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Fuel Saving Achieved in the Field Test of Two Tandem Trucks

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PATH PROGRAM TO-4214: FINAL REPORT

ABSTRACT

The fuel consumption of two tandem trucks is recorded for truck spacings of 3, 4, 6, 8, and 10 meters. The trucks are linked by means of an electronic control system, and are operated on an unused runway at Crows Landing, California. Fuel consumption data is averaged while traveling in both directions over the same central strip of runway to cancel the effect of runway slope and to partially cancel the effect of wind. The average fuel consumption saving to be achieved by tandem operation varies from about 11% at 3-4 meters spacing to about 8% at 8-10 meters spacing.

Key Words: Aerodynamic Modeling, Commercial Vehicle Operations,
Trucking, Vehicle Follower Control

EXECUTIVE SUMMARY

Two separate fuel consumption tests are described. The first takes place on October 30-31, 2003, and makes use of two identical Freightliner tractors pulling 53-foot trailers of similar outside geometry. One trailer is empty, and the second trailer contains the Mobile Emissions Research Laboratory developed and maintained by Matthew Barth at the University of California, Riverside. On October 30 the fuel emissions trailer is operated in the lead position, and measures real-time emission from the lead truck. On October 31, MERL performs the same function in the trailing truck position. Truck speeds on these two days is 22.4 m/s (50 mph). Five truck spacings in the range 3-10 m are examined. A total of 38 usable runs are accumulated.

A second and more extensive set of data is gathered on December 4-5, 2003. For these tests, the two 53-foot trailers are empty. The truck speed is slightly higher, 24.6 m/s (55 mph). From four to six passes in both directions are made for five truck-spacings in the range 3-10 meters for a total of approximately 75 runs.

The present two-truck close-following tests are performed on an unused airfield runway at Crows Landing at the northern end of the San Joaquin valley. The main runway is approximately 2400 meters in length, and is oriented roughly north-south. The runway slopes rather uniformly upward from north-to-south. Over the distance of 2290 meters between our two "start" markers at either end of the runway, the net change in elevation is a little over ten meters. Test results clearly show the greater fuel consumption required to lift the two trucks against gravity in the southbound direction. For this reason, it is important that the tests be averaged over a round trip circuit—that is, a run in *both* directions over the identical portion of the roadway.

Northbound-southbound averages require an overlap segment of the runway (near the middle of the runway) where the trucks—starting from either end—have achieved their target speed. This overlap region is approximately 350 meters in length. Typically a run and the return run are accomplished within about 5-8 minutes. Runs in isolation (∞ spacing), for which the two trucks proceed along the track separately, are interspersed liberally between the close-following runs. These runs are required, since it is the *difference* in fuel consumption between close-following and isolation that is of interest.

The measured fuel saving at a spacing of 10 meters is 10% and 6%, respectively, for the trail and lead truck. In the spacing range 3-10 m, fuel consumption savings lie in the range 10-12% for the trail truck and 5-10% for the lead truck—with the larger values of saving occurring at the shorter spacings.

Fuel Saving Achieved in the Field Test of Two Tandem Trucks

1. INTRODUCTION: EXPECTATION FOR FUEL SAVING

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 recognized early-on that close-following would likely decrease the average vehicle drag, and therefore also decrease the average fuel consumption.

Fuel consumption tests were performed by PATH in July of 1999, and reported in PATH Report UCB-ITS-PRR-2000-14 (see also Michaelian & Browand, 2001). The tests took place on the same limited-access 12 km section of I-15. Tests this time involved 2, 3, and 4-car platoons at spacings of 3, 4, 5 and 6 meters. The findings are that fuel savings for individual vehicles within a platoon are strongly correlated with position within the platoon for all 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%. 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, since no runs were made at this spacing.)

Bonnet and Fritz (2000) have reported on fuel consumption for two partially-loaded, tandem trucks at close spacing in connection with Project Chauffeur. Various spacing between 7 m and 14 m are investigated. As an example, at a spacing of 10 m and a speed of 80 km/hr (50 mph), their trail truck consumes about 20% less fuel and the lead truck consumes about 6% less fuel than a comparable truck in isolation. These are the only field tests of tandem trucks at close spacing known to us.

Browand and Hammache (2004) have described wind tunnel tests for two model trucks in tandem. In addition, simpler bodies of higher and lower drag coefficient were tested to determine the limits of possible drag behavior. These drag savings can be translated into fuel consumption savings for trucks of comparable drag coefficient by making assumptions about the operational state of the trucks.

In the report to follow, we describe two separate fuel consumption tests. The first takes place on October 30-31, 2003, and makes use of two identical Freightliner tractors pulling 53-foot trailers of similar outside geometry. One trailer is empty, and the second trailer contains the Mobile Emissions Research Laboratory developed and maintained by Matthew Barth at the University of California, Riverside. On October 30 the fuel emissions trailer is operated in the lead position, and measures real-time emission from the lead truck. On October 31, MERL performs the same function in the trailing truck position. Truck speeds on these two days is 22.4 m/s (50 mph). Five truck spacings in the range 3-10 m are examined. Rain on October 31 makes much of this second-day data unusable.

A second and more extensive set of data is gathered on December 4-5, 2003. For these tests, the two 53-foot trailers are empty. The truck speed is slightly higher, 24.6 m/s (55 mph). From four to six passes in both directions are made for five truck-spacings in the range 3-10 meters for a total of approximately 75 passes, or runs.

The test site, the trucks, and the data acquisition procedures are first described. Results are discussed beginning on page 12. A run summary—containing our fuel consumption evaluations for each run—is given in Appendix A for the data of October 30-31, and in Appendix B for the data of December 4-5.

