.5	95.6	40.1
668	22.8	22.1	39.5	38	28.3	8.7	20.9	35.5	77.4	34.2
669	22.8	22.1	39.5	38	28.3	8.7	20.9	35.5	77.4	34.2
713	23.1	24.3	24.2	16.8	16.2	38.9	20.8	32	67.5	21.4
715	26.5	20.7	20.7	20.2	19.6	35.5	24.2	35.4	64	24.8
716	39.9	33.8	19.6	33.6	33	48.9	36.7	48.8	77.1	38.2
719	37.2	15	6.4	34.3	33.7	41.4	33.3	49.5	58.4	38.9
722	63.5	36.5	22.7	63.4	62.8	66.2	59.6	78.7	71.6	68.1
723	63.5	36.5	22.7	63.4	62.8	66.2	59.6	78.7	71.6	68.1
728	84.5	62.4	46.7	81.6	81	88.7	80.6	96.9	95.1	86.3
729	98.6	76.4	60.7	95.7	95	103	94.7	111	97	100
727	72.9	46	34.3	73	71.2	74.7	69	88.2	70.7	77.6
734	62.1	51.4	35.7	55.8	55.2	71.1	58.9	71	94.8	60.5
735	66.2	44.1	28.4	63.3	62.7	70.4	62.3	78.6	87.4	68

crew	11	12	13	14	15	16	17	18	19	20
613	4.7	20.2	56.8	13.3	14.3	34.4	18.6	26.9	34.9	17.5
638	11.5	23.9	47.4	18.2	21.8	42.8	11.6	33.3	27.9	17.3
620	11.8	28.4	63.1	7.6	30	31.7	19.3	35.1	36	25.7
621	13.2	29.8	64.5	9	31.4	33.1	17.9	36.5	34.6	27.1
622	4.7	20.2	56.8	13.3	14.3	34.4	18.6	26.9	34.9	17.5
626	24.5	26.6	50.2	28.4	34	52.5	2.9	43.5	17.2	20.1
630	39.9	43	47.4	43.5	49.5	67.7	18.6	59.9	3.9	36.4
631	76.1	79.2	83.6	79.7	85.7	104	54.8	96.1	40.9	72.6

632	71.5	74.6	98.1	75.1	81.1	99.3	50.2	91.5	44.3	68
633	30.9	34	57.5	34.5	40.5	58.7	9.6	50.9	7.6	27.5
681	5.9	16.8	64	17.4	10	33.4	25.7	23.5	42.1	14
701	17	1.2	60.6	30.2	21.9	46.1	30	16.7	43.8	11.1
703	17	1.2	60.6	30.2	21.9	46.1	30	16.7	43.8	11.1
683	4.6	19.7	54.6	17.2	14.9	35.9	18.2	26.4	34.5	13.8
691	27.8	21.2	79.7	37.2	25.1	49.3	47.2	5	62.5	30.2
705	20.3	14.9	73.3	29.2	17.1	41.3	42.8	13.6	56.6	23.9
707	20.3	14.9	73.3	29.2	17.1	41.3	42.8	13.6	56.6	23.9
642	18.1	18.2	75.7	28.7	9.3	33.5	39.6	19.3	55.9	29.7
645	13.2	19.2	70.8	24.5	3.2	29.4	34.7	24.5	51	25.5
651	11.5	28.4	69.1	4.9	9.4	23.4	32.2	35.1	48.5	26.5
652	5.8	21.6	63.4	13.5	7.1	29.5	27.7	26.4	44	18.1
657	17	18	74.6	27.6	8.2	32.4	38.5	20.4	54.2	27
662	26.7	39.4	89.6	24.8	20.2	10.1	50.8	46.5	67.5	38.9
663	31.9	44.6	88.9	24	25.4	3.9	50	50.7	66.7	44.1
668	22.4	37.2	70.7	5.8	17.9	19.3	31.8	42.6	48.5	36.7
669	22.4	37.2	70.7	5.8	17.9	19.3	31.8	42.6	48.5	36.7
713	16.6	4.4	55.3	37.1	24.8	48.2	24.8	21.3	38.6	5.9
715	13.2	7.8	51.8	33.6	21.4	44.8	21.2	24.7	35	2.6
716	26.6	21.2	37.8	42.1	34.8	58.1	34.3	38.1	48.1	12
719	21.1	21.9	37.5	27.9	31.4	52	15.7	38.8	29.5	15.4
722	48	51.1	26.5	52.7	57.7	76.8	28.7	68	42.6	44.5
723	48	51.1	26.5	52.7	57.7	76.8	28.7	68	42.6	44.5
728	68.4	69.3	12.8	75.2	78.7	99.4	63.4	86.2	46.7	62.7
729	82.4	83.3	26.8	89.2	92.7	113	62.5	100	48.6	76.7
727	57.5	60.6	25.1	61.1	67.1	85.3	36.2	77.5	22.3	54
734	48.8	43.5	14.2	64.2	57	80.3	52	60.3	63.6	34.2
735	50.1	51	7.6	56.9	60.4	81.1	45.1	67.9	58.5	44.4

