ISSN 1047-3289 J. Air & Waste Manage. Assoc. 46: 985-989

Cost-Effectiveness of Emissions Reduction through Vehicle Repair Compared to CNG Conversion

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ABSTRACT
In return for a temporary waiver from converting five vehicles to operate on compressed natural gas (CNG) for the Denver Clean Fuels program, the University of Denver identified, tested, repaired, and retested nine employee commuter vehicles. The results of the study validated the concept that employer-based identification and repair programs can be carried out in a cost-effective way. On average, each repaired vehicle removed fifty times more carbon monoxide (CO) emissions from Denver air than each CNG conversion. The average cost of each repair was eight times less than the average cost of each conversion. The average fuel economy benefit from the repairs was enough to pay for the average cost of repairs in less than three years of normal driving. When the expected lifetimes of repairs and conversions are included, the targeted repair program appears to be over sixty times more cost-effective as a CO emissions reduction strategy than CNG conversion.

INTRODUCTION
The City of Denver Alternative Fuels Ordinance (No. 330) mandates that businesses operating fleets of ten or more vehicles must convert 10% of that fleet to run on alternative fuels such as compressed natural gas (CNG) or propane (LPG).[1] The University of Denver (DU) was required to convert nine of its 91 vehicles in order to comply with the ordinance. In the first phase of compliance, four gasoline-powered 1992 Chevrolet S10 light-duty pickup trucks were converted to operate on both CNG and gasoline. The cost of each conversion was about $3,000.

IMPLICATIONS
Alternative fuel conversions for light duty vehicles have been proposed, even mandated, as a pollution reduction measure. This research shows that identification and repair of a few gross polluters is at least twenty times more cost effective as a carbon monoxide emission reduction measure than natural gas conversion, even when optimistic assumptions are made about the usage of the new fuel, and no penalty is assessed for the impact of the extra mileage required both to obtain the alternative fuel and to make up for the loss of payload caused by the extra fuel tank.

The S10 pickups are used by the janitorial staff. The CNG conversion adds a pressure vessel in the cargo space, resulting in a 20% loss in carrying capacity. The necessity to purchase CNG requires the vehicles be driven an extra four miles for each refueling. It takes about six minutes to fill the CNG tank. This is not an onerous time commitment, except when there are other vehicles in line. There is only one CNG outlet in our area, so four vehicles standing in line ahead can cause a significant delay.

After converting four vehicles to CNG as a component of their compliance with the program mandates, the DU administration requested from the City of Denver a temporary waiver of the requirement for the other five vehicles, using the argument that it was possible to obtain significantly greater emissions reduction for the money being spent. The emissions reduction would be accomplished by finding high-emitting vehicles among the DU commuting fleet and demonstrating, through repair of these vehicles, that their emissions would be reduced significantly and more cost-effectively than by converting the pickup trucks to use CNG.[2]

The argument for the variance requested was twofold. Converting already low-emitting vehicles to operate on CNG would be expected to show minimal emissions reduction, and furthermore, these vehicles were not driven very far. The DU Administration expected us to find high-emitting vehicles that were driven comparable or more miles than the DU trucks. These vehicles, when repaired, were expected to have their emissions reduced by an amount which would have a greater impact on Denver's air quality than further conversions of DU gasoline-powered vehicles.

Most of the participating vehicles were identified using FEAT (Fuel Efficiency Automobile Test), a remote sensing system capable of measuring the carbon monoxide (CO) and hydrocarbon (HC) emissions of vehicles in less than a second as the vehicle is driven past the instrument. The instrument is a nondispersive infrared (NDIR) device designed to emulate the emissions readings one would obtain had the vehicle been driven with an exhaust probe from a traditional exhaust analysis machine inserted in its tailpipe. The instrument can be coupled with a video system to provide a recorded image of the license plate with the vehicle's emissions written on the screen. Details about the instrument's operation and ability to accurately measure exhaust emissions have been documented elsewhere.[3-5]

Remote sensing has been used in several locations to successfully identify high-emitting vehicles.[2,6]

EXPERIMENTAL

Remote sensors were set up at the entrances to DU parking lots to measure arriving commuter vehicles for exhaust emissions screening. At most locations the remote sensing test observed vehicles in a low speed (near idle) driving mode. Drivers of vehicles with exhaust %CO readings greater than 3.5% were approached for possible participation in the repair program. In addition to the minimum emissions requirement, vehicle owners were also asked to estimate the number of miles they drove, with the goal in mind of exceeding the average distance traveled by a typical DU dual-fueled vehicle (over a several-month period, this average had been observed to be about 10 miles per day). Vehicle owners were promised free repairs to reduce their vehicle's emissions and use of loaner vehicles should repairs cause transportation inconvenience. Willingness to participate on the part of vehicle owners was good once they understood the program and what we were trying to accomplish.