2. THE CROWS LANDING SITE

The present two-truck close-following tests are performed on an unused airfield runway at Crows Landing at the northern end of the San Joaquin valley. The main runway is approximately 2400 meters in length, and is oriented roughly north-south, as shown in figure 1(a). The elevation of the runway—determined from our recent survey—is shown in exaggerated vertical scale in figure 1(b). As can be seen, there is an elevation change along the runway. The runway slopes rather uniformly upward from north-to-south. Over the distance of 2290 meters between our two “start” markers at either end of the runway, the net change in elevation is a little over ten meters. Because the runway is relatively flat, the elevation gain is difficult to see visually. However the test results clearly show the greater fuel consumption required to lift the two trucks against gravity in the southbound direction. For this reason, it is important that the tests be averaged over a round trip circuit—that is, a run in *both* directions over the identical portion of the roadway.

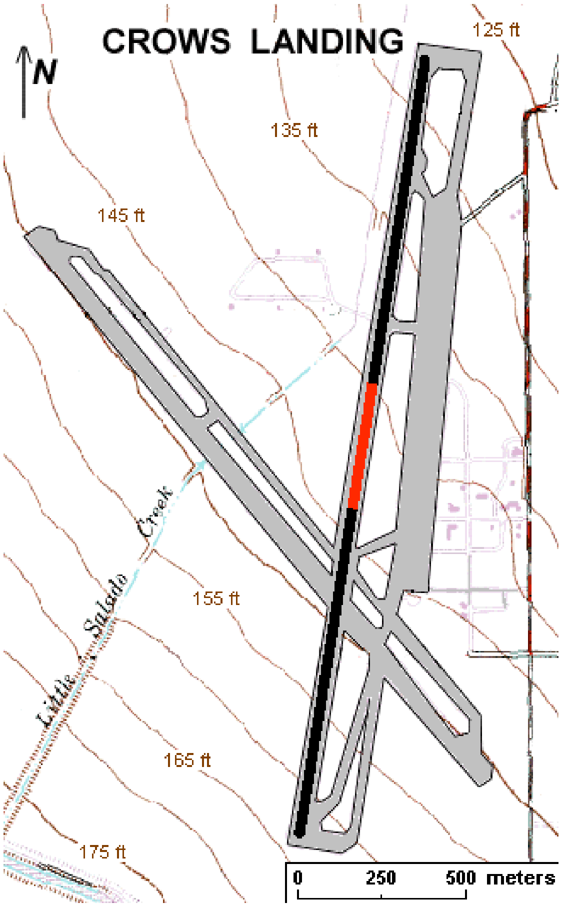

Figure 1(a). Plan view of the Crows Landing site. Red marks measurement area.

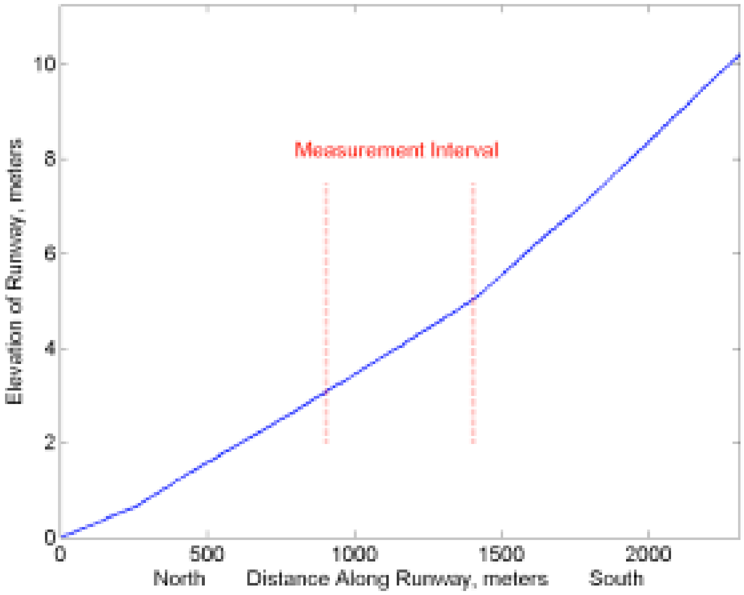

Figure 1(b). Runway elevation from North to South. Marked central section indicates the region of data acquisition.

The condition of the concrete runway surface is generally good. This surface is clean, and substantially free from cracks (and potholes).

3. TRUCKS AND TRAILERS

Two Freightliner 2001 Century Class trucks are available for the tests. The trucks are identical, and are powered by Cummins N14 Celect engines developing a maximum of 350 HP. The trucks have automatic transmissions. The engine controls have been modified to allow throttle and braking to take place under programmed computer control. The control algorithm includes input from a laser ranging device mounted on the front of the following truck. The control system is able to maintain a fixed separation between the trucks to within a tolerance of a few centimeters. As presently configured, the trucks have only longitudinal controls; lateral position is controlled in the conventional way by driver steering.

Figure 2 is a photograph of the two trucks running southbound on the runway at Crows Landing at a spacing of 3 meters. Another view is displayed in figure 3.

Figure 2. The two Freightliner trucks running southbound at 3-meter spacing, December 4, 2003.

The trailers are rented. They are standard 53 foot trailers chosen to be similar in make and tire condition. They are mounted in similar positions with respect to each truck. The 5th wheel is set three notches from the rear. The distance from the rear of the cab to the front of the trailer, measured at the center-plane, is in both cases 1.32 meters (52 inches). The distance from the downstream end of the cab extender to the front plane of each trailer is 0.84 meters (33 inches).