Table 10. CNG Fueling Stations Listed in the U.S. Dept. of Energy Website

NO.	name	address	city	type of access
1	City of Alhambra	900 S New Ave	Alhambra	Private access only
2	SoCalGas - Azusa Base	950 N Todd Ave	Azusa	Public - credit card at all times
3	South Coast Air Quality Management District	21865 E Copley Drive	Diamond Bar	Public - card key after hours
4	City of El Monte Transportation Services	3629 Cypress Ave	El Monte	Private access only
5	LACMTA - Division 9	3449 Santa Anita Ave	El Monte	Private access only
6	LACMTA - Division 18	450 W Griffith St	Gardena	Private access only
7	LA Unified School District	18263 S Hoover Street	Gardena	Private - government only
8	Southern California Gas Company	44416 N Division Street	Lancaster	Public - card key at all times
9	Downtown Long Beach - Clean Energy	400 W Broadway	Long Beach	Public - credit card at all times
10	LACMTA - Division 10	742 N Mission Rd	Los Angeles	Private access only
11	LACMTA - Division 3	630 W Avenue 28	Los Angeles	Private access only
12	Los Angeles World Airports (LAX)	7350 World Way W	Los Angeles	Private - government only
13	LACMTA - Division 7	8800 Santa Monica Ave	Los Angeles	Private access only
14	LACMTA - Division 2	720 E 15th St	Los Angeles	Private access only
15	LADWP Downtown (Duco) Yard	444 Ducommun St	Los Angeles	Private - government only
16	LACMTA - Division 1	1130 E 6th St	Los Angeles	Private access only
17	Westwood UCLA - Clean Energy	741 Charles Young Dr	Los Angeles	Public - credit card at all times
18	LACMTA - Division 5	5425 S Van Ness Ave	Los Angeles	Private access only
19	UPS - Los Angeles	1800 N Main Street	Los Angeles	Private access only
20	NASA - Jet Propulsion Laboratory	4800 Oak Grove Drive	Pasadena	Private - government only
21	City of San Fernando	120 N Macneil St	San Fernando	Public - credit card at all times
22	City of Santa Monica	2500 Michigan Ave	Santa Monica	Private access only
23	Santa Monica - Big Blue Bus	1660 7th St	Santa Monica	Private - government only
24	LA County Sanitation District	2808 Workman Mill Rd	Whittier	Private - fleet customers only
25	LACMTA - Division 15	11900 Branford St	Sun Valley	Private access only
26	City of Los Angeles - East Valley Station	11050 Pendleton St	Sun Valley	Private - government only
27	LADWP Truesdale Yard	11760 Truesdale St	Sun Valley	Private - government only
28	Long Beach Water Department	1800 E Wardlow Rd	Long Beach	Private access only
29	City of Los Angeles - South LA Station	786 S Mission Rd	Boyle Heights	Private - government only

30	City of Thousand Oaks	1993 Rancho Conejo Blvd	Thousand Oaks	Public - credit card at all times
31	SoCalGas - Van Nuys Base	16645 Saticoy St	Van Nuys	Public - credit card at all times
32	City of Los Angeles - West Valley Station	8840 Vanalden Ave	Northridge	Private - government only
33	Simi Valley Transit	490 W Los Angeles Ave	Simi Valley	Private access only
34	SoCalGas - Oxnard Base	1650 Patton Ct	Oxnard	Public - credit card at all times
35	Gold Coast Transit	301 E 3rd St	Oxnard	Private access only

