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Authors

Michaelian, Mark
Browand, Fred

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Mark Michaelian, Fred Browand
University of Southern California

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Field Experiments Demonstrate Fuel Savings for Close-Following

by

Mark Michaelian and Fred Browand
Department of Aerospace and Mechanical Engineering
University of Southern California
Los Angeles, California 90089-1191

Overview

The California PATH is a joint venture of the University of California, and the California Department of Transportation in collaboration with private groups (such as the University of Southern California) to develop more efficient transit and highway systems. The goal of PATH is to increase the capacity of the most frequented highways and to decrease traffic congestion, air pollution, accident rates, and fuel consumption.

There are only two ways to increase the throughput of vehicles on a highway—either construct more freeway lanes, or accommodate a shortened average spacing between individual vehicles (while maintaining speed). Providing a rational means for close-following is an attempt to accomplish the latter.

The maximum throughput for a typical freeway lane is about 2000 vehicles/hour, and is roughly independent of the attributes of any particular freeway. The number is remarkably inelastic—varying little over the past twenty years in spite of great improvements in the design of freeways and in the handling characteristics of automobiles (see Browand, Zabat & Tokumaru, 1997, for a recent example). Surprisingly, the average vehicle spacing at maximum throughput is approximately 35 meters. Shortening this headway to the order of a car length (five meters, typically) while maintaining a high speed would provide a significant improvement in throughput. Practical estimates that take into account safety—particularly in wet weather—suggest that a factor of between two and three improvement in throughput may be a reasonable goal (Kanaris, Ioannou & Ho, 1997).

It was recognized early-on that close-following would likely decrease the average vehicle drag, and therefore also decrease the average fuel consumption. At the time, we were aware of no information in the open literature quantifying the drag savings for a series of closely spaced vehicles. Of equal importance to the individual operators, is the question of how drag and fuel savings are apportioned between the various vehicles within any close-following group. Aerodynamic wind tunnel experiments were undertaken at the University of Southern California in 1991 to provide new information on drag savings for each of the individual vehicles comprising the platoon. Quantitative information on drag was available in 1994 and published in 1995 (see Zabat, et al., 1995a; Zabat, et al., 1995b). Several of the interesting general conclusions to come from this work are: that drag saving can be substantial for the 1991 Lumina van models tested—for example, the average savings is 35% for a four-vehicle platoon at a spacing of 0.5 vehicle length; that *all* vehicles in the close-following group participate in the drag saving, including the lead vehicle. An attempt was made to generalize these results in so far as possible, and to estimate what these wind tunnel measured drag savings would mean in terms of improved fuel economy. For this purpose, the method devised by Sovran and Bohn (discussed in Sovran & Bohn, 1981; Sovran, 1983) was utilized. The method consists of relating fuel consumption to total power expenditure while operating over the Highway Driving Cycle established by the Environmental Protection Agency in the early 1980's. The contributions to fuel expenditure from drag, rolling resistance, auxiliary power, are all identified explicitly. For our application, the sensitivity coefficient for drag then relates *changes* in fuel consumption to the *changes* in drag associated with close-following. Estimates were made for possible fuel savings based upon wind tunnel measurements of drag savings for close following in Zabat, et al., 1995a, 1995c, for the Lumina vans as a function of spacing and number of vehicles in the platoon.

In the summer of 1997, close-following platoon operation was first demonstrated in this country by PATH. The trial utilized eight Buick LeSabres under fully automatic longitudinal and lateral control, operating within a 12 kilometer stretch of limited-access freeway situated just north of San Diego. It was also recognized that sufficient information was available to directly monitor the instantaneous fuel consumption by making use of outputs from the Power Control Module (PCM computer), and the control system outputs normally recorded during platoon operation. Indeed the only additional quantity needing to be recorded is the fuel injector pulse width, and this is available from the PCM. PATH personnel made modifications to the programming to include the acquisition of the fuel injector signal in the spring of 1999.

The results reported are from tests on July 6-8, 1999, on a limited-access 12km section of I -15 in San Diego. The tests involved 2, 3 and 4-car platoons operated and maintained by PATH personnel under the auspices of CALTRANS and utilized Buick LeSabre sedans under fully automatic longitudinal and lateral control. Multiple sensor data was acquired, including the fuel injector pulse width.

We demonstrate that the fuel injector pulse width, in combination with engine RPM and forward speed, can be used to determine accurate estimates of instantaneous fuel consumption. The repeatability for total fuel consumed over a 2.4 km portion of the test path is ±1% based upon multiple single car runs over the three day period, with the major portion of the uncertainty arising from changing wind conditions.

Fuel savings for individual vehicles vary from 0-10% depending upon number of vehicles, vehicle spacing, and vehicle position within the platoon. Fuel savings increase with additional vehicles, and with shortened vehicle spacings. Interior vehicles gain the greatest benefits—consistent with the decreases in aerodynamic drag seen in previous wind tunnel tests (Zabat, et al., 1995a,b).

TESTING PROCEDURES

THE TEST SITE

A 12-kilometer portion of Interstate-15 just north of San Diego contains two limited-access lanes operated by the California Department of Transportation. The two HOV lanes and two service lanes are situated in the center of I-15, sandwiched between four lanes of northbound and four lanes of southbound traffic. A standard concrete divider (approximately one meter in height) divides the HOV lanes (and service lanes) from the normal freeway traffic. The lanes are normally opened to in-bound (San Diego bound) traffic during the morning hours and are opened to outbound traffic in the afternoon. For a two-week period in July, between 9:30 AM and 1:30 PM, the lanes were made available to PATH personnel for platoon operation.

The HOV lanes begin at the Caltrans south control yard (Kearny Mesa off-ramp) and run north to Ted Williams Parkway/Route 56. For the platoon fuel economy tests described here, the runs begin at a point three kilometers north of the south terminus and extend approximately six kilometers to Ted Williams Parkway/Route 56. A central 2.4-kilometer section is chosen for the fuel consumption calculations. Within this interval the vehicles have established their proper platoon configuration, and are traveling at the target speed of 96.6 kph (60 mph).

The topography of this 2.4 kilometer section is displayed in Figure 1(a),(b). Note that the vertical scale in 1(b) is exaggerated by a factor of 200. As can be seen, there are elevation changes along the section. From the south end to the north end, the elevation rise is approximately 12 meters. This may seem like an inconsequential rise but, in fact, the test results clearly show the effect of work done in lifting the vehicles against gravity. For this reason, it is important that the tests be carried out on a round trip circuit—that is, in *both* directions over the identical portion of the roadway.

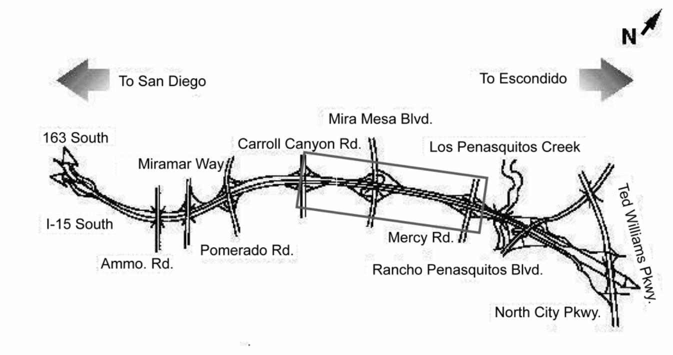

Figure 1(a). Plan view of 2.4 km testing section of HOV lane on I-15.

Absolute position along the roadway is established by means of the embedded magnetic markers. The

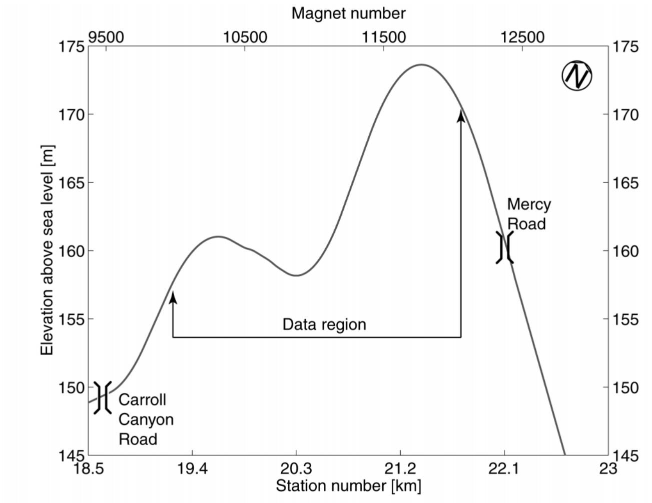

Figure 1(b). Elevation of 2.4 km testing section of HOV lane on I-15.

markers—placed at 1.2m intervals along the center of the lane—are utilized for lateral vehicle control. Magnetometers, spaced across the width of each car under the front bumper, sense the lateral position of the vehicle with respect to the magnets. The resolution of lateral position is of the order of one centimeter. In addition, the buried magnets have arbitrary polarity, and the entire array represents a coded sequence so that magnetometer signals can be translated to give unambiguous distance information. Magnet number, or position along the roadway, is one of the thirty-one signals output from the computer-control system and recorded during each run.