Rolling resistance is sensitive to tire inflation pressure. As a rule-of-thumb, a 10% increase (decrease) in tire pressure can decrease (increase) the rolling resistance by about 1%. For these tests, trailer tire inflation is set to 110 psig: truck tire inflation is set to 115 psig.

The single observable difference between the two rigs is that the forward trailer has a laser reflector plate attached to the rear bumper. It can be seen in Figure 2 just forward of the head lamps of the trailing truck, and can be seen more clearly in Figure 3.

The October tests feature real-time emissions measurements. The Mobile Emissions Research Laboratory (MERL) is owned and operated by the UC riverside, College of Engineering—Center for Environmental Research and Technology. MERL is housed in a standard 53-foot trailer as shown in Figure 4. The rear door is a pull-down. It can be open or closed, but when the emissions lab is operating, the rear door must be open—as in Figure 4(b).

Figure 3. A second view showing the laser reflector plate along the base of the lead truck below the door.

Tractors and trailers are weighed at standard weighing stations. There is one within twenty miles of Crows Landing. The tractors are weighed fully fueled. Weights are as follows:

Gold tractor: 8532 kg (83,614 N); Blue tractor: 8441 kg (82,722 N)
Emissions trailer: (MERL) 20,412 kg (200,038 N)
Rented trailer, October 30-31: 6296 kg (61,701 N)
Rented trailers, December 4-5: 6447 kg (63,181 N), 6831 kg (66,944 N)

The uncertainty in these weights is less than one percent.

(a) (b)

Figure 4. (a) UC Riverside mobile emissions research laboratory (MERL); (b) MERL operating as lead truck in platoon.

4. LOCAL WEATHER CONDITIONS

Temperature, humidity, wind speed and direction, and barometric pressure are recorded at the central position along the runway. The anemometer, and the temperature and humidity units are solar powered—the barometer is battery and solar powered. The anemometer and wind vane are placed on a staff 3 meters above the runway surface, and approximately 30 meters to the side of the truck line of travel. All instruments telemeter data to a central battery powered control unit (Oregon Scientific, model WMR 968). The data is digitized into a laptop computer by means of software provided by Ambient (www.WeatherConnect.com). Weather information is updated every minute.

On test days October 30-31, over the period of the testing, the temperature varies from a low of 48º to a high of 69º. The winds during the testing period are generally light at 4-5 mph. On October 31, testing began in light rain with standing water on the runway. The data, corresponding to runs 29-45, are not sufficiently reliable to be useful. By about 11:20 AM, the runway conditions improved so that runs 46-54 can be used.

On test days December 4-5, the temperature varies more narrowly from 52º to 63º, and the maximum wind speeds are somewhat higher at 7-8 mph. On all of the testing days, winds are observed to blow primarily either northward or southward along the axis of the valley. Since the runway is oriented approximately N-S, the wind direction is usually parallel to the runway.

5. TEST PROTOCOL & DATA ACQUISITION

5.1 RUNWAY LENGTH

The major operating constraint at the Crows Landing test site for these close-following tests is the limited length of the runway. Because there is insufficient width for the two vehicles to make a turn at either end of the runway, they must brake to a stop, turn and begin again. To cancel the unwanted influence of runway slope and wind (to lowest order, at least) the round-trip run must consist of the average of separate northbound and southbound runs. Northbound-southbound averages require an overlap segment of the runway (near the middle of the runway) where the trucks—starting from either end—have achieved their target speed. For the data of October 30-31, while the emissions trailer is in use, the top speed attainable is 50 mph—resulting in an overlap region of no more than 220 meters. This central region is traversed in 9.8 seconds. For the data of December 4-5, the two trailers are run empty and a top speed of 55 mph is attained in an overlap region of 340 meters length. The overlap is traversed in 13.8 seconds. In either case, the overlap is the region on the runway over which the northbound and southbound data are averaged.

Each run—from beginning to end—is made under the same computer algorithm control. A typical sequence starts at a fixed point at one end of the runway with the two trucks in close-following position. Computer control is initiated, data acquisition begins, and the trucks accelerate together as a close-following unit at the preset spacing. When the programmed acceleration ramp terminates, the two trucks continue along the runway at the preset cruise speed—for October 30-31 this speed is 22.34 meters/second; for December 4-5, the cruise speed is 24.58 meters/second. Distance along the track is determined by integration of the forward speed. At a pre-determined distance, the braking sequence is initiated, and the trucks slow to a stop at the far end of the runway. Data acquisition stops and the run file is logged in the computer. The trucks are turned, and made ready for the return from a second fixed point on the track. Typically a run and the return run are accomplished within about 5-8 minutes. Runs in isolation (∞ spacing), for which the two trucks proceed along the track separately, are interspersed liberally between the close-following runs. These runs are required, since it is the *difference* in fuel consumption between close-following and isolation that is of interest. The complete sequence of spacings used is {∞, 10, 8, ∞, 6, 4, ∞, 3, 3, ∞, 4, 6, ∞, 8, 10, ∞}. A sequence takes about three hours to complete. When a sequence is completed, a new sequence begins—as weather and time permit.

5.2 DIGITIZED SIGNALS & SMOOTHING

Examples of typical raw data signals for a pair of runs on December 4, 2003, are shown in Figure 5. The three plots are engine speed, forward speed and fuel rate, respectively, as a function of distance along the runway. Red is the southbound run (run 52) and blue is the northbound run (run 51), corresponding to the Gold truck running in isolation. In the top plot, the gear changes can be seen, as well as the region of uniform engine speed attained in the central section of the runway. The northbound run begins at the south end of the runway (blue), and the gear changes reflect this starting position. The step-wise drops in engine rpm (at 1650 meters for red, and 650 meters for blue) mark the end of the run and the beginning of the braking phase.