Table 11. Nearest Distance CNG Fueling Stations (miles)

	Provided Stations			Public stations			All stations		
crew	**1st nearest**	**2nd nearest**	**3rd nearest**	**1st nearest**	**2nd nearest**	**3rd nearest**	**1st nearest**	**2nd nearest**	**3rd nearest**
613	4.7	8.2	13.3	4.7	8.2	13.3	3.5[19]	3.8[11]	4[10]
638	4.8	11.5	11.6	4.8	11.5	11.6	4.8	9.6[26]	11.5
620	7.6	11.8	14.5	7.6	11.8	14.5	0.7[20]	7.6	11.8
621	9	13.2	15.9	9	13.2	15.9	2.2[20]	9	13.2
622	4.7	8.2	13.3	4.7	8.2	13.3	3.5[19]	3.8[11]	4[10]
626	2.9	13	13.6	2.9	13	13.6	2.9	7[25]	7.5[27]
627	2.9	13	13.6	2.9	13	13.6	2.9	7[25]	7.5[27]
630	3.9	18.6	28.4	3.9	14.5[21]	18.6	3.9	18.6	28.4
632	2.3	44.3	50.2	0.8[8]	2.3	44.3	0.8[8]	2.3	44.3
681	5.9	10	11.9	5.9	10	11.9	0.9[14]	1.1[16]	2.4[15]
701	1.2	11.1	11.6	1.2	11.1	11.6	1.2	4.4[12]	7.4[18]
703	1.2	11.1	11.6	1.2	11.1	11.6	1.2	4.4[12]	7.4[18]
683	4.6	10.1	13.8	4.6	10.1	13.8	4.6	4.6[15]	5.3[16]
691	5	8.2	11.6	4.9[9]	5	8.2	4.9[9]	5	8.2
705	3.7	4.7	7.9	3.7	4.7	5[9]	3.7	4.7	5[9]
707	3.7	4.7	7.9	3.7	4.7	5[9]	3.7	4.7	5[9]
651	4.9	9.4	11.5	4.9	9.4	11.5	2.7[1]	2.7[5]	3.1[4]
652	5.8	7.1	9	5.8	7.1	9	3.8[29]	4.8[10]	5.2[16]
657	4	6	8.2	4	6	8.2	1.1[24]	4	5.4[4]
662	10.1	11.2	20.2	4.5[3]	10.1	11.2	4.5	10.1	11.2
663	3.9	10.6	24	3.9	6.2[3]	10.6	3.9	6.2[3]	10.6
668	5.8	8.7	17.9	4[2]	5.8	8.7	4[2]	5.8	8.7
669	5.8	8.7	17.9	4[2]	5.8	8.7	4[2]	5.8	8.7
713	4.4	5.9	16.2	4.4	5.9	16.2	4.4	5.5[12]	5.9
715	2.6	7.8	13.2	2.6	3.3[17]	7.8	2.6	3.3[17]	4.5[22]
716	12	19.6	21.2	12	19.6	21.2	10.2[23]	12	19.6
719	6.4	15	15.4	4.9[31]	6.4	15	4.9[31]	5.2[32]	6.4
722	22.7	26.5	28.7	14.9[30]	22.7	26.5	4.5[33]	14.9[30]	22.7
723	22.7	26.5	28.7	14.9[30]	22.7	26.5	4.5[33]	14.9[30]	22.7
728	12.8	46.7	46.7	9.3[34]	12.8	46.7	8.2[35]	9.3[34]	12.8
729	26.8	48.6	60.7	26.8	48.6	60.7	25[35]	26.8	48.6
727	22.3	25.1	34.3	22.3	25.1	34.3	16.1[33]	22.3	25.1
734	14.2	34.2	35.7	14.2	23.7[30]	34.2	14.2	23.7[30]	34.2
735	7.6	28.4	44.1	6.8[30]	7.6	28.4	6.8[30]	7.6	28.4