TEMPERATURE AND WIND SPEED

Temperature and wind speed were recorded at a central position within the 2.4 kilometer test segment (between Carroll Canyon Road and Mira Mesa Blvd). Ambient air temperature in the shade was determined with a digital thermometer. On test days July 6 and 7, the temperature at 9:30am was about 24°C and rose to about 28°C by 1:30pm. On test day July 8, the temperatures were higher—beginning at about 26°C and rising to 33°C by early afternoon. Since the differences in fuel consumption during platoon operation result from differences in drag, and differences in drag are directly proportional to ambient density, the changes in temperature will reflect changes in drag. However, these drag differences are small—of the order of one percent—and can be anticipated to produce differences in fuel expenditure of the order of half this amount. Therefore no temperature correction has been attempted.

Wind speed was recorded by means of a small vane anemometer mounted on a tripod. The anemometer, manufactured by Taylor Industries, logs the total number of vane revolutions, and reads directly in feet. Dividing by the time interval gives the estimated average wind speed. Two-minute average wind speeds were determined at intervals throughout the test period at three tripod positions—3.05 meters above the ground in the center of the service lane immediately west of the HOV lanes, 1.22 meters above the ground in the center of the service lane, and 1.22 meters above the ground in the center of the northbound HOV lane used for the tests.

On the three test days, the wind was observed to blow from the north— almost directly parallel to the test portion of I-15. Very roughly, on July 6-7, the wind speed parallel to the freeway in the HOV lane was in the range 2-3 meters/second. On July 8 the speed increased to the range 3.5-4 meters/second. Interestingly, the wind speed measured in the service lane just to the west of the HOV lane is consistently higher by the order of one meter/second. This difference can be attributed to the induced flow produced by a relatively steady southbound traffic. A similar northbound traffic produces an equal and oppositely directed induced flow on the opposite side of the freeway, and the two effects cancel where the HOV lanes are situated.

TEST PROTOCOL/RUN SCHEDULE

Platoons of two, three and four cars are formed and operated at spacings of 3m, 4m, 5m, and 6m. In terms of the length of the Buick LeSabre, 5.1 meters, the spacings become 0.59, 0.78, 0.98, and 1.18 vehicle lengths. Specifically, the two-car platoon and the three-car platoon are tested at all four spacings; the four-car platoon is tested at 0.78, 0.98, and 1.18 vehicle lengths. Several such platoon configurations are illustrated in Figures 2 and 3. All of the configurations were first run

Figure 2 Four Buick LeSabres in formation south-to-north in the HOV lane (I-15).

south-to-north and then returned north-to-south. We shall refer to this as a round trip. During the three test days, twenty-two separate round trips are recorded. For some cases multiple round trips are made for the same configuration: in other cases we must make do with a single realization. All the two-car results are averages of two independent realizations. The three-car platoon result at the spacing of 3 meters is an average of two realizations. The four-car platoon result at the spacing of 4 meters is an average of five realizations. Two round trips each testing day (six of the twenty-two) are made for each car running separately. These runs are made to establish the baseline fuel consumption for each vehicle over the same 2.4 km section. It will be seen shortly that the fuel consumption values measured for each vehicle operating alone are similar, but not identical. To properly account for the differences between vehicles, all of our fuel consumption estimates for close-following will be expressed as a fraction of the value obtained for the *identical vehicle* traveling alone. Because conditions of wind and temperature change over the test period, we feel the most

Figure 3. Buick LeSabres in formation north-to-south in the HOV lane (I-15).

reliable procedure is to take the fuel consumption values determined for each car in a given close following configuration, and to normalize by the *nearest adjacent (in time)* respective single car fuel consumption value. The close-following trips are never separated by more than an hour from respective single car trips.

In all, six PATH engineers participated as drivers in the tests, and the successful completion of the experiment is due in no small measure to their willing cooperation and professionalism. They are: Benedicte Bougler, Dan Empey, Pushkar Hingewe, Xiao-Yun Lu, David Nelson, and Han-Shue Tan.

DATA ACQUISITION AND DATA REDUCTION

DIGITIZED SIGNALS

The Buick LeSabres designed for close-following employ radar sensors to monitor spacing, and magnetometer sensors for lane keeping. These inputs must be accompanied by the appropriate computer algorithms to allow autonomous steering, throttling, and braking. A variety of engine parameters (thirty in all) are recorded digitally during normal platooning operations. Of particular use in this study are engine rpm, forward velocity, absolute position on the roadway (magnetic marker position), intake manifold pressure, brake pressure, and longitudinal acceleration. The last three are not used directly, but prove useful in evaluating the quality of the individual trips. These data, sampled continuously at 100 Hz, are stored in a laptop computer installed next to the driver.

To obtain estimates of instantaneous fuel consumption for each car, the engine fuel injector signals must be added to this list. The engine Power Control Module (computer) generates a pulse train that is output to the fuel injectors to establish the timing and duration of fuel injector openings and closings. Since engine rpm gives the timing, it is the pulse width, or duration, that must be determined.

Instantaneous pulse width is evaluated by counting between the rise and fall of the voltage signal at the rate of 1 MHz. Since typical pulse widths are the order of 5 milliseconds, the pulse width will be determined with an accuracy of better than one part in 10^3. The count is stored in a buffer, and is updated on the next pulse counted. The buffered number is read out at 100 Hz as part of the previously described data string.

At the termination of each one-way run, the data sets are transferred to hard disk in the laptop. At the end of each day of testing, the runs for the day are written to Zip disk. Each file for each car is roughly 3/4 Mb in size, so the total data set comprises approximately 200 Mb.

SMOOTHING

Examples of the digitized signals as they come from the laptop are shown along the top row in Figure 4. The signals are, respectively, forward velocity, engine rpm and fuel injector pulse width. The signals are plotted as a function of (absolute) magnetic marker position within the 2.4 km test interval described earlier. The bottom row contains the same signals now interpolated upon a 2000 point grid to insure uniform spacing, and smoothed with a cubic spline. The lower row of signals are used to determine fuel consumption over any desired interval.

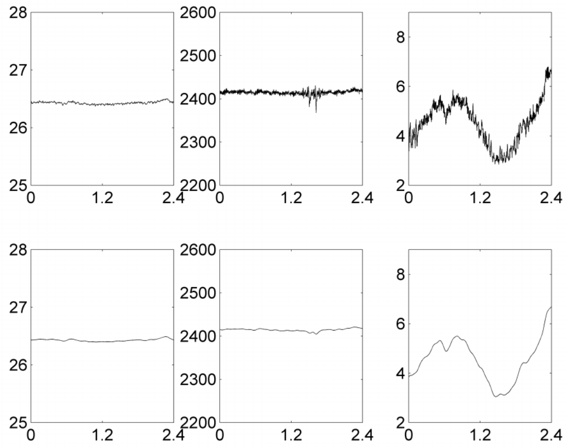

Figure 4. Top row, respectively forward speed (m/s), engine rpm, and fuel injector pulse width (ms), for a representative south-to-north run over a 2.4 km test interval. Bottom row, the same three signals filtered with a cubic spline.

THE EXPRESSION FOR FUEL EXPENDITURE

By fuel expenditure we mean the rate of fuel usage. The fuel injector operates as a valve. For pulse times above a small threshold time, the grams of fuel delivered during a single pulse is linearly proportional to the open time, or pulse width (PW). Thus,

$$\frac{\text{gm}}{\text{pulse}} = C_1 * [\text{PW}],$$

where PW is the pulse width measured in milliseconds, and the constant C_1 = .002826 gm/ms, for the injectors used on the Buick LeSabre. (This information was kindly supplied by Andrew Degner of Delphi Automotive Systems.) There is one pulse per cylinder every other crankshaft revolution for a four cycle engine, and the rate of fuel expenditure in gm/sec becomes,

$$\frac{\text{gm}}{\text{sec}} = C_1 * [\text{PW}] * \left[\frac{\text{RPM}}{2}\right] * N * \left(\frac{1}{60}\right),$$

where RPM is revolutions per minute and N is the number of cylinders (six in this case). The corresponding volume flow rate is given by dividing by the density of gasoline, ρ,

$$\frac{\text{ml}}{\text{sec}} = \left[\frac{C_1}{\rho}\right] * [\text{PW}] * \left[\frac{\text{RPM}}{2}\right] * N * \left(\frac{1}{60}\right).$$

Finally the expression for ml/km is obtained by dividing by the speed of travel, V,

$$\frac{\text{ml}}{\text{km}} = C_2 * [\text{PW}] * \frac{[\text{RPM}]}{[\text{V}]},$$

and all the constant quantities in the previous expression have been lumped into C_2. Thus instantaneous fuel expenditure requires the quantity [PW]*[RPM]/[V] to be determined at every point along the path. These quantities—as illustrated in Figure 4 for a representative run—are available at every digitization step. Fuel expenditure can also be averaged over any desired portion of the roadway. When fuel consumption estimates are presented in the results section, the value of C_2 must be known and applied. For pulse width in milliseconds, rpm in revolutions per minute, and velocity in meters/second, the dimensional constant C_2 takes the value, $C_2=0.20779$. The expression for gallons/mile is identical, with the constant C_2 adjusted to the value $C_2=8.833\text{x}10^{-5}$. Many of our results are expressed as a *ratio* of fuel consumption in close-following to fuel consumption in isolation. Note that this *ratio* is independent of the value of C_2, since the constant will appear in both numerator and denominator and cancel out.