The overlap region where a constant speed is attained can clearly be seen in the central section of the runway—extending between about 850 and 1400 meters. The actual window used for data averaging is from 974 to 1316 meters. Within this window, the broadcast fuel rate is reasonably constant, but not free from fluctuation, as illustrated in the lowest of the three plots.

Three more plots are shown at increased magnification for this central portion of the runway. Figure 6 is vehicle speed, figure 7 is fuel rate, and figure 8 is the fuel rate divided by vehicle speed, giving fuel consumption directly in liters/kilometer.

The solid curve in figure 6 is a smoothing, cubic-spline. One can see the termination of the accelerated portion of each run, and the constant speed portion of the run. The average speed in the constant speed portion is pre-determined within the computer algorithm, and becomes 24.58 ±0.01 m/s—held within this tolerance for both trucks throughout the day.

In figure 7, the effect of truck acceleration on fuel rate can be seen to diminish and to disappear in the overlap (constant speed) region—974 to 1316 meters. However, the higher frequency *fluctuations* in fuel rate are still present, and contribute to the run-to-run *variability* of the estimated fuel consumption.

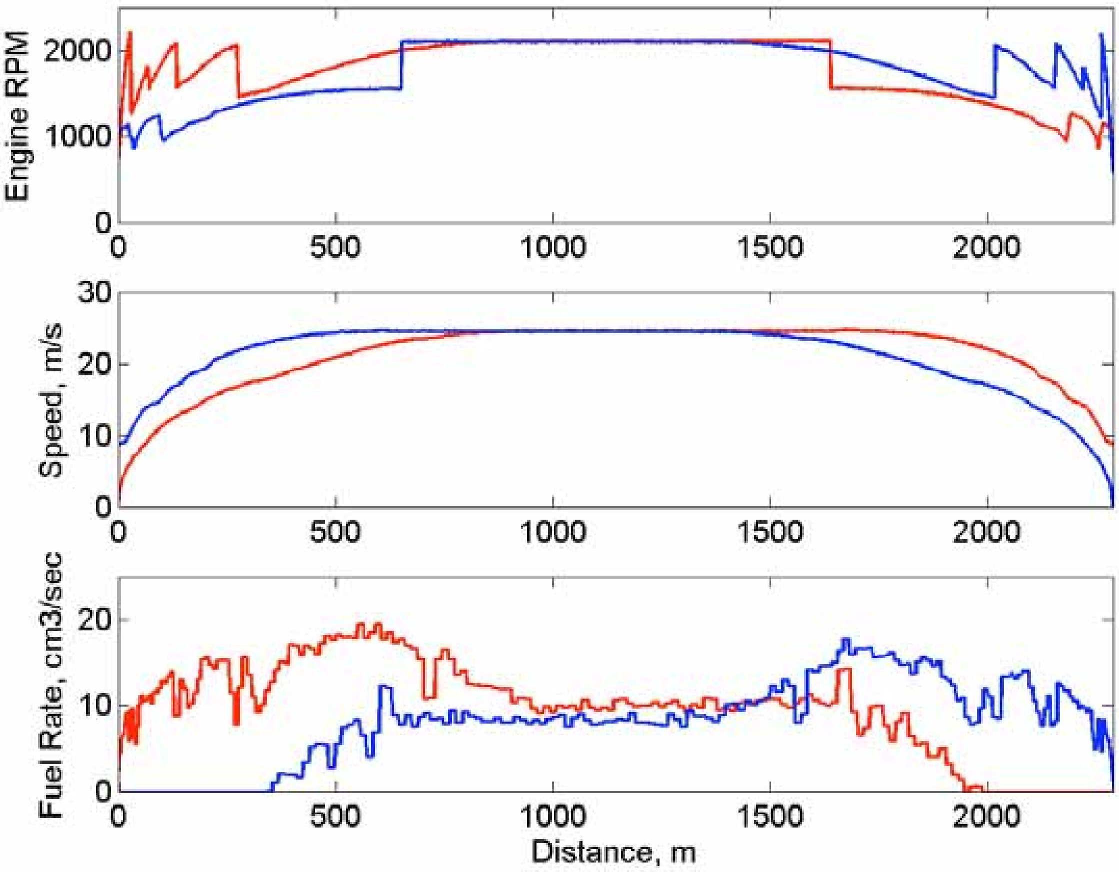

Figure 5. Raw data for run 51 (northbound in blue) and run 52 (southbound in red), December 4, 2003. Data is typical for Gold truck running in isolation.

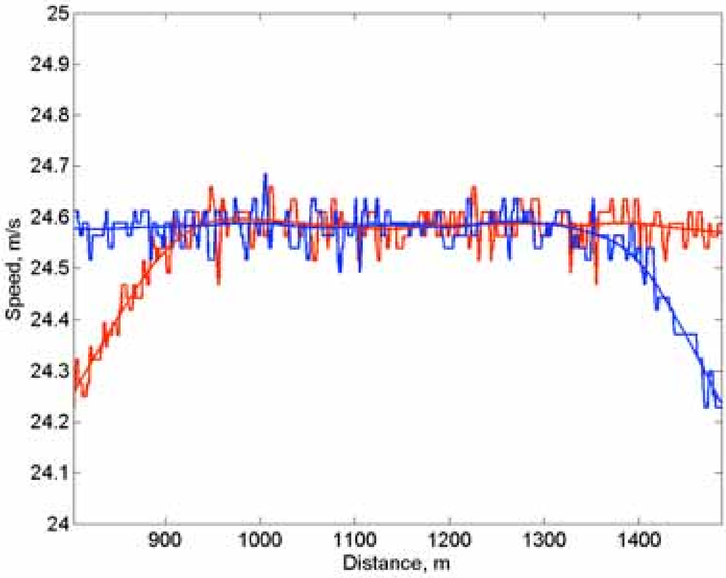

Figure 6. Truck speed along the central portion of the runway, raw signal, and cubic-spline fit to data, runs 51 & 52.