Table 12. Total Improvement in Travel Distance to CNG Fueling Station

	Public Stations			All Stations		
	1st nearest	2nd nearest	3rd nearest	1st nearest	2nd nearest	3rd nearest
Total Improvement (miles)	32.2	146.5	95.7	92.1	259.2	241.5
Percent Improvement (all crews)	9%	16%	12%	25%	37%	35%
Percentage Improvement (improved crews)	31%	42%	28%	44%	46%	41%

6.1 Promotion of Additional Fueling Stations

From the previous analysis, it is clear that the distances between the crews and the fueling stations affect the productivity. And it is desirable to identify fueling stations that are as close as possible to the yards of the crews. Since only twenty out of the possible sixty CNG fueling stations located in the Los Angeles Area are currently being used, there is opportunity to reduce the distance to the fueling stations by promoting the use of the additional stations. Table 8 lists the CNG fueling stations that are currently being used and Table 10 shows the additional stations in the area that are not currently being used. These additional stations are not currently being used for a number of reasons, including the fact that some of the stations do not accept the payment cards. This next analysis determines which of these stations Caltrans should focus on promoting their use. The analysis is only from the perspective of reducing the distance traveled to these stations and does not consider the degree of difficulty for Caltrans to negotiate with the respective parties to accept payment of their cards.

We develop a mathematical model that determines which of the 35 not used CNG fueling stations Caltrans should focus their efforts on promoting their use. Let p be the number of additional CNG fueling stations that Caltrans needs to promote their use. The model selects the best p CNG fueling stations that minimize the distance to the yards. In the model, the weight of each crew is based on the assigned road miles. Hence, a crew which is assigned a large amount of road sweeping miles is weighted more in determining the best location for the CNG fueling stations than a crew that has less assigned road sweeping miles. In the analysis, we assume all crews use the closest CNG fueling station. We next define the variables of the model.

Inputs:

i	denotes the crew number, $i = 1, 2, 3 \ldots 37$
j	denotes the CNG fueling station number, $j = 1, 2, 3 \ldots 35$
w_i	denotes the road miles assigned to crew i
d_{ij}	denotes the reduced distance for crew i by changing to use CNG fueling station j
p	denotes the desired number of CNG fueling stations to promote

Variables:

Let $x_j = \begin{cases} 1 \text{ if station } j \text{ is opened to use} \\ 0 \text{ else} \end{cases}$

Let $y_{ij} = \begin{cases} 1 \text{ if crew } i \text{ uses station } j \\ 0 \text{ if else} \end{cases}$

Mathematical Model:

$$\max \sum_{i=1}^{37} \sum_{j=1}^{35} w_i * d_{ij} * y_{ij}$$

Subject to:

$$\sum_{j=1}^{35} x_j \le p \qquad (1)$$

$$\sum_{j=1}^{35} y_{ij} \le 1 \qquad i = 1, 2, 3 \ldots 37 \qquad (2)$$

$$\sum_{i=1}^{37} y_{ij} \le M * x_j \qquad j = 1, 2, 3 \ldots 35 \qquad (3)$$

As the model shows, the objective is to maximize the improvement on the weighted distance to the fueling stations gas station, where the weight is based on the assigned road miles to the crew. The first constraint limits the number of new stations to use to *p*. The second type of constraint states that each crew is assigned to at most one new station. The third constraint links the relationship between the two decision variables y_{ij} and x_j, where M is a large number

Table 13 shows a summary of the results for different values of *p*, considering only the additional public stations. Note that the table shows that there is no benefit in promoting more than six additional stations since the improved distance measure is not significantly reduced when seven or more stations are considered. Table 14 provides the specific recommendations for the stations to promote for the different values of *p*. For example, if only one station is desired to be promoted (*p=1*), it should be the fueling station managed by the City of Thousand Oaks. From Table 13, this would reduce the distance traveled to the fueling stations by 16.4 miles. Note that from Table 10, the City of Thousand Oaks currently only accepts credit cards for payment, but this analysis illustrates the importance of negotiating with the City of Thousand Oaks for them to accept the card payment method or for Caltrans to seek alternative payment methods. Along similar lines with $p=2$, Caltrans should promote the use of both the City of Thousand Oaks and the SoCalGas - Oxnard Base. Table 14 lists all the combinations up to $p=7$ since there is no benefit in terms of distance reduction with greater number of stations to promote.