THE IMPORTANCE OF ROUND TRIPS

It was mentioned earlier that an elevation change occurs from the south end to the north end of the test interval, and that the elevation change will result in a different fuel expenditure for the same vehicle depending upon the direction of travel. This circumstance is easily observed by viewing the fuel injector signals for the same vehicle—in this case car P4—as it travels in isolation in both directions over the 2.4 km test interval (Figure 5). The fuel injector pulse width for the two cases are almost mirror images of one another. This primarily reflects changes in elevation along the test path. The peaks in south-to-north travel—corresponding to valleys in north-to-south travel—are the portions of steepest roadway slope. At these locations, the vehicle is either going uphill or downhill depending upon the direction of travel. The curves cross at the three points representing the crests and troughs in the roadway. All three points fall at the identical pulse width of about 5 milliseconds, representing travel on a level roadway (neglecting any small effect from wind on this day).

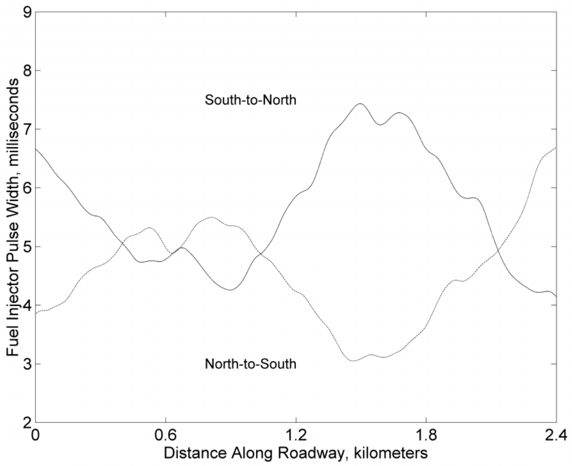

Figure 5. Vehicle P4 traveling south-to-north and north-to-south over the same section of roadway.

Many of the small features in the fuel injector pulse width signal are reproducible from one run to another. For example, the slight relative minimum at 0.65 km (north-to-south) is always present, as is the slight dip at 1.6 km (more prominent south-to-north). The dip at 0.65 km can be traced to the very small change in roadway slope occurring in Figure 1(b) in the vicinity of the Mira Mesa overpass (at magnet number 10,500).

One possible means for evaluating fuel expenditure would be to take out the effects of non-zero road slope by seeking these crossing points. It was felt that more reliable estimates are obtained by averaging the signals over the entire 2.4-kilometer distance. Since the average is greater for south-to-north travel because there is more uphill travel in this direction, a proper measure of average fuel expenditure must insure each vehicle returns to the starting point elevation by summing south-to-north and north-to-south runs.

Referring again to Figure 1(b), the steepest portion of the roadway within the 2.4 km test portion is seen to lie between markers 11,000 and 11,500. When traveling north-to-south, this section is a downhill pitch, and many of the vehicles in platoon travel must apply a slight brake pressure to maintain constant speed. A typical sample north-to-south run is illustrated in Figure 6. The vehicle, P4, is the interior vehicle in a 3-vehicle platoon. Vehicle rpm falls (bottom row, 1st panel), but evidently not enough to control forward speed. A slight brake pressure is applied, as shown in the top row, 1st panel. One would imagine that additional fuel expenditure would be used to compensate the power dissipated in the braking process. In order to assess this effect, a second test circuit was formed by simply removing from consideration the portion of the roadway between magnetic marker 11,000 and magnetic marker 11,500. This second test circuit is referred to as the 1.8km abridged round trip.

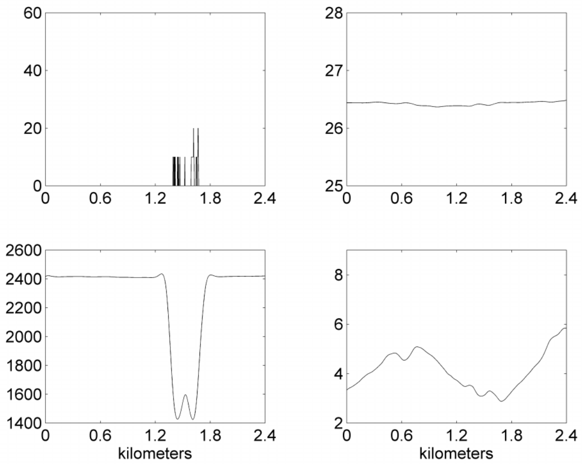

Figure 6. Illustration of slight braking on steepest portion of roadway during north-to-south travel. Data for P4 - the middle car in a 3-car platoon. Top row respectively, brake pressure (psi), and forward speed (m/s): bottom row, engine rpm, and fuel injector pulse width (ms).

RESULTS

FUEL CONSUMPTION FOR SINGLE CARS

The six single-car trips for vehicle P8 are displayed in Figure 7. To again illustrate the differences observed depending upon direction of travel, each round trip is divided into the south-to-north and north-to-south components. The uppermost circles give the fuel consumption (liters per kilometer and gallons per mile) for the south-to-north journey over the 2.4-kilometer test distance. The lowermost circles give the fuel consumption for the return (north-to-south). Note the expanded vertical scale.

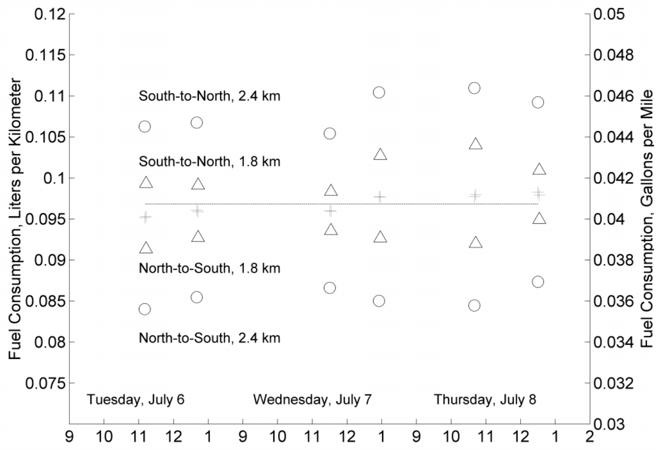

Figure 7. Fuel consumption, one-way (run) averages and two-way (trip) averages for single car, P8. The dotted line is the mean value of fuel consumption for the three-day test period. The + symbols represent the two-way (trip) averages.

The difference in fuel consumption for south-to-north and north-to-south trips is about twenty-five percent, and is easily measurable. The triangles show the same data, but now over the 1.8km abridged portion of the test circuit leaving out the one-quarter of the roadway having the steepest road slope. Because slopes are less steep, the differences between south-to-north and north-to-south travel are smaller, of the order of ten percent. *What is most important, however, is that the trip averages, indicated by the crosses, are virtually identical.* In fact they differ by less than 0.1 percent. Thus the fuel consumption measurement is independent of the particular path chosen, provided a round-trip circuit is always made.

A measure of the repeatability or reliability of the fuel consumption estimations can be obtained by comparing the trip averages for the six runs (Figure 8). A slight upward trend is observed over the three days; the three trips beginning in the early afternoon on July 7 and extending through July 8 have slightly higher fuel consumption. (This increase is probably due to increased wind, of the order of 1-2 meter per second, rising in the early afternoon on Wednesday and continuing into Thursday. Drag is a quadratic function of relative wind speed, so a small increase in the ambient wind will produce changes in drag that do not precisely cancel out in a round-trip.) The mean of the trips (dotted line) is 0.0968 liters/km (0.0412 gpm), and the standard deviation—expressed as a percent of the mean value—is 0.0128. We believe this relative error of a little over one percent is a reasonable estimate of the overall accuracy of the fuel consumption estimates. Later plots will display a bar of plus-minus one standard deviation as a measure of data reliability and repeatability.

The values of trip average fuel consumption obtained during single car runs are shown in Figure 8 for all cars. Car P2 is used on July 6 and for a portion of July 7, and is replaced by P9 on July 8. We fail to obtain round trip data for car P4 during the last single car runs on July 8.

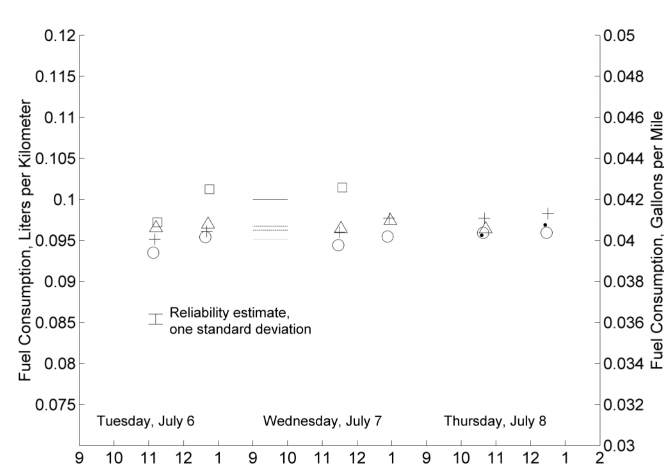

Figure 8. Fuel consumption averaged over the 2.4 kilometer round trip for all single cars during the three-day test (Legend: P2 - □; P4 - □; P6 - ○; P8 - +; P9 - •). Short lines near middle of plot represent mean values for each single car.