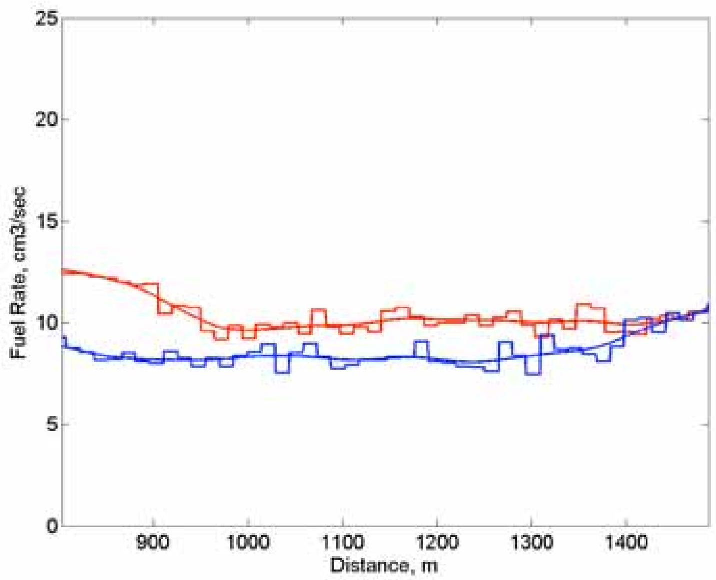

Figure 7. Fuel rate signal along central portion of runway, raw signal and cubic-spline fit to data, runs 51 & 52.

Figure 8 shows the smoothed fuel consumption signal, but now only over the window actually used for averaging. The cubic-spline smoothing used in figure 8 (and in figure 7) is useful in estimating the termination points of the acceleration period (in both directions), and in providing a measure of the quality of the signal in the constant speed, overlap window.

The cubic-spline smoothing does not remove the run-to-run variability caused by fuel rate fluctuations, as might at first be presumed. It can easily be demonstrated that computing fuel consumption from the unsmoothed signal or from the smoothed result—over the identical distance window—gives identical results to better than one part in two thousand. The reason is that the value of the smoothed curve must still reflect the shape of the unfiltered signal. The only way to remove the effect of the fuel rate fluctuation is to widen the averaging window—a choice, unfortunately, we do not have.

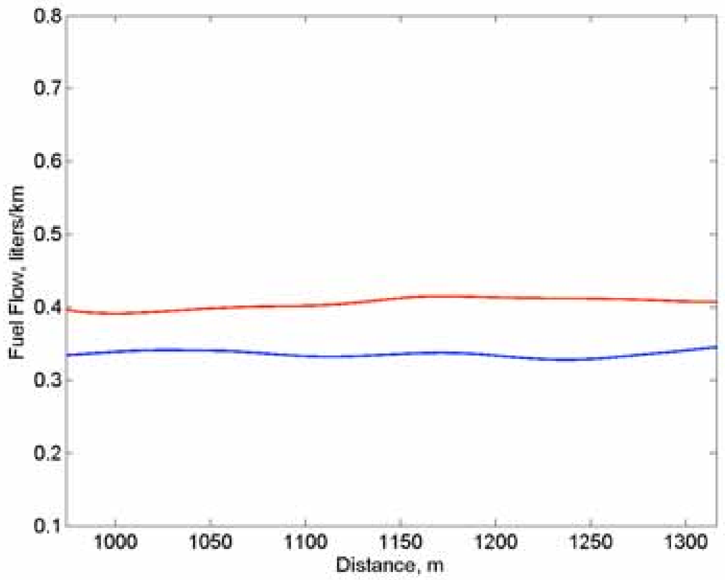

Figure 8. Cubic-spline fit to fuel flow in liters/km. Fuel consumption estimates are averages of this signal over the distance window shown above (runs 51 & 52).

The difference between the northbound and southbound values of fuel consumption in figure 8 is a result of the difference in runway elevation change and of the effect of wind.

5.3 NORTH-SOUTH RUN-PAIRS MINIMIZE THE EFFECT OF RUNWAY SLOPE AND OF WIND

Figure 9 has been prepared to illustrate the combined effects of runway elevation change and wind, and to emphasize the importance of combining each north-south run-pair into a single fuel consumption estimate. Aerodynamic drag is quadratic in the relative wind speed. For a wind nearly parallel to the runway, the aerodynamic drag is proportional to $(U_T + W)^2$ in one direction, and proportional to $(U_T - W)^2$ in the opposite direction, where U_T is truck speed and W is wind speed. The force required to propel the truck up or down a slope is $W_T\sin(\theta)$, where W_T is truck weight, and $\tan(\theta)$ is the runway slope.

The abscissa in figure 9 is the component of wind in the direction of the runway, and measured positive for a wind blowing northward. The wind is estimated from the wind speed and direction measure at the weather station at the center of the runway at the time of truck passage (± 30 seconds). The quantity plotted on the ordinate is the measured *difference* in fuel consumption (southbound – northbound) divided by the *sum* of the fuel consumptions (twice the average fuel consumption for the southbound-northbound run pair). All the runs in isolation for both trucks are utilized—there are 25 data points for the December 4-5 period plotted.