Table 13. Summary of Results – Public

number of stations (p)	objective value	improved distance (mile)
1	482.794	16.4
2	672.494	19.9
3	797.846	23.5
4	916.376	25.0
5	1026.304	30.6
6	1097.134	32.1
7	1098.054	32.2

Table 14. Fueling Station Selection – Public

Station /Number of stations (p)	1	2	3	4	5	6	7
2 SoCalGas - Azusa Base			*	*	*	*	*
3 South Coast Air Quality Management District					*	*	*
8 Southern California Gas Company				*	*	*	*
9 Downtown Long Beach - Clean Energy							*
30 City of Thousand Oaks	*	*	*	*	*	*	*
31 SoCalGas - Van Nuys Base						*	*
34 SoCalGas - Oxnard Base		*	*	*	*	*	*

Table 15 shows a summary of the results for different values of p, considering now both the public and private stations. With both public and private stations included in the analysis, there is no benefit in promoting more than fourteen additional stations since the improved distance measure is not significantly reduced when fifteen or more stations are considered. Table 16 provides the specific recommendations for the stations to promote for the different values of p. For example, if only one station is desired to be promoted (*p=1*), it should be the fueling station managed by the Simi Valley Transit. From Table 15, this would reduce the distance traveled to the fueling stations by 42.6 miles. Note that from Table 10, Simi Valley Transit does not accept the Caltrans payment cards, but this analysis illustrates the importance of negotiating with Simi Valley Transit to accept the card payment method or for Caltrans to seek alternative payment methods. Table 16 lists all the combinations up to *p=15* since there is no benefit in terms of distance reduction with greater number of stations to promote.

Table 15. Summary of Results – Public and Private

number of stations (*p*)	objective value	improved distance (mile)
1	1347.828	42.6
2	1829.681	56.3
3	2182.303	62.7
4	2391.373	68.1
5	2516.725	71.7
6	2635.255	73.2
7	2745.183	78.8
8	2830.588	81.7
9	2901.418	83.2
10	2966.200	85.0
11	3028.130	87.2
12	3066.260	89.2
13	3102.070	91.2
14	3124.430	92.0
15	3125.350	92.1

Table 16. Fueling Station Selection – Public and Private

Station /Number of stations (*p*)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1 City of Alhambra										*						*	
2 SoCalGas - Azusa Base						*	*	*	*	*	*	*	*	*	*	*	*
3 South Coast Air Quality Management District					*	*	*	*	*	*	*	*	*	*	*	*	*
5 LACMTA - Division 9											*	*	*	*	*		*
6 LACMTA - Division 18								*	*	*	*	*	*	*	*	*	*
8 Southern California Gas Company									*	*	*	*	*	*	*	*	*
9 Downtown Long Beach - Clean Energy																	*
10 LACMTA - Division 10											*	*					
14 LACMTA - Division 2			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
19 UPS - Los Angeles													*	*	*	*	*
20 NASA - Jet Propulsion Laboratory		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
23 Santa Monica - Big Blue Bus														*	*	*	*
24 LA County Sanitation District							*	*	*	*	*	*	*	*	*	*	*
28 Long Beach Water Department																*	*
29 City of Los Angeles - South LA Station													*	*	*	*	*
30 City of Thousand Oaks															*	*	*
31 SoCalGas - Van Nuys Base												*	*	*	*	*	*
33 Simi Valley Transit	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
35 Gold Coast Transit				*	*	*	*	*	*	*	*	*	*	*	*	*	*

7. Balancing the Routes

From the previous analysis of the assigned road miles, it showed that the workload varies significantly from region to region and from crew to crew. A better balance of the assigned miles to the crews could significantly improve the productivity of the crews. In this section, we present a mathematical model that optimizes the assignment of road miles to crews.

In order to minimize the disruption to current operations, we only consider shifting road miles from one crew to another that are in the same region and cover adjacent areas. Furthermore, we only consider the road crews which perform the regular sweeping operation.