All other trips are shown. The cars have similar fuel consumption values, including a similar slight, rising trend during the three days. The mean values for each single car are displayed as the short dotted lines. The mean values lie within the range of our previously determined reliability estimate—with the exception of P2, which has a measurably greater fuel consumption.

FUEL CONSUMPTION FOR INDIVIDUAL VEHICLES IN CLOSE-FOLLOWING PLATOONS

The major fuel consumption results for close-following are displayed in Figures 9-11 for the individual cars in platoons of two, three and four vehicles, respectively. Again, all of the fuel consumption estimates for close-following are expressed as a fraction of the value obtained for the *identical vehicle* traveling alone over the same round-trip path. The upper numbers are for the full 2.4 kilometer section, the lower numbers are for the 1.8 kilometer abridged portion. The close-following trips are never separated by more than one hour from the adjacent single car trips used for normalization.

The first conclusion from the data is that the fuel consumption savings resulting from close-following do not depend upon which of the two round-trip paths are chosen. The differences between the round-trips are never more than 11 counts in 1000, and are usually much less. These differences—not exceeding about one percent—lie within the bounds of our estimate of measurement reliability.

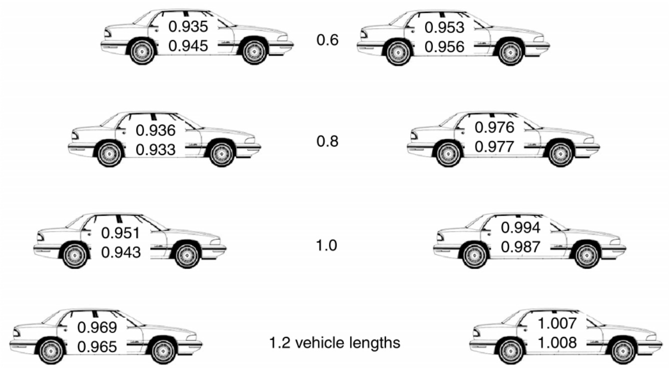

Figure 9. Fuel consumption for vehicles in a 2-vehicle platoon relative to fuel consumption for the identical single vehicle for the identical trip. Top numbers are for the 2.4 kilometer round-trip; bottom numbers for the less steep 1.8 kilometer portion.

Thus the slight braking that sometimes occurs on the steepest slope of the 2.4 kilometer round-trip, does not lead to measurable changes in the fuel consumption. Since the entire 2.4 kilometer round-trip is probably more representative of normal freeway terrain, we will henceforth use the upper set of numbers (and refer to the 2.4 kilometer trip) exclusively.

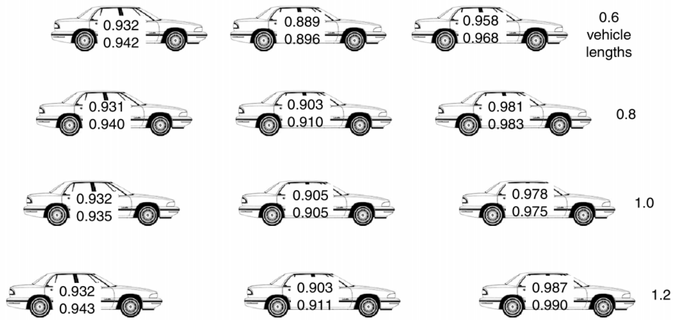

Figure 10. Fuel consumption for vehicles in a 3-vehicle platoon relative to fuel consumption for the identical single vehicle for the identical trip. Top numbers are for the 2.4 kilometer round-trip; bottom numbers for the less steep 1.8 kilometer portion.

Another important conclusion from Figures 9-11 is that interior vehicles gain the most benefit from close-following. Interior cars typically save about 10 percent in fuel consumption at the spacings tested,

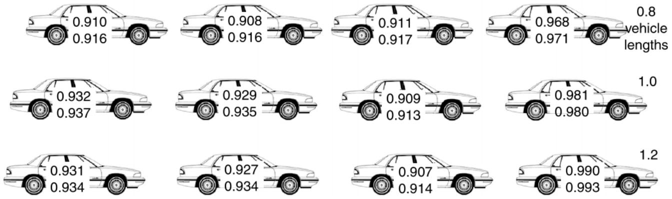

Figure 11. Fuel consumption for vehicles in 4-vehicle platoon relative to fuel consumption for the identical single vehicle for the identical trip. Top numbers are for the 2.4-kilometer round-trip; bottom numbers for the less steep 1.8-kilometer portion.

whereas the trailing vehicle saves fuel on the order of 7 percent. The lead vehicle saves least for all the spacings tested. Further insight can be obtained from a plot of fuel consumption versus spacing, as shown in Figure 12.

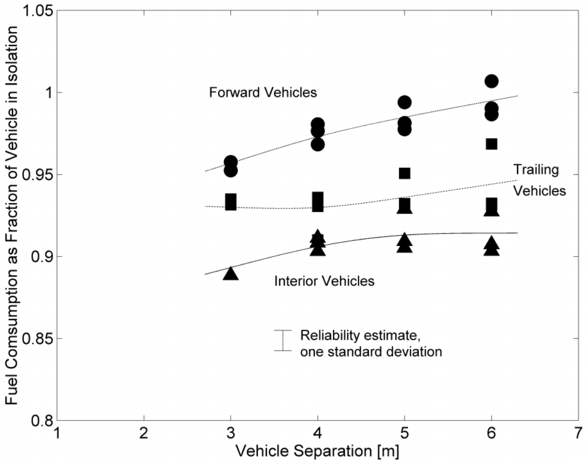

Figure 12. Fuel consumption for close-following relative to fuel consumption for a single vehicle over the same 2.4 kilometer round-trip. All results for 2-, 3-, and 4-vehicle platoons are plotted.

The vehicles in all platoons have been grouped into three categories; lead vehicles, trail vehicles, and interior vehicles. The solid lines represent cubic spline smoothing, with a stiffness chosen so that all the appropriate points lie within about one standard deviation of the smoothed curves. Again, the interior vehicles generate the most fuel savings; trail vehicles and lead vehicles follow in that order. Based upon the slopes of the spline fits, it is possible to extrapolate—crudely at least—and to conclude, for example, that the lead vehicle and interior vehicles will gain significant additional fuel savings at shorter spacings. It is indeed likely that at 1-1/2 - 2 meter spacing, the lead vehicle fuel consumption will become less than that of the trail vehicle!

The above results and extrapolations are qualitatively consistent with predictions that can be made from the drag behavior of platoons of 2-, 3-, and 4-vehicles as determined from previous wind tunnel tests (Zabat, et. al., 1995a,b), which show an equivalent cross-over between lead and travel vehicles observed in values of drag coefficient. These wind tunnel tests also showed that the interior vehicles in all platoons have the smallest values of drag coefficient, and would therefore be predicted to have the smallest fuel consumption, a prediction confirmed by the field test results.

Finally, comparisons can be made for the platoon-averaged fuel savings as a function of spacing between vehicles in the platoon. Figure 13 displays this information for each of the three platoons tested. The vertical axis represents the savings in fuel consumption

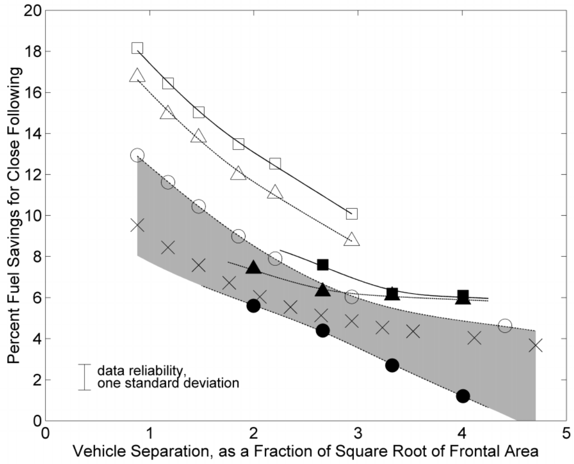

Figure 13. Averaged fuel savings for 2-, 3-, and 4-vehicle platoons. Filled symbols represent the present LeSabre field tests (● – 2 cars; ▲ – 3 cars; ■ – 4 cars). Open symbols (○ – 2 vans; △ – 3 vans; □ – 4 vans) represent predicted savings for 2-, 3-, 4-vehicle platoons over the EPA Highway Driving Schedule, based upon wind tunnel drag measurements for minivans (Zabat, et. al., 1995a). The × symbols represent a prediction for 2-vehicles based upon geometrically averaged minivan drag results (Zabat, et. al., 1995a). Gray band brackets a possible dependence upon vehicle geometry for two vehicle platoons.