It can be shown that the quantity, (*diff fuel consumption)*/(*sum fuel consumption*), is approximately

$$\Delta(FC)/\Sigma(FC) = [2C_D(\rho/2)SU_TW + W_T\sin(\theta)]/[C_D(\rho/2)S(U_T^2 + W^2) + W_Tr + auxP/U_T], \qquad (1)$$

where, in addition to the quantities defined in the first paragraph, r = coefficient of rolling resistance, S = cross sectional area of truck, C_D = truck drag coefficient, and auxP refers to the power required to operate auxiliary equipment. The equation assumes constant truck speed. The quantity plotted is thus approximately linear in wind speed. At zero wind speed, the value of the ordinate is proportional to the runway slope term, $W_T\sin(\theta)$.

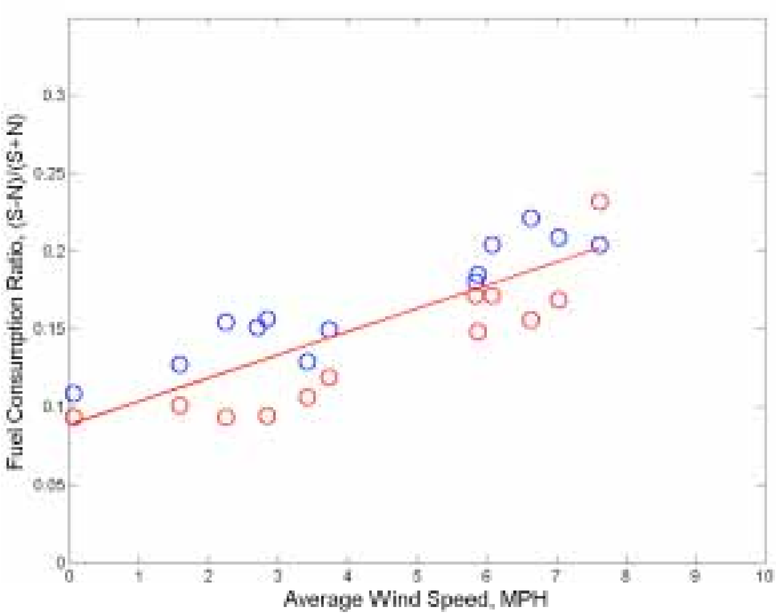

Figure 9. The effect of wind and runway slope on single north or south passages. The quantity plotted is fuel consumption *difference* (soutbound – northbound) divided by fuel consumption *sum* (southbound + northbound).

The runs for the blue truck are shown as the blue symbols—those for the gold truck are red. On average the blue symbols seem to lie above the red symbols, but there is no obvious reason. The two trucks have very nearly the same weight and the same performance. The average values of fuel consumption for the two trucks over the two-day period, December 4-5, only differ by about 0.5 %.

The data also appear to cluster, or group, into several circular regions for no obvious reason. It might however reflect the range of variability of wind speed during several different periods of operation.

Fitting a least squares straight line through *all* the data—blue and red—gives the red line shown in figure 9. The *intercept* at zero wind speed is reasonably predicted by equation (1) for the runway slope determined in figure 1(b). However, the *slope* of the least squares line in figure 9 is about 30% lower than the slope predicted by use of equation (1).

It can also be seen from the denominator of equation (1) that the average value of a southbound-northbound run pair is *independent* of runway slope and has quadratic dependence rather than linear dependence on wind. Since the wind speed is low compared to truck speed, this is a much weaker dependence. Plotting Σ(FC) relative to the zero-wind sum, and normalizing by the zero-wind sum (achieved in very light wind on the afternoon of December 4), should show the quadratic dependence on W:

$$(\Sigma FC - \Sigma FC_{ZEROWIND})/\Sigma FC_{ZEROWIND} = [C_D(\rho/2)S(W^2)]/[C_D(\rho/2)S(U_T^2) + W_T r + auxP/U_T]. \quad (2)$$

The same 25 fuel consumption pairs, arranged and normalized as on the left-hand-side of equation (2) are plotted in figure 10. The zero-wind sum used is the average value for the nine runs at wind speeds less than 3 MPH. For the quantity plotted, we would expect to observe increasing fuel

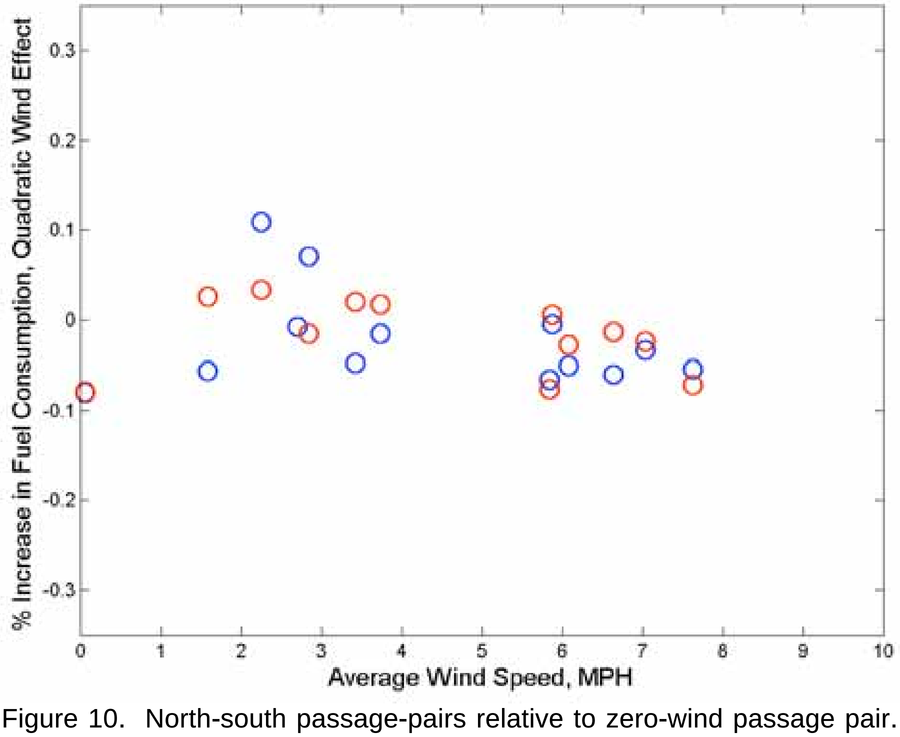

Figure 10. North-south passage-pairs relative to zero-wind passage pair.