Inputs:

i ,j denotes the road crew, i = 613, 620, 621…

R_{ij} denotes the maximum possible road miles that crew i could shift to crew j

A_i denotes the original assigned miles of crew i

U denotes the average miles of the region

Variables:

X_{ij} denotes the road miles that crew i shifts to crew j

Mathematical Model

$$\min \sum_i \left| A_i - \sum_j X_{ij} + \sum_j X_{ji} - U \right|$$

Subject to:

$$X_{ij} \leq R_{ij} \tag{1}$$

$$X_{ji} \leq R_{ji} \tag{2}$$

$$X_{ij} \geq 0 \tag{3}$$

$$X_{ji} \geq 0 \tag{4}$$

As the model shows, the objective is to minimize the deviation between the assigned miles of each crew and the average miles of the region. The smaller this objective value the more balanced the routes are and an objective value of zero means that each route in the region has exactly the same number of miles. The first and second constraints limit the miles that crew *i* can shift to another crew. The data establishment of R_{ij} is based on the physical connection of two adjacent crews since we only allow the reassignment of miles if the two crews are in the same region and are next to each other in the freeway. The third and fourth constraints state the non-negativity property of the variables.

Table 17 displays the objective of the current road mile assignment, the road mile assignment from the optimization model, and from an adjustment to the optimization model. The objective is the deviation of the crew miles from the average miles of the region. The average miles for each region are 34.35 for the North, 24.89 for the South, 25.38 for the East and 37.27 for the West. To facilitate the ease of entry and exist from the freeway, we make adjustments to the solution from the optimization model to consider freeway exist locations and other operational considerations of the freeway network. The results of this adjustment are listed in the third column. We note that the adjustment causes the objective value to slightly worsen but by taking into consideration the physical characteristics of the freeway network it is a more practical balance of the roadway miles to the crew. In comparison to the current crew to road miles assignment the recommended solution provides an assignment that provides a significantly better balance of the routes. The improvement in the balance of the routes is 15.15%, 57.72%, 47.32%, and 44.33% for the North, South, East, and West regions, respectively.

Table 17. Objective Values of the Road to Crew Assignment

	current obj. value	optimized obj. value	adjusted obj. value
North Region	127.90	100.18	108.52
South Region	70.93	28.99	29.99
East Region	51.48	27.12	27.12
West Region	109.19	60.79	60.79

Table 18 lists the assigned miles to each crew for the current and recommended solutions. Note the better balance of the miles assigned to the crews for the recommended solution. Table 19 shows the routes that should be reassigned based on the recommended solution. For example, for the North Region, we recommend shifting the assignment of crew 613 from milepost 0 to 13.34 on the Ventura Freeway. The current assignment is from milepost 2.94 to 6.1. The table also shows that we recommend shifting miles posted from 6.1 to 13.34 from crew 620 to crew 613.

Table 18a. Crew Road Miles– North Region

Crew	current solution (miles)	recommended solution (miles)
613	20.90	20.06
620	30.65	31.41
621	39.76	30.76
622	10.30	21.32
626	28.57	29.34
630	30.90	39.41
631	44.29	30.18
632	79.02	79.02
633	38.29	38.89
638	20.84	23.13

Table 18b. Crew Road Miles– South Region

Crew	current solution (miles)	recommended solution (miles)
681	41.03	34.03
683	12.64	19.64
691	9.2	21.97
701	40.32	29.12
703	21.77	21.77
705	28.79	26.52
707	20.49	21.19

Table 18c. Crew Road Miles– East Region

crew	current solution (miles)	recommended solution (miles)
642	22.96	22.96
645	18.98	21.38
651	28.15	24.95
652	20.21	23.41
657	29.45	24.45
662	19.63	22.23
663	19.36	24.70
668	39.48	34.14
669	30.16	30.16

Table 18d. Crew Road Miles– West Region

crew	current solution (miles)	recommended solution (miles)
713	20.23	31.41
715	25.84	27.97
716	35.99	31.79
719	47.22	38.11
722	27.36	33.13
723	31.67	31.67
727	44.11	38.34
728	54.2	42.54
729	57.39	57.39
734	38.04	38.04
735	27.95	39.61