Once a vehicle was recruited into the program, a chassis dynamometer test was used before and after repair to quantify the emissions benefit. The chassis dynamometer test used was the IM240, which is a 240-second transient driving cycle in which emissions for CO, HC, carbon dioxide (CO_2), and oxides of nitrogen (NO_x) are determined on a gram-per-mile basis. The IM240 is based on and was designed to correlate with the Federal Test Procedure (FTP) which was, in turn, designed to emulate typical urban and suburban driving patterns. The facility used for the IM240 testing was at the National Center for Vehicle Emissions Control and Safety (NCVECS), a laboratory grade dynamometer facility located in Fort Collins, Colorado, a 120-mile round trip from Denver.

RESULTS

The benefits of the program were determined by comparing grams-per-year emissions reduction from the DU trucks when operated on CNG versus gasoline to the emissions benefit obtained by repairing nine vehicles. The grams-per-year benefit was calculated by multiplying the change in grams per mile obtained on the IM240 emissions tests before and after repairs by the number of miles traveled based on extrapolations of odometer data. The costs were compared using the known conversion cost of the trucks versus the cost of repairs paid for the nine vehicles. Actual costs of some repairs were estimated, since they were performed by individuals who were not part of the commercial repair industry. The emissions benefit from one vehicle, a 1980 AMC Eagle, had to be estimated based on portable analyzer data because it was a fulltime four wheel drive vehicle, and the dynamometer facility used could not test such a vehicle.[7]

Table 1 summarizes the results from the program estimated as daily emissions benefits. Daily miles driven and the estimated cost of repair provide the cost/benefit numbers. The DU dual-fueled vehicles were driven an average of ten miles

Table 1. Emissions reductions are based upon IM240 data and miles driven daily. AVG. column does *not* include emissions data from the 4WD 1980 AMC Eagle nor does it incorporate the cost of repair for that vehicle.

	DU CNG	*'71 Saab*	*'82 Caddy*	*'85 Ranger*	*'79 280ZX*	*'73 CJ5*	*80 Cita.*	*'88 190E*	*'80 Eagle*	*'84 Sentra*	*AVG*
Miles/day	10	8	20	45	11	20	40	50	35	24	28
Initial CO gm/mile	3.5	56	118	24	25	173	68	97	88(est)	82	80
Final CO gm/mile	0.16	14	13	17	7.5	37	21	0.31	29(est)	2.5	14
CO benefit gm/mile	3.3	42.0	105.0	7.0	17.5	136.0	47.0	96.7	59(est)	79.5	66
CO benefit gm/day	33	840	2100	315	193	2720	2115	4835	2065(est)	1908	1878
Initial HC gm/mile	0.14	7.7	12	4.2	1.3	6	3.3	2.7	1.5(est)	2.5	5.0
Final HC gm/mile	1	2.9	0.75	2.9	0.37	3.2	0.29	0.04	0.21(est)	0.17	1.3
HC benefit gm/mile	-0.86	4.80	11.25	1.30	0.93	2.80	3.01	2.66	1.29(est)	2.33	3.6
HC benefit gm/day	-13*	96	225	59	10	56	135	133	45(est)	56	96
Initial NO_x gm/mile	0.52	1.47	2.03	3.12	1.74	1.68	2.14	0.32	NA	0.87	1.67
Final NO_x gm/mile	1.07	2.00	3.32	2.93	2.13	3.44	0.52	0.60	NA	0.26	1.90
NO_x benefit gm/mile	-0.55	-0.53	-1.29	0.19	-0.39	-1.76	1.62	-0.28	NA	0.61	-0.23
NO_x benefit gm/day	-5.51	-4.26	-25.80	8.37	-4.34	-35.14	64.76	-13.95	NA	14.6	0.53
Repair Cost	$3,000	$120	$150	$1,015	$40	$470	$700	$200	$250	$300	$374
MPG Before Repair	—	25	15	20	20	12	23	22	NA	26	20
MPG After Repair	—	30	19	24	21	16	23	27	NA	33	24
Annual Fuel Savings @ $1.20/gal	—	$23	$123	$164	$11	$183	$0	$184	$0	$86	$97