averaged over all vehicles within the platoon, and expressed as a percentage of the isolation fuel consumption values. Field test results for platoons of size 2-, 3-, and 4-LeSabres are plotted as the filled symbols (● – 2 cars; ▲ – 3 cars; ■ – 4 cars). The open symbols (○ – 2 vans; △ – 3 vans; □ – 4 vans) represent predicted fuel savings for Lumina minivans driving the EPA Highway Driving Schedule, based upon the wind tunnel drag measurements (Zabat, et. al., 1995a). The separation between vehicles—the horizontal axis—is measured in units of the square root of the vehicle frontal area, √A. It is reasonable to suppose that the aerodynamic influence of one vehicle upon another will scale with the cross sectional area of the vehicle. Thus the minivan with a blunt base and large frontal area will have a stronger influence than a passenger car at the same physical separation. Scaling separation by √A is an attempt to bring the results for passenger cars and for minivans into as close agreement as possible. The curve marked by the × symbols is the fuel savings prediction for two vehicles based upon a determination of an average drag coefficient for two Lumina van models *in various orientations with respect to one another*. The different configurations are normal (back-to-front) orientation, front-to-back orientation, back-to-back orientation, and front-to-front orientation. This particular averaging scheme—the all-geometries average—is an attempt to establish a result that is, in so far as possible, independent of the particular shape of the models tested (Zabat et al., 1995a).

While the fuel consumption for the LeSabre sedan platoons was measured directly in the field tests, the minivan predictions in Figure 13 (open-symbols) require some further explanation. The predictions utilize the Standard Environmental Protection Agency Highway Driving Cycle in the manner detailed by Sovran & Bohn (1981) and Sovran (1983). The roadway in the EPA Highway Cycle is without hills, but there are accelerations and decelerations during the test. Sovran & Bohn establish the relationship between an incremental change in drag coefficient and the incremental fuel savings to be expected over this particular driving cycle. The relationship can be expressed as follows,

$$\%\ \text{fuel savings} = \xi * [\ \%\ \text{drag reduction}].$$

The quantity ξ is the influence coefficient, or sensitivity, and it has the following form for the specific EPA Highway Driving Cycle (Sovran 1983)

$$\xi = \frac{0.89}{1 + \frac{[0.031 r_0 + 0.000126]}{C_D A / M}}.$$

Clearly, the sensitivity depends upon the operating characteristics for each particular vehicle, as well as upon the driving cycle. In the expression above, r_o is the coefficient of rolling resistance; C_D, the drag coefficient of the single vehicle; A, the frontal area, and M is the vehicle mass. The expression is not dimensionless and A is measured in m^2, while M is measured in kilograms. The assumption is that the tests take place at standard sea level. For the GM Lumina, the following values are assumed: r_o=0.012, C_D=0.32, A=2.816 m^2 and M=1736 kilograms. The open symbols in Figure 13 (○ – 2 vans; △ – 3 vans; □ – 4 vans) represent the fuel savings that would be anticipated for the GM Lumina minivans in close-following geometries *based upon the drag reductions observed in previous wind tunnel tests* (Zabat et. al., 1995a). In comparing the field observations with the estimated fuel savings for minivans, several points must be remembered. The field test results are for Buick LeSabres, and the estimates are for Lumina vans—two different geometries. Second, the roadway for the present observations is different from the EPA Highway Driving Cycle, and no simple connection has been established. Finally, the prediction is termed optimal because it is assumed that the engine operates at the *same specific fuel consumption under the decreased load*. This is not possible without modification to the drive train as Sovran points out (Sovran, 1983), so the optimal predicted fuel savings will overestimate the actual fuel savings. For these reasons, comparisons must be approached with caution, but they are instructive nevertheless.

The gray area shown in Figure 13 represents the difference between the LeSabre field test result and our limited model predictions for the 2-vehicle GM Lumina minivan platoon. A similar band exists for the 3- & 4-vehicle platoon results, although these bands are not plotted for the sake of clarity. At vehicle separations of 2-3$\sqrt{A}$, the Buick LeSabre measurements and the minivan estimates differ by about 35% for all three platoon lengths. These differences are considerably greater than any estimated margin of error. Taken together, the two results probably bracket the results anticipated for other vehicle geometries. We expect car-like geometries to fall near the result for the Buick LeSabres, and the more bluff vehicle shapes—vans and SUV's—to fall nearer the minivan result. The differences between the two may be due in part to the uncertain use of the EPA Highway Driving Schedule, but it is more likely due to the real differences in geometry between vans and passenger cars. This supposition is supported by the geometrically-averaged vehicle result for the 2-vehicle platoon (the ×-symbols) in Figure 13, which lie within the region spanned by the limiting cases. The geometric difference effect on fuel consumption reduction in vehicle platoons has also been observed by Bonnet and Fritz (2000) in their observations of a platoon of two trucks.

Figure 13 also indicates that fuel savings increase substantially with decreased spacing between vehicles, and greater fuel savings can be confidently anticipated at even shorter spacings. The jump from 2- to 3-vehicles also results in a significantly increased saving at all vehicle spacings. This is because a middle car is sheltered front-to-back, and has the least drag. Adding a fourth car has the expected effect of increased fuel savings at the shortest spacing tested, since now two sheltered vehicles are present, although the difference between 3- and 4-vehicles is the same order as our experimental uncertainty estimates. Curiously, at larger spacing (spacing > $3\sqrt{A}$), the addition of the fourth vehicle has very little incremental effect—as the raw numbers in Figure 11 also bear out.

CONCLUSIONS

Determination of instantaneous over-the-road fuel consumption by monitoring vehicle RPM, vehicle speed, and most importantly fuel injector pulse width, is an accurate and relatively simple procedure. It may be of use in other applications.

Fuel savings for individual vehicles within a platoon are strongly correlated with position within the platoon for all the spacings tested (3m - 6m). Interior vehicles—that is, those having a car in front and a car in back—experience fuel savings of the order of 10% above the “traveling-in-isolation” value. Trail vehicles experience approximately 7% savings, and forward vehicles (lead vehicles) show a gain of 3-4%. However, at shorter spacings than those tested, our results indicate the forward vehicle would gain a greater relative advantage. These results are in qualitative agreement with previous wind tunnel tests on minivans.

Regarding the platoon as a whole, the average fuel savings for 2-, 3-, 4-LeSabre platoons at a spacing of 3 meters are 5.5, 7.5, and 8.5 percent, respectively. (The 3 meter 4-vehicle result is extrapolated.) Predicted fuel savings for platoons of minivans traveling the EPA Highway Driving Schedule are about 35 percent greater than these numbers. The two results taken together probably bracket the fuel savings for different car and minivan geometries, and different highway driving conditions.

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APPENDICES

APPENDIX A: DEMO ’99 EXPERIMENTAL RUN SCHEDULE

APPENDIX B: DEMO ’99 TEMPERATURE AND WIND DATA

APPENDIX A: DEMO ’99 EXPERIMENTAL RUN SCHEDULE

DEMO ‘99 runs: Vehicle P2

Run	**Filename**	**Spacing**	**Position, other cars in platoon**	**Riders**	**Notes**
Day 1: Tuesday, 7/6/99					
00	p2sn1_00.dat	6m	Car 2 of 2 car platoon (P6 - **P2**)	X.-Y. Lu	
01	p2ns1_01.dat	6m	Car 2 of 2 car platoon (P6 - **P2**)	X.-Y. Lu	
02	p2sn1_02.dat	4m	Car 2 of 2 car platoon (P6 - **P2**)	X.-Y. Lu	
03	p2ns1_03.dat	4m	Car 2 of 2 car platoon (P6 - **P2**)	X.-Y. Lu	
04	p2sn1_04.dat	∞	**P2**	X.-Y. Lu	
05	p2ns1_05.dat	∞	**P2**	X.-Y. Lu	
06	p2sn2_06.dat	4m	Car 2 of 4 car platoon (P6 - **P2** - P8 - P4)	D. Nelson & M. Michaelian	
07	p2ns2_07.dat	4m	Car 2 of 4 car platoon (P6 - **P2** - P8 - P4)	D. Nelson & M. Michaelian	
08	p2sn2_08.dat	4m	Car 2 of 4 car platoon (P6 - **P2** - P8 - P4)	D. Nelson & M. Michaelian	P6 - manual steering
09	p2ns2_09.dat	4m	Car 2 of 4 car platoon (P6 - **P2** - P8 - P4)	D. Nelson & M. Michaelian	P6 - manual steering Fully automatic steering at bottom of hill
10	p2sn2_10.dat	4m	Car 2 of 4 car platoon (P6 - **P2** - P8 - P4)	D. Nelson & M. Michaelian	P6 - steering ok
11	p2ns2_11.dat	4m	Car 2 of 4 car platoon (P6 - **P2** - P8 - P4)	D. Nelson & M. Michaelian	P6 - steering ok
12	p2sn2_12.dat	∞	**P2**	D. Nelson & M. Michaelian	
13	p2ns2_13.dat	∞	**P2**	D. Nelson & M. Michaelian	
Day 2: Wednesday, 7/7/99					
14	p2sn2_14.dat	4m	Car 2 of 4 car platoon (P6 - **P2** - P8 - P4)	H.-S. Tan & G. Landreth	
15	p2ns2_15.dat	4m	Car 2 of 4 car platoon (P6 - **P2** - P8 - P4)	H.-S. Tan & G. Landreth	P2 data incorrect
16	p2sn2_16.dat	3m	Car 2 of 2 car platoon (P6 - **P2**)	H.-S. Tan & G. Landreth	P2 data incorrect
17	p2ns2_17.dat	3m	Car 2 of 2 car platoon (P6 - **P2**)	H.-S. Tan & G. Landreth	P2 data incorrect
18	p2sn2_18.dat	∞	**P2**	H.-S. Tan & G. Landreth	
19	p2ns2_19.dat	∞	**P2**	H.-S. Tan & G. Landreth	
20	p2sn2_20.dat	3m	Car 1 of 3 car platoon (**P2** - P4 - P8)	H.-S. Tan & G. Landreth	Crest of hill came at 180 sec
21	p2ns2_21.dat	3m	Car 1 of 3 car platoon (**P2** - P4 - P8)	H.-S. Tan & G. Landreth	P2 - manual steering
22	p2sn2_22.dat	3m	Car 1 of 3 car platoon (**P2** - P4 - P8)	H.-S. Tan & G. Landreth	
23					Not in operation
24					Not in operation
25					Not in operation
26					Not in operation
27					Not in operation
Day 3: Thursday, 7/8/99					
28					Not in operation
29					Not in operation
30					Not in operation
31					Not in operation
32					Not in operation
33					Not in operation
34					Not in operation
35					Not in operation
36					Not in operation
37					Not in operation
38					Not in operation
39					Not in operation
40					Not in operation
41					Not in operation
42					Not in operation
43					Not in operation