Table 19a. Route Reassignment- North Region

crew	Current Route		Recommended Route				
	from	to	from	to	freeway	name	description
613	2.94	6.1	0	13.34	134	Ventura Fwy	Riverside Dr. UC to JCT. 134/210/710 Fwy
613	22.26	33.28					shift to 622
638	0	2.94					shift to 613
638	33.28	37.41	33.28	42.64	5	Golden State Frwy	Roscoe Blvd. to Roxford Street
622	19.72	22.26	19.72	33.28	5	Golden State Frwy	Broadway Ave. to Roscoe Blvd.
620	18.2	24.33	18.2	33.33	2	Glendale Fwy.	Colorado Bl. To JCT Angeles Crest Hwy/AngelesForest Hwy
620	6.1	13.34					shift to 613
620	10.13	25.29	11.13	25.29	210	Foothill Fwy	Sunland Blvd. to Fair Oaks
621	24.33	64.09	33.33	64.09	2	Angeles Crest Hwy	JCT Angeles Crest Hwy/Angeles Forest Hwy to JCT 002/039
626	37.41	42.64					shift to 638
626	4.93	10.13	0	11.13	210	Foothill Fwy	JCT 005/210 to Sunland Blvd.
630	49.4	74.5	54.6	88.61	5	Golden State Frwy	0.3 miles N. of Rye Canyon Rd. to LA/KRN County
633	43	49	43	54.6	5	Golden State Frwy	Roxford to 0.3 miles N. of Rye Canyon Rd.
633	0	5					shift to 626
631	74.5	88.61					shift to 630

Table 19b. Route Reassignment- South Region

crew	Current Route		Recommended Route				
	from	to	from	to	freeway	name	description
681	15.99	21.99					shift to 683
683	21.9	24.16	15.99	24.16	110	Harbor Fwy.	Manchester Ave. to College st. OC
701	12.59	23.3	16.59	23.3	405	San Diego Fwy	JCT 91/405 TO Manchester OC
701	6.01	6.72					shift to 707
701	11.55	29.08	18.05	29.08	1	Pacific Coast Hwy	Palos Verdes Blvd. to Manchester Ave.
705	0	12.59	0	16.59	405	San Diego Fwy	Orange County Line to JCT 91/405
705	0.74	7.01					shift to 691
707	6.69	14.6	6.01	14.6	91	Artesia Fwy	Vermont Ave. to Lakewood
691	8.43	11.55	8.43	18.05	1	Pacific Coast Hwy	Classification OH to Palos Verdes Blvd.
691			0.74	7.01	110	Harbor Fwy.	9th/Gaffey st. to Carson St. OC

Table 19c. Route Reassignment- East Region

crew	Current Route		Recommended Route				
	from	to	from	to	freeway	name	description
645	8.39	12.41	8.39	14.81	605	San Gabriel Fwy.	Firestone Bl. To Beverly Blvd.
651	22.31	28.52	23.91	28.52	10	San Bernardino Buswy	S. Garfield Ave. to El Monte Terminal
651	22.31	39	23.91	39	10	San Bernardino Fwy	S. Garfield Ave. UC. to Holt Ave. UC.
652	19.67	22.31	19.67	23.91	10	San Bernardino Buswy	LA City Limits to S. Garfield Ave.
652	19.67	22.31	19.67	23.91	10	San Bernardino Fwy	Indiana Ave. OC to S. Garfield Ave.
657	6.86	17	6.86	19.6	60	Pomona Fwy.	Greenwood Ave. OC. to 7th Ave.
657	12.41	19.85	14.81	19.85	605	San Gabriel Fwy.	Beverly Blvd. to Walnut Creek
662	17	30.46	19.6	30.46	60	Pomona Fwy.	7th. Ave to LA/SBDO County Line
663			0	5.34	66	Foothill Blvd.	Baseline Road to S. Bernardino County Line
668	0	5.34					shift to 663