* Apparent increase due to methane.

per day. The average number of miles driven daily for the repaired vehicles was 28. All but one of the repaired vehicles averaged more than 10 miles per day. The average CO emission benefit for each vehicle repaired was 1878 grams per day, compared to a 33-gram-per-day maximum estimated benefit from converting a single vehicle to CNG. The smallest emissions benefit of the nine vehicles recruited and repaired resulted in a daily emissions reduction about equal to the total expected benefit from converting five additional Chevy S10 trucks. However, even this vehicle's repair was cost-effective as it was the least expensive (an estimated $40). An average annual per-vehicle CO benefit of about 1,500 lbs was estimated by multiplying the average daily emission benefit by 365 days/year and dividing by 454 grams/pound. This figure includes only those eight vehicles which received IM240 testing before and after repair. The annual total repaired vehicle emissions reduction was approximately 12,000 pounds, compared to a predicted 133 pounds from conversion of five DU trucks. The reduction does not include an estimated 1,600 lb benefit from the fulltime four wheel drive 1980 AMC Eagle.

The average daily HC benefit from the repairs was 96 grams, compared to an expected HC emissions *increase* of 13 grams per day from the CNG-powered trucks. The average annual HC reduction for the repaired vehicles was approximately 77 pounds per vehicle, calculated in the same manner as the CO benefit. The annual total HC reduction was about 617 lbs or about 94 gallons of gasoline—again, not including any benefit from repairs to the 1980 AMC Eagle, which removed an estimated annual 36 lbs of HCs or saved an additional 5.5 gallons of gasoline. Even though there was an apparent increase in HC emissions from CNG operation, it should be pointed out that the major HC component is methane;[8] while it is a greenhouse gas, methane is considered to be nonreactive in the atmosphere and thus does not contribute to ozone production.

Vehicles emit large amounts of CO because of incomplete combustion in their cylinders. This results in a lower combustion temperature. The engine output of NO_x is correlated with combustion temperature. Despite the fact that all repaired vehicles ran leaner, and thus with higher combustion temperatures as a result of the repairs, the average annual NO_x emissions reduction was about 0.4 lb, for a total program reduction of about 3.4 lbs annually. Most vehicles experienced small increases in their NO_x emissions following repair for CO emissions, as did the dual-fueled trucks when operated on CNG compared to gasoline. In fact, the average per-mile change in NO_x emissions was a small increase of 0.23 grams/mile. However, the three vehicles which experienced reductions in their NO_x emissions compensated for the increase in the other five because of the larger number of miles driven. Two of these vehicles received new catalytic converters as part of the repair process. The DU trucks also experienced an increase of 0.55 grams/mile of NO_x emissions when operated on CNG instead of gasoline.

The average cost of repair was $374 per vehicle, compared to a cost of about $3,000 per vehicle to convert the Chevy S10 pickups. The average cost of repair was calculated without including the estimated $250 cost for repairing the AMC Eagle. Repair work costs included the cost of rental replacement vehicles. It did not include the costs of transporting the vehicles to the test center or the cost of testing. The cost of repair did not correlate with repair effectiveness. The most expensive repair produced the second-lowest benefit while the fourth least-expensive repair produced the highest benefit. Furthermore, expediency of repair took precedence over our desire to have as much of the work as possible performed by the repair industry. Therefore, repairs were performed by the owners, by the authors, and by NCVECS personnel, as well as by professional mechanics. When the repairs were performed by others, two assumptions were made. The first and most important was that the repair industry would correctly diagnose the problem. Diagnostic errors and improper repair can quickly add to the cost of emissions reduction, a situation which can be observed in the two vehicles with the highest repair cost. The second assumption involved the use of standard shop labor rate estimates to translate the work performed into a reasonable shop charge.