DEMO ‘99 runs: Vehicle P9

Run	Filename	Spacing	Position, other cars in platoon	Riders	Notes
Day 1: Tuesday, 7/6/99					
00					Not in operation
01					Not in operation
02					Not in operation
03					Not in operation
04					Not in operation
05					Not in operation
06					Not in operation
07					Not in operation
08					Not in operation
09					Not in operation
10					Not in operation
11					Not in operation
12					Not in operation
13					
Day 2: Wednesday, 7/7/99					
14					Not in operation
15					Not in operation
16					Not in operation
17					Not in operation
18					Not in operation
19					Not in operation
20					Not in operation
21					Not in operation
22					Not in operation
23					Not in operation
24					Not in operation
25					Not in operation
26					Not in operation
27					Not in operation
Day 3: Thursday, 7/8/99					
28	p9sn1_28.dat	5m	Car 1 of 2 car platoon (P6 - **P9**)	D. Nelson & M. Michaelian	
29	p9ns2_29.dat	5m	Car 1 of 2 car platoon (P6 - **P9**)	D. Nelson & M. Michaelian	
30	p9sn2_30.dat	∞	**P9**	D. Nelson & M. Michaelian	
31	p9ns2_31.dat	∞	**P9**	D. Nelson & M. Michaelian	
32	p9sn2_32.dat	5m	Car 3 of 3 car platoon (P6 - **P9** - P8)	D. Nelson & M. Michaelian	
33	p9ns2_33.dat	5m	Car 3 of 3 car platoon (P6 - **P9** - P8)	D. Nelson & M. Michaelian	
34	p9sn2_34.dat	5m	Car 3 of 4 car platoon (P6 - **P9** - P8 - P4)	D. Nelson & M. Michaelian	
35	p9ns2_35.dat	5m	Car 3 of 4 car platoon (P6 - **P9** - P8 - P4)	D. Nelson & M. Michaelian	
36	p9sn2_36.dat	6m	Car 3 of 4 car platoon (P6 - **P9** - P8 - P4)	D. Nelson & M. Michaelian	
37	p9ns2_37.dat	6m	Car 3 of 4 car platoon (P6 - **P9** - P8 - P4)	D. Nelson & M. Michaelian	
38	p9sn2_38.dat	6m	Car 3 of 3 car platoon (P6 - **P9** - P8)	D. Nelson & M. Michaelian	
39	p9ns2_39.dat	6m	Car 3 of 3 car platoon (P6 - **P9** - P8)	D. Nelson & M. Michaelian	
40	p9sn2_40.dat	∞	**P9**	D. Nelson & M. Michaelian	
41	p9ns2_41.dat	∞	**P9**	D. Nelson & M. Michaelian	P8 - brake failure @ end
42	p9sn1_42.dat	4m	Car 3 of 4 car platoon (P6 - **P9** - P8 - P4)	D. Nelson & M. Michaelian	
43	p9ns1_43.dat	4m	Car 3 of 4 car platoon (P6 - **P9** - P8 - P4)	D. Nelson & M. Michaelian	

DEMO ‘99 runs: Vehicle P4

Run	Filename	Spacing	Position, other cars in platoon	Riders	Notes
Day 1: Tuesday, 7/6/99					
00	p4sn2_00.dat	6m	Car 1 of 2 car platoon (**P4** - P8)	D. Nelson & M. Michaelian	
01	p4ns2_01.dat	6m	Car 1 of 2 car platoon (**P4** - P8)	D. Nelson & M. Michaelian	
02	p4sn2_02.dat	4m	Car 1 of 2 car platoon (**P4** - P8)	D. Nelson & M. Michaelian	
03	p4ns2_03.dat	4m	Car 1 of 2 car platoon (**P4** - P8)	D. Nelson & M. Michaelian	
04	p4sn2_04.dat	∞	**P4**	D. Nelson & M. Michaelian	
05	p4ns2_05.dat	∞	**P4**	D. Nelson & M. Michaelian	
06	p4sn1_06.dat	4m	Car 4 of 4 car platoon (P6 - P2 - P8 - **P4**)	X.-Y. Lu	P4 - smooth
07	p4ns1_07.dat	4m	Car 4 of 4 car platoon (P6 - P2 - P8 - **P4**)	X.-Y. Lu	
08	p4sn1_08.dat	4m	Car 4 of 4 car platoon (P6 - P2 - P8 - **P4**)	X.-Y. Lu	P6 - manual steering
09	p4ns1_09.dat	4m	Car 4 of 4 car platoon (P6 - P2 - P8 - **P4**)	X.-Y. Lu	P6 - manual steering - automatic at bottom of hill
10	p4sn1_10.dat	4m	Car 4 of 4 car platoon (P6 - P2 - P8 - **P4**)	X.-Y. Lu	P6 - steering ok
11	p4ns1_11.dat	4m	Car 4 of 4 car platoon (P6 - P2 - P8 - **P4**)	X.-Y. Lu	P6 - steering ok
12	p4sn1_12.dat	∞	**P4**	X.-Y. Lu	
13	p4ns1_13.dat	∞	**P4**	X.-Y. Lu	
Day 2: Wednesday, 7/7/99					
14	p4sn2_14.dat	4m	Car 4 of 4 car platoon (P6 - P2 - P8 - **P4**)	D. Empey & P. Hong	
15	p4ns2_15.dat	4m	Car 4 of 4 car platoon (P6 - P2 - P8 - **P4**)	D. Empey & P. Hong	
16	p4sn2_16.dat	3m	Car 2 of 2 car platoon (P8 - **P4**)	D. Empey & P. Hong	
17	p4ns2_17.dat	3m	Car 2 of 2 car platoon (P8 - **P4**)	D. Empey & P. Hong	
18	p4sn2_18.dat	∞	**P4**	D. Empey & P. Hong	
19	p4ns2_19.dat	∞	**P4**	D. Empey & P. Hong	
20	p4sn2_20.dat	3m	Car 2 of 3 car platoon (P2 - **P4** - P8)	D. Nelson & M. Michaelian	Crest of hill came at 180 sec
21	p4ns3_21.dat	3m	Car 2 of 3 car platoon (P2 - **P4** - P8)	D. Nelson & M. Michaelian & B. Bougler	P2 - manual steering
22	p4sn3_22.dat	3m	Car 2 of 3 car platoon (P2 - **P4** - P8)	D. Nelson & M. Michaelian & B. Bougler	
23	p4ns2_23.dat	3m	Car 2 of 3 car platoon (P6 - **P4** - P8)	D. Nelson & M. Michaelian	P2 - steering ailment - out
24	p4sn2_24.dat	∞	**P4**	D. Nelson & M. Michaelian	
25	p4ns2_25.dat	∞	**P4**	D. Nelson & M. Michaelian	
26	p4sn2_26.dat	4m	Car 2 of 3 car platoon (P6 - **P4** - P8)	D. Nelson & M. Michaelian	
27	p4ns2_27.dat	4m	Car 2 of 3 car platoon (P6 - **P4** - P8)	D. Nelson & M. Michaelian	
Day 3: Thursday, 7/8/99					
28	p4sn2_28.dat	5m	Car 2 of 2 car platoon (P8 - **P4**)	D. Empey & D. Lazarra	
29	p4ns2_29.dat	5m	Car 2 of 2 car platoon (P8 - **P4**)	D. Empey & D. Lazarra	
30	p4sn2_30.dat	∞	**P4**	D. Empey & D. Lazarra	
31	p4ns2_31.dat	∞	**P4**	D. Empey & D. Lazarra	
32					Not in operation
33					Not in operation
34	p4sn2_34.dat	5m	Car 4 of 4 car platoon (P6 - P9 - P8 - **P4**)	D. Empey & D. Lazarra	
35	p4ns2_35.dat	5m	Car 4 of 4 car platoon (P6 - P9 - P8 - **P4**)	D. Empey & D. Lazarra	
36	p4sn2_36.dat	6m	Car 4 of 4 car platoon (P6 - P9 - P8 - **P4**)	D. Empey & D. Lazarra	
37	p4ns2_37.dat	6m	Car 4 of 4 car platoon (P6 - P9 - P8 - **P4**)	D. Empey & D. Lazarra	
38					Not in operation
39					Not in operation
40	p4sn2_40.dat	∞	**P4**	D. Empey & D. Lazarra	
41	p4ns2_41.dat (**non-existent file**)	∞	**P4**	D. Empey & D. Lazarra	P8 - brake failure @ end
42	p4sn2_42.dat	4m	Car 4 of 4 car platoon (P6 - P9 - P8 - **P4**)	D. Empey & D. Lazarra	
43	p4ns2_43.dat	4m	Car 4 of 4 car platoon (P6 - P9 - P8 - **P4**)	D. Empey & D. Lazarra	