Table 19d. Route Reassignment- West Region

crew	Current Route		Recommended Route				
	From	to	from	to	freeway	name	description
713	29.08	34.53	29.08	40.8	1	Lincoln Blvd.	84th to JCT 001/027
713			23.26	27.96	405	San Diego Fwy	Manchester Ave. to Matteson Ave.
715	23.26	37.08	27.96	44.74	405	San Diego Fwy	Matteson Ave. to Nordhoff St.
715	34.5	35.38	34.5	35.38	1		shift to 713
716	35.2	59.9	40.8	59.9	1	Lincoln Blvd.	JCT 001/027 to Decker Canyon Road JCT 001/023
716	0	10.68	0	12.08	27	Topanga Canyon Blvd.	Pacific Coast Hwy to JCT 027/101
719	37.03	44.74	37.03	44.74	405		shift to 715
719	10.68	20.1	12.08	20.1	27	Topanga Canyon Blvd.	JCT 027/101 to JCT 027/118
722	12.95	18.4	12.95	24.17	23	Moorpark Ave/Walnut	Los Angeles Ave. to JCT 023/126
727	18.4	24.17	18.4	24.17			shift to 722
728	0	5.1	0	5.1			shift to 735
728	21.25	27.81	21.25	27.81			shift to 735
735			21.25	27.81	1	Pacific Coast Hwy.	JCT 033/101 to JCT 150
735			0	5.1	126	Santa Paula Fwy.	JCT 126/101 to Wells Rd.

8. Conclusions and Future Work

A review of the literature shows that the critical factors that determine successful implementation of CNG vehicle are the size of the fleet, proper training of maintenance personnel, sufficient number of fueling stations and in particular access to an on-site fueling station, and a commitment to a natural gas program by the agency. Regarding the fleet size issue, the advantage of having more CNG vehicles is that the maintenance professionals are more familiar with the problems and the infrastructure supporting the CNG is used more often (e.g., justifying an on-site fueling station).

We visited two sweeping crews, one in the East Region and the other in the South Region. The two crews differed in their views of the CNG sweepers with the East Region crew having a strong negative opinion of these sweepers. Consistent with the literature, the problem with the fueling stations was listed as one of the primary problems with the CNG sweepers. Also, both crews provided specific recommendations to improve the design of the CNG sweepers. It is recommended that the complete list of design suggestions outlined in Section 3 be presented to the CNG sweeper manufacturers to see if any of these problems could be corrected.

Our productivity comparison was based on lane miles (LAMI) data provided from IMMS. We analyzed resource usage data based on LAMI from 2002-2008 as recorded in IMMS. We focused on studying crews for which there was data for both diesel and CNG sweepers. After removing for outliers, five crews had over a 10% average reduction in their lane miles after switching to CNG sweepers, four crews had little change (within 10%), and one crew had over a 10% average increase in their lane miles.

To offset the lost productivity, additional CNG sweepers will need to be purchased in District 7. Two additional sweepers will need to be purchased for the North Region to maintain the same productivity for these studied crews, assuming new routes can be created to better balance the workload of these crews. For the East region, the studied crews were 11.7% more productive in terms of LAMI when using diesel. One additional sweeper will need to be purchased for the East Region to maintain the same productivity for the studied crews, assuming new routes can be created to better balance the workload of these crews. We note that with additional equipment extra crews will need to be staffed. Since there was no pre- and post use data for the South and West Regions, no determination on the number of required CNG sweepers can be made at this time. We note that there can also be productivity improvements if some of the vehicle design suggestions outlined in Section 3 are made and the issues with the CNG fueling stations are resolved.

The cost analysis showed only significant differences in the purchase cost, with the CNG sweepers costing almost double than their diesel counterparts. Consistent with other applications, there is no significant difference between the maintenance cost of the diesel and CNG sweepers. We note that no comparison of fuel costs was made since no data on fuel usage was provided.

Since it is clear that there has been some productivity reduction with the implementation of CNG sweepers and that the fueling stations contributed to this reduction, we recommend that Caltrans promote the use of more fueling stations. Only twenty out of the possible sixty CNG fueling stations located in the Los Angeles Area are currently being used. A mathematical model was developed to identify which of these stations Caltrans should focus on promoting their use. Considering only the public CNG fueling stations, the analysis showed that there is no benefit in promoting more than six additional stations since the improved distance measure was not significantly reduced when seven or more stations were considered. Considering both the public and private CNG fueling stations, the analysis showed that there is no benefit in promoting more than fourteen additional stations since the improved distance measure was not significantly reduced when fifteen or more stations were considered.

We developed an optimization model that determined the assignment of road miles to crews that minimized the total deviation of the crew miles from the average miles of the region. In comparison to the current crew to road miles assignment the recommended solution provides an assignment that provides a significantly better balance of the routes. The improvement in the balance of the routes is 15.15%, 57.72%, 47.32%, and 44.33% for the North, South, East, and West regions, respectively.

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