consumption with increasing wind speed. Again, there is considerable scatter, but if anything, the fuel consumption decreases with increasing wind. Clearly a more stable zero-wind average would be desirable. However, on the basis of figure 10, *and provided we use round-trip run pairs*, there is no reason to exclude any of the present data at the higher wind speeds.

5.4 THE EFFECT OF TEMPERATURE VARIATION

Changes in ambient temperature will result in changes in drag through the drag dependence on air density. At steady speeds of 50-60 mph, overcoming aerodynamic drag requires approximately half the engine power output. Thus a variation of ± 5 degrees —as on December 4-5—will result in variations in drag of the order of ± 1%, and can be expected to produce differences in fuel consumption of the order of half this amount. Ambient temperature also affects tire rolling resistance, but to a much lesser extent.

5.5 COMBINED UNCERTAINTIES

Two major sources of uncertainty combine to produce the run-to-run variability observed in the fuel consumption estimates. These are, respectively, the effect of ambient temperature and wind, and the effect of fluctuations in fuel rate signal as observed, for example, in figure 7. Combining all the run-pairs over the two-day period December 4-5, the total uncertainty (rms error) in fuel consumption rate for either the blue or the gold truck is about 4-5%. As a rough partition, the uncertainty coming from the imperfect averaging of the fuel consumption fluctuations is probably in the range 1.5-2%, leaving 2-3% as the uncertainty arising from wind and temperature variation (and all other causes) combined.

6. RESULTS

6.1 FUEL CONSUMPTION FOR TRUCKS IN ISOLATION

The single truck runs of December 4-5 are the most extensive, and provide the best estimate of fuel consumption for the trucks in isolation. These results will be used as the denominator in our succeeding estimates of *relative* performance. In all, there are 13 north-south pairs in isolation for the Blue truck, and 12 for the Gold truck. (Several data sets were not recorded, or recorded incorrectly). The results for average fuel consumption over the two-day period are:

Average fuel consumption in isolation Blue = 0.3937 ± 0.0134, liters/km,
Average fuel consumption in isolation Gold = 0.3960 ± 0.0102, liters/km.

The second number is the estimated confidence level for 95% confidence in the mean value. The standard deviations of the measurements are, in the two cases respectively, ± 0.0223 and ± 0.0162. These are relatively large values—on the order of 4-5%. However the confidence level to be placed on the magnitudes of the averages is better than this. With 12-13 estimates, the data give 95% confidence that the mean values will lie within ± 0.013 and ± 0.010 for the Blue and Gold trucks, respectively. That is, on statistical grounds, the expectation is that 95 of every 100 additional estimates of the mean values of fuel consumption will lie within (approximately) ± 0.012 of the mean values expressed above.

The difference in fuel consumption between Blue and Gold running in isolation is about 0.0023, and is not statistically significant based upon the number of observations available.

The single truck runs for the October 30-31 tests are not so extensive. Rain and standing water on the runway on October 31 make runs 29-45 unusable. There remains on the 30th – 31st, three Gold truck run-pairs and two Blue truck run-pairs in isolation hauling an empty trailer. The average fuel consumptions are 0.4050 and 0.4051 liters/km, respectively, for Gold and Blue. These numbers can be compared directly with the above averages, and although they are higher, the differences are not statistically significant.

Two run-pairs are available for the Gold truck and the Blue truck hauling MERL in isolation with the rear door open. The averages are 0.4950 and 0.4887 liters/km, respectively, for Gold and Blue. Again, the difference between the two values is not significant, but clearly, hauling MERL increases fuel consumption by about 20% due to the added trailer weight.

A single run-pair is available for the Blue truck hauling MERL in isolation with rear door closed. This value is 0.4694 liters/km. The effect of the open rear door on MERL is an increased fuel consumption of approximately 4%, although it is risky to place much significance on this single data point.

6.2 FUEL CONSUMPTION FOR TANDEM TRUCKS

Figure 11 below presents the major result of the tandem truck tests. All of the data from December 4-5 is presented as the *difference fuel consumption*, $\{FC_{ISOLATION} - FC_{TANDEM}\}$, expressed as a fraction of the isolation value determined above. We believe this is the most accurate quantity available from the data. The small numbers in parentheses represent the number of run-pairs that define each of the mean values. The plus and minus one standard deviation limits are also plotted as the dotted lines for each value of spacing. The confidence in the mean value at the 95 % confidence level is also approximately bounded by the standard deviation bars.