DEMO ‘99 runs: Vehicle P6

Run	**Filename**	**Spacing**	**Position, other cars in platoon**	**Riders**	**Notes**
Day 1: Tuesday, 7/6/99					
00	p6sn1_00.dat	6m	Car 1 of 2 car platoon (**P6** - P2)	B. Bougler	
01	p6ns1_01.dat	6m	Car 1 of 2 car platoon (**P6** - P2)	B. Bougler	
02	p6sn1_02.dat	4m	Car 1 of 2 car platoon (**P6** - P2)	B. Bougler	
03	p6ns1_03.dat	4m	Car 1 of 2 car platoon (**P6** - P2)	B. Bougler	
04	p6sn1_04.dat	∞	**P6**	B. Bougler	
05	p6ns1_05.dat	∞	**P6**	B. Bougler	
06	p6sn1_06.dat	4m	Car 1 of 4 car platoon (**P6** - P2 - P8 - P4)	B. Bougler	P4 - smooth
07	p6sn1_07.dat	4m	Car 1 of 4 car platoon (**P6** - P2 - P8 - P4)	B. Bougler	
08	p6sn1_08.dat	4m	Car 1 of 4 car platoon (**P6** - P2 - P8 - P4)	B. Bougler	P6 - manual steering
09	p6ns1_09.dat	4m	Car 1 of 4 car platoon (**P6** - P2 - P8 - P4)	B. Bougler	P6 - manual steering - automatic at bottom of hill
10	p6sn1_10.dat	4m	Car 1 of 4 car platoon (**P6** - P2 - P8 - P4)	B. Bougler	P6 - steering ok
11	p6ns1_11.dat	4m	Car 1 of 4 car platoon (**P6** - P2 - P8 - P4)	B. Bougler	P6 - steering ok
12	p6sn1_12.dat	∞	**P6**	B. Bougler	
13	p6ns1_13.dat	∞	**P6**	B. Bougler	
Day 2: Wednesday, 7/7/99					
14	p6sn1_14.dat	4m	Car 1 of 4 car platoon (**P6** - P2 - P8 - P4)	B. Bougler	
15	p6sn1_15.dat	4m	Car 1 of 4 car platoon (**P6** - P2 - P8 - P4)	B. Bougler	P2 - data incorrect
16	p6sn1_16.dat	3m	Car 1 of 2 car platoon (**P6** - P2)	B. Bougler	P2 - data incorrect
17	p6ns1_17.dat	3m	Car 1 of 2 car platoon (**P6** - P2)	B. Bougler	P2 - data incorrect
18	p6sn1_18.dat	∞	**P6**	B. Bougler	
19	p6ns1_19.dat	∞	**P6**	B. Bougler	
20					Crest of hill came at 180 sec
21					P2 - manual steering
22					
23	p6ns3_23.dat	3m	Car 1 of 3 car platoon (**P6** - P4 - P8)	H.-S. Tan & G. Landreth & B. Bougler	P2 - steering ailment - out
24	p6sn3_24.dat	∞	**P6**	H.-S. Tan & G. Landreth & B. Bougler	
25	p6ns3_25.dat	∞	**P6**	H.-S. Tan & G. Landreth & B. Bougler	
26	p6sn3_26.dat	4m	Car 1 of 3 car platoon (**P6** - P4 - P8)	H.-S. Tan & G. Landreth & B. Bougler	
27	p6ns3_27.dat	4m	Car 1 of 3 car platoon (**P6** - P4 - P8)	B. Bougler & G. Landreth	
Day 3: Thursday, 7/8/99					
28	p6sn1_28.dat	5m	Car 1 of 2 car platoon (**P6** - P9)	B. Bougler	
29	p6ns1_29.dat	5m	Car 1 of 2 car platoon (**P6** - P9)	B. Bougler	
30	p6sn1_30.dat	∞	**P6**	B. Bougler	
31	p6ns1_31.dat	∞	**P6**	B. Bougler	
32	p6sn1_32.dat	5m	Car 1 of 3 car platoon (**P6** - P9 - P8)	B. Bougler	
33	p6ns1_33.dat	5m	Car 1 of 3 car platoon (**P6** - P9 - P8)	B. Bougler	
34	p6sn1_34.dat	5m	Car 1 of 4 car platoon (**P6** - P9 - P8 - P4)	B. Bougler	
35	p6ns1_35.dat	5m	Car 1 of 4 car platoon (**P6** - P9 - P8 - P4)	B. Bougler	
36	p6sn1_36.dat	6m	Car 1 of 4 car platoon (**P6** - P9 - P8 - P4)	B. Bougler	
37	p6ns1_37.dat	6m	Car 1 of 4 car platoon (**P6** - P9 - P8 - P4)	B. Bougler	
38	p6sn1_38.dat	6m	Car 1 of 3 car platoon (**P6** - P9 - P8)	B. Bougler	
39	p6ns1_39.dat	6m	Car 1 of 3 car platoon (**P6** - P9 - P8)	B. Bougler	
40	p6sn1_40.dat	∞	**P6**	B. Bougler	
41	p6ns1_41.dat	∞	**P6**	B. Bougler	P8 - brake failure @ end
42	p6sn2_42.dat	4m	Car 1 of 4 car platoon (**P6** - P9 - P8 - P4)	B. Bougler & P. Hingewe	
43	p6ns2_43.dat	4m	Car 1 of 4 car platoon (**P6** - P9 - P8 - P4)	B. Bougler & P. Hingewe	