Recently we have retested four of the repaired vehicles as part of the requirements for continuing the program described in this paper. The 1980 Citation which tested at 21 grams/mile CO on May 4, 1994 was measured at 12 grams/mile on March 3, 1995. During the interval between tests, the car was driven about 16,000 miles. The owner did not report having done any additional work to the car that could have altered its emissions; however, there may have been differences in fuel or vehicle preparation which could have had an influence on the test results. The 1971 Saab, which tested at 14 grams/mile CO on October 12, 1994 after receiving repairs, was retested at 11 grams/mile on March 2, 1995. However, the Saab owner did additional work (replacing the engine computer) which would have affected the vehicle's emissions. This repair seems to have had more effect on the HC emissions than on the CO emissions, as they were reduced from 2.9 grams/mile in October 1994 to 1.5 grams/mile in March 1995. The Saab's odometer was not working properly so the number of miles driven is not known. These last two vehicles were retested at Environmental Testing Corporation, a commercial federally certified emissions laboratory located in Aurora, Colorado. The 1988 Mercedes, which was tested at 0.31 grams/mile on June 1, 1994, was retested on January 9, 1996. During the interval between tests, the vehicle was driven over 20,000 miles, after which time its CO emissions were measured at 0.70 grams/mile. The 1984 Nissan Sentra, which was tested at 2.5 grams/mile on May 18, 1994, was retested on January 9, 1996. During that interval, the vehicle was driven over 10,000 miles, after which its CO emissions were measured at 4.4 grams/mile. These last two vehicles were retested at the Envirotest research and teaching facility located at 8494 S. Colorado Blvd. in Littleton, Colorado.

The DU truck, which was tested to determine the emissions benefits of the CNG conversion, was also retested at the Littleton Envirotest facility. During this 2.5-year period, the vehicle was driven about 8700 miles. When operated on gasoline, its CO emissions decreased from 3.5 to 2.5 grams/mile, while when operated on CNG, its CO emissions increased from 0.16 grams/mile to 2.7 grams/mile.

DISCUSSION

The costs of this operation involved IM240 testing and personnel time for testing, research, and report writing. When this program began, Denver did not have IM240 facilities available for public use. A commercial laboratory-grade IM240 test costs about $300 to $400, which results in a minimum annual cost of $5,400 if only two tests are required per vehicle on nine vehicles. Personnel costs are estimated at $12,400 for the time needed to deal with those nine vehicles. Much of the personnel cost for this particular program involved time spent transporting vehicles to and from Fort Collins. There were also fuel and oil costs, again mainly because of the large distances traveled for testing. Another significant block of the time was spent negotiating with vehicle owners so that the repair work could be performed at their convenience. This, too, was made more difficult by the long drives to Fort Collins and back, which took four to five hours. The cost of leasing a remote sensor is about $500/day, without operating personnel who were included earlier. Five days of remote sensing were needed, adding $2,500 to the cost of the program. An estimated 500 to 700 vehicles were tested to locate seven of the nine high emitters.

The total of these costs, combined with the cost of repair, was about $23,000 for this program in which expensive testing and time commitments were made. The benefit for the $23,000 was emissions reductions of 12,000 lbs per year, estimated to last for at least four years. Thus the DU program achieved reductions for about $1.90 per pound. We could have spent the same $23,000 converting seven vehicles. This conversion would remove only 186 lbs of CO from the air at a cost of about $124 per pound. The DU program appears at first to be over 60 times more cost-effective than the mandatory CNG conversions.

However, the new fuel is available for the lifetime of the vehicle. The lifetime of a truck conversion is estimated at 12 years while EPA (TechV model for I/M repair) estimates an emissions repair will last at least four years. If we take only that factor into account, the DU program as carried out was at least 20 times more cost-effective than CNG conversions. If the program had been carried out without the expensive testing in Fort Collins, the cost/benefit is estimated to be almost two times better, or about $1 per pound. Under those circumstances the program would revert to being about 40 times more cost-effective than fuel conversion. A summary of the repairs performed is given in Table 2, and in each case it is believed that repairs will last more than the four years assumed in this calculation.

Several other factors also affect the comparison. For instance, the dual-fueled vehicles are not always driven on CNG, and the loss of payload increases the miles driven. There should be a cold-start advantage to using CNG because the fuel starts as a vapor; however, in examining a National Renewable Energy Laboratory (NREL) database which includes data from 13 dual-fueled vehicles, one can see little advantage to using CNG in dual-fueled vehicles, even when examining only bag 1 data (which includes a cold start) from the full Federal Test Procedure.[8] Thus, the benefits observed from CNG operation can be thought of as representing an ideal situation, where the DU vehicles are always operated on CNG and have not had their payload reduced some 20% by the intrusion of the CNG tank. The necessity of driving additional miles to obtain the CNG fuel also increases emissions and costs personnel time, which discourages its use.