DEMO ‘99 runs: Vehicle P8

Run	**Filename**	**Spacing**	**Position, other cars in platoon**	**Riders**	**Notes**
Day 1: Tuesday, 7/6/99					
00	p8sn1_00.dat	6m	Car 2 of 2 car platoon (P4 - **P8**)	D. Empey	
01	p8ns1_01.dat	6m	Car 2 of 2 car platoon (P4 - **P8**)	D. Empey	
02	p8sn1_02.dat	4m	Car 2 of 2 car platoon (P4 - **P8**)	D. Empey	
03	p8ns1_03.dat	4m	Car 2 of 2 car platoon (P4 - **P8**)	D. Empey	
04	p8sn1_04.dat	∞	**P8**	D. Empey	
05	p8ns1_05.dat	∞	**P8**	D. Empey	
06	p8sn1_06.dat	4m	Car 3 of 4 car platoon (P6 - P2 - **P8** - P4)	D. Empey	P4 - smooth
07	p8ns1_07.dat	4m	Car 3 of 4 car platoon (P6 - P2 - **P8** - P4)	D. Empey	
08	p8sn1_08.dat	4m	Car 3 of 4 car platoon (P6 - P2 - **P8** - P4)	D. Empey	P6 - manual steering
09	p8ns1_09.dat	4m	Car 3 of 4 car platoon (P6 - P2 - **P8** - P4)	D. Empey	P6 - manual steering - automatic at bottom of hill
10	p8sn1_10.dat	4m	Car 3 of 4 car platoon (P6 - P2 - **P8** - P4)	D. Empey	P6 - steering ok
11	p8ns1_11.dat	4m	Car 3 of 4 car platoon (P6 - P2 - **P8** - P4)	D. Empey	P6 - steering ok
12	p8sn1_12.dat	∞	**P8**	D. Empey	
13	p8ns1_13.dat	∞	**P8**	D. Empey	
Day 2: Wednesday, 7/7/99					
14	p8sn2_14.dat	4m	Car 3 of 4 car platoon (P6 - P2 - **P8** - P4)	D. Nelson & M. Michaelian	
15	p8ns2_15.dat	4m	Car 3 of 4 car platoon (P6 - P2 - **P8** - P4)	D. Nelson & M. Michaelian	
16	p8sn2_16.dat	3m	Car 1 of 2 car platoon (**P8** - P4)	D. Nelson & M. Michaelian	
17	p8ns2_17.dat	3m	Car 1 of 2 car platoon (**P8** - P4)	D. Nelson & M. Michaelian	
18	p8sn2_18.dat	∞	**P8**	D. Nelson & M. Michaelian	
19	p8ns2_19.dat	∞	**P8**	D. Nelson & M. Michaelian	
20	p8sn2_20.dat	3m	Car 3 of 3 car platoon (P2 - P4 - **P8**)	D. Empey & P. Hong	Crest of hill came at 180 sec
21	p8ns2_21.dat	3m	Car 3 of 3 car platoon (P2 - P4 - **P8**)	D. Empey & P. Hong	P2 - manual steering
22	p8sn2_22.dat	3m	Car 3 of 3 car platoon (P2 - P4 - **P8**)	D. Empey & P. Hong	
23	p8ns2_23.dat	3m	Car 3 of 3 car platoon (P2 - P4 - **P8**)	D. Empey & P. Hong	P2 - steering ailment - out
24	p8sn2_24.dat	∞	**P8**	D. Empey & P. Hong	
25	p8ns2_25.dat	∞	**P8**	D. Empey & P. Hong	
26	p8sn2_26.dat	4m	Car 3 of 3 car platoon (P6 - P4 - **P8**)	D. Empey & P. Hong	
27	p8ns2_27.dat	4m	Car 3 of 3 car platoon (P6 - P4 - **P8**)	D. Empey & P. Hong	
Day 3: Thursday, 7/8/99					
28	p8sn1_28.dat	5m	Car 1 of 2 car platoon (**P8** - P4)	H.-S. Tan	
29	p8ns2_29.dat	5m	Car 1 of 2 car platoon (**P8** - P4)	H.-S. Tan & P. Hingewe	
30	p8sn2_30.dat	∞	**P8**	H.-S. Tan & P. Hingewe	
31	p8ns2_31.dat	∞	**P8**	H.-S. Tan & P. Hingewe	
32	p8sn2_32.dat	5m	Car 3 of 3 car platoon (P6 - P9 - **P8**)	H.-S. Tan & P. Hingewe	
33	p8ns2_33.dat	5m	Car 3 of 3 car platoon (P6 - P9 - **P8**)	H.-S. Tan & P. Hingewe	
34	p8sn2_34.dat	5m	Car 3 of 4 car platoon (P6 - P9 - **P8** - P4)	H.-S. Tan & P. Hingewe	
35	p8ns2_35.dat	5m	Car 3 of 4 car platoon (P6 - P9 - **P8** - P4)	H.-S. Tan & P. Hingewe	
36	p8sn2_36.dat	6m	Car 3 of 4 car platoon (P6 - P9 - **P8** - P4)	H.-S. Tan & P. Hingewe	
37	p8ns2_37.dat	6m	Car 3 of 4 car platoon (P6 - P9 - **P8** - P4)	H.-S. Tan & P. Hingewe	
38	p8sn2_38.dat	6m	Car 3 of 3 car platoon (P6 - P9 - **P8**)	H.-S. Tan & P. Hingewe	
39	p8ns2_39.dat	6m	Car 3 of 3 car platoon (P6 - P9 - **P8**)	H.-S. Tan & P. Hingewe	
40	p8sn2_40.dat	∞	**P8**	H.-S. Tan & P. Hingewe	
41	p8ns2_41.dat	∞	**P8**	H.-S. Tan & P. Hingewe	P8 - brake failure @ end
42	p8sn1_42.dat	4m	Car 3 of 4 car platoon (P6 - P9 - **P8** - P4)	H.-S. Tan	
43	p8ns1_43.dat	4m	Car 3 of 4 car platoon (P6 - P9 - **P8** - P4)	H.-S. Tan	

APPENDIX B: DEMO '99 TEMPERATURE AND WIND DATA

Notes:

- On Tuesday (7/7/99)--the truck is parked on westbound side of HOV, 4.5 miles from south end, just north of the Mira Mesa underpass and opposite Scripps Westview.
- On Wednesday/Thursday truck parked 0.2 miles north of Carroll Canyon overpass at marker 15:25.
- The thermometer is electronic, sensor is shaded in back of truck.
- Using the Taylor vane anemometer--it has not been calibrated recently.
- At position #1 anemometer is on tripod 76 1/4 inch above bed of truck, and approx. 103 3/4 inch above the ground.
- At position #2 anemometer is 15 feet north of truck in the west access lane. At the lowest position, it is 49 3/4 inch above ground. The concrete barrier, is about 4 feet to the west, and is about 3 feet high.
- At position #3 anemometer is between the two HOV lanes at this same low position.
- Wind readings on Tuesday are 6 minute averages, on Wed & Thurs they are 2 minute averages.

Run #	Time	#Car-Dir	temp [deg F]	wind #1 [ft/sec]	wind #2 [ft/sec]	wind #3 [ft/sec]
Day 1: Tuesday, 7-6-99						
1	9:56	2-N				
	10:00	2-N		13.3		
2	10:15	2-S				
	10:19	2-S		13		
	10:25		75	12.17		
3	10:34	2-N	76.7			
	10:38	2-N	76.7			
	10:38		77	13.4		
4	10:46	2-S				
	10:51	2-S				
	10:50		78.1	12.4		
5	10:58	1-N				
	11:00	1-N				
	11:03	1-N				
	11:05	1-N				
	11:03		79.9	10.8		
6	11:12	1-S				
	11:15	1-S				
	11:17	1-S				
	11:19	1-S				
	11:23		80.85	14.4		
7	11:32	4-N				
	11:36		80.9	13.8		
8	11:45	4-S				
	11:49		82.6	12.1		
9	11:54	4-N				
	11:59		82.6	12.7		
10	12:04	4-S				
	12:14		82.6	10.5		
11	12:16	4-N				
	12:22		82	13.1		
12	12:26	4-S				

Run #	Time	#Car-Dir	temp [deg F]	wind #1 [ft/sec]	wind #2 [ft/sec]	wind #3 [ft/sec]
	12:30		81.15	14.2		
13	12:33	1-N				
	12:35	1-N				
	12:37	1-N				
	12:39	1-N				
	12:42		81.5	13.4		
14	12:47	1-S				
	12:49	1-S				
	12:51	1-S				
	12:53	1-S				
Day 2: Wednesday, 7-7-99						
	10:00		76.6	7.1		
15	9:59	4-N				
	10:09	1-N				
	10:05		76.4		8.7	9.2
	10:25		78.6	13.8	12.2	
16	10:32	4-S				
	10:36		77.1	10.7	9.7	7.8
17	10:48	2-N				
	10:51	2-N				
	10:58		79.8	10	9.4	6.1
18	11:06	2-S				
	11:10	2-S				
	11:15		79.45	11.7	12.7	6.4
19	11:14	1-N				
	11:16	1-N				
	11:18	1-N				
	11:21	1-N				
20	11:37	1-S				
	11:40	1-S				
	11:43	1-S				
	11:46	1-S				
	11:50		81.8	11.5	12.2	5.6
21	11:56	1-N				
	11:58	3-N				
22	12:14	3-S				
23	12:24	3-N				
	12:30		78.85	11.2	10.8	9
24	12:39	3-S				
25	12:45	1-N				
	12:48	1-N				
	12:51	1-N				
	12:54		76.8	13.7	12.2	11.1
26	1:00	1-S				
	1:03	1-S				
	1:05	1-S				
27	1:14	3-N				
	1:19		75.9	14.9	12.9	8.3
28	1:30	3-S				
Day 3: Thursday, 7-8-99						
29	9:58	2-N				
	9:59	1-N				
	10:02	2-N				
	10:03		79.4	15.3	7.1	12.3
30	10:14	2-S				
	10:27	2-S				
	10:31		80.75	16.6	15.6	12.8
31	10:33	1-N				
	10:37	1-N				

Run #	Time	#Car-Dir	temp [deg F]	wind #1 [ft/sec]	wind #2 [ft/sec]	wind #3 [ft/sec]
	10:40	1-N				
32	10:50	1-S				
	10:52	1-S				
	10:55	1-S				
	10:58		83.8			
33	11:03	3-N				
	11:06		84.2	15.3	13.7	10.7
34	11:14	3-S				
35	11:24	4-N				
	11:27		86.15	15.2	15.9	11.8
36	11:35	4-S				
37	11:45	4-N				
	11:51		88.8	14.5	13.4	9.6
38	11:57	4-S				
	12:01		92.5			
39	12:03	3-N				
	12:13		94.2			
40	12:14	3-S				
	12:21		94.3	10.8	13.9	11.1
41	12:19	1-N				
	12:21	1-N				
	12:23	1-N				
	12:26	1-N	92.8			
42	12:35	1-S	91.4			
	12:37	1-S	89.4			
	12:40	1-S	89.2			
	12:42	1-S	89			
	12:48		87.3		14.9	11.7
43	12:52	4-N	85.3			
44	1:03	4-S	84			