An often overlooked but significant factor in the cost-effectiveness of vehicle repair is the savings accrued to the owner in the form of lower fuel expenses. In this particular study, based on average values of fuel economy measured by IM240 before and after repair and based on the average annual miles driven, an emissions-related repair can be

Table 2. Summary of repair work performed.

Vehicle	*Repairs Performed*	*Cost*
1992 Chevy S-10	CNG Conversion	$3,000
1971 Saab	Used Manifold Pressure Regulator Replacement	$120 (est)
1982 Cadillac	New O_2 Sensor, Vacuum Line Replacement	$150
1985 Ford Ranger	Minor Tune-up, New Air Injection System Valves, New Throttle Position Sensor	$1,015
1979 Nissan 280ZX	Adjusted Air Flow Sensor	$40 (est)
1973 Jeep CJ5	Replaced Carburetor, Minor Tune-up	$470 (est)
1980 Chevy Citation	Carburetor Rebuild, Tune-up and Carburetor Adjustment, Replaced Converter Pellets	$700 (est)
1988 Mercedes 190E	New O_2 Sensor	$200
1984 Nissan Sentra	New O_2 Sensor, Reconnect Mixture Control Solenoid, New Catalytic Converter	$300 (est)
1980 AMC Eagle	Tune-up Adjustments, New Catalytic Converter	$250 (est)

expected to pay for itself in under four years. This result, based on fuel at $1.20 per gallon, falls just within the four-year assumed lifetime of the repair.

CONCLUSIONS

Over the time period covered in this project, there can be no doubt that identification and repair of high-emitting vehicles is a more cost-effective alternative to reducing mobile source CO inventory than taking already low-emitting vehicles and converting them to operate on CNG. The program described in this paper is expected to continue over the next several years. During that time, not only will new vehicles be recruited for repair, but we hope to be able to monitor the longevity of the repairs already performed, including the emissions of the dual-fueled vehicles. One possibility could still make CNG conversion appear more cost effective: that is, if the emissions of the dual-fueled trucks increase when operated on gasoline (due to deterioration of fuel delivery systems or the buildup of engine deposits, for example), while the emissions when operated on CNG remain the same, although after the first round of retesting, the opposite seems to have occurred.

Several observations can be made from the data and level of support from the participants which may have an impact on future I/M programs. One interesting aspect of this program was finding these high-emitting vehicles among a population of vehicles that reside in an area with an annual decentralized inspection and maintenance program. Every one of the vehicles had valid emissions stickers. Some of these vehicles passed because their idle emissions were low while their on-road emissions, measured by remote sensing, were quite high. In some cases, the vehicle may have developed high emissions due to some component failure since its previous test. The 1982 Cadillac was one of those. According to its owner, we detected its high emissions only shortly after the "Check Engine" light had come on. This vehicle would likely have received repairs even without DU intervention. However, the 1988 Mercedes also had an oxygen sensor failure that its computer was unable to detect. In this case, without our intervention, the car would have been driven thousands of miles more, resulting in further damage to the emissions control system, especially the catalytic converter. In one case, a vehicle's on-road emissions were increased as the result of an adjustment to get the vehicle to pass an idle emissions test. Even with the onset of loaded mode (IM240) testing, the situation could still arise where an undetected but vital emissions control component fails shortly after passing the test, allowing that vehicle to operate up to two years before the problem is detected.

Another interesting aspect of this program was what it revealed about the repair industry's difficulty in diagnosing and repairing vehicles with high on-road (as opposed to idle) emissions. In part, this difficulty is due to years of experience in getting cars to pass idle tests. Even more important is the general lack in the repair world of an economical means to perform loaded-mode testing. The portable exhaust analyzers used in this experiment proved useful in this area, both as diagnostic tools and as predictors of repair effectiveness.[7]

ACKNOWLEDGMENTS

The assistance of the City and County of Denver, Department of Health and Hospitals, Air Quality/Environmental Protection Division, the administration and staff of the University of Denver and the staff of the Remote Sensing Institute is greatly appreciated. Micro Processor Systems, Inc., of Stirling Heights, MI, supplied the PGA 9000 and Owatonna Tool Co. of Owatonna, MN, supplied their Model 3400, enabling us to experiment with new tools which we believe will be vital to the repair industry for diagnosing and fixing on-road emissions problems. Our gratitude is also extended to Envirotest for allowing us to use one of their facilities to perform IM240 followup testing at much greater convenience to us.

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