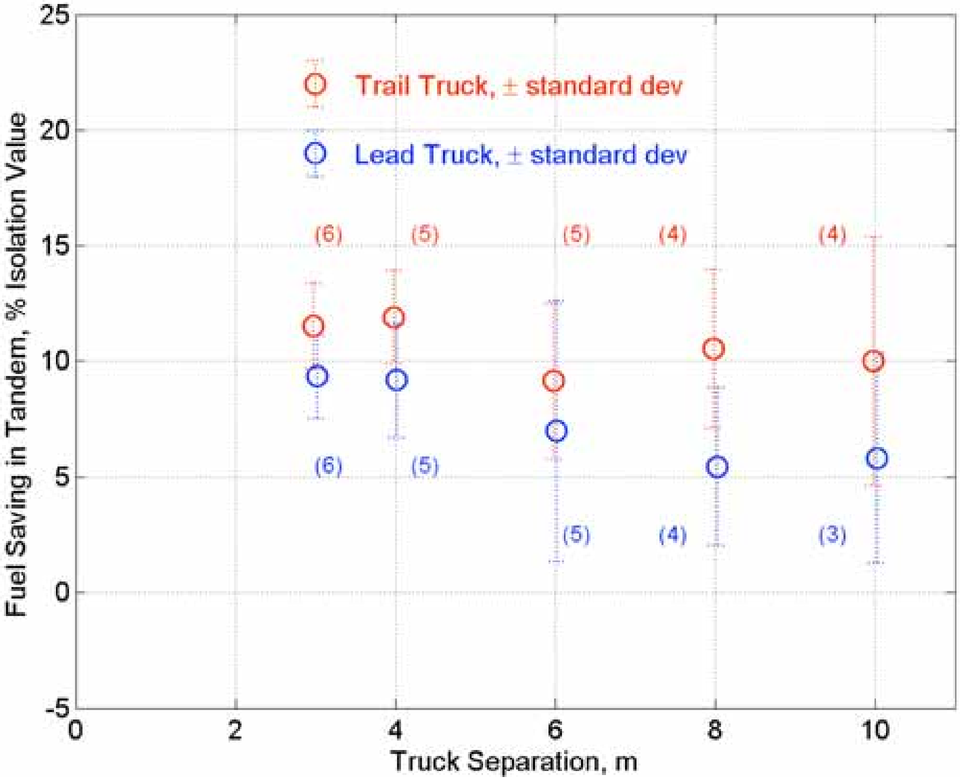

Figure 11. Fuel consumption saving for each of two trucks in tandem, as a fraction of the isolation fuel consumption.

Several results are expected. It is expected that the trail truck experiences the greater fuel saving, and that saving generally increases with decreasing spacing. What might not be anticipated is the degree to which the lead truck participates in the fuel consumption saving—particularly at the two shorter spacings. The *average* saving at 3- and 4-meter spacing is in the range of 10% or more—11-12% for the trail truck and 9 % for the lead truck.

A second interesting point is that—although the savings are smaller at greater separations—the savings do not diminish as rapidly as one might suppose. Thus at a truck spacing of 10 meters, the *average* fuel consumption saving is still about 8%. This is an important point considering the relative simplicity of maintaining a spacing of 10 meters compared to control system requirements for maintenance of 3-meter spacing.

6.3 COMPARISONS WITH WIND TUNNEL TESTS

The field test results can be compared with previous wind tunnel measurements performed at USC. In these tests, two model trucks—with drag coefficients similar to the drag coefficients for the trucks used in the field tests—have been placed in tandem in the wind tunnel. In the wind tunnel, changes in drag—or drag coefficient—are measured rather than changes in fuel consumption. The relationship between the drag change and fuel consumption change in tandem operation depends upon correctly modeling the operational state of the trucks in the field test. Such a state relationship is derived by expressing the power consumption of the truck as a sum of terms including the power required to overcome rolling resistance, aerodynamic drag, and an increase in road elevation. In addition, one must allow for power consumption by auxiliary devices such as engine cooling fan, water pump, alternator, turbo-charger, and air-conditioner. In equation form, the power consumption is

$$\text{Power} = \eta\ [\text{ rolling resistance + aerodynamic drag +climbing}]\ U_T + \text{auxP}, \tag{3}$$

where U_T is the constant truck speed, and η is an efficiency factor. The fuel consumption is simply the product of *brake specific fuel consumption* multiplied by the power consumed.

$$\text{Fuel Consumption} \equiv \text{FC} = \mathit{bsfc}\ [\text{Power}]. \tag{4}$$

Fuel consumption is always measured for the run-pairs in both directions over the same portion of runway, so there is no net power expended for climbing. The rolling resistance and auxiliary power are assumed to be similar for operation in isolation and operation in tandem. The *difference* in fuel consumption for isolation and tandem operation is then directly related to the *difference* in aerodynamic drag for isolation and tandem operation. The relationship is

$$\Delta FC/FC_A = [\Delta C_D/C_{DA}] \,/\, [\ 1 + (\text{rolling resistance} + \text{auxP}/U_T)/(\text{aerodynamic drag})]. \tag{5}$$

The quantity $\Delta FC/FC_A$ is the percentage improvement in fuel consumption, measured for tandem operation. The quantity $\Delta C_D/C_{DA}$, the percentage improvement in drag coefficient measured for tandem operation, could be derived from the tests if the factor in brackets were known. Alternatively, the value of $\Delta FC/FC_A$ could be derived from the wind tunnel drag data and compared with the present field tests if the factor in brackets were known. We choose the latter comparison. The factor in brackets—the sensitivity factor—is given by

$$\xi \equiv 1/\ \{1 + [W_T r + \text{auxP}/U_T]/\ [C_{DA} S(\rho/2)\ U_T^2(1+W^2/U_T^2)]\}, \tag{6}$$

and all of these symbols have previously been defined. The following parameter values are chosen for the two trucks.

W_T = 148425 N r = 0.0054 S = 10 m^2 U_T = 24.6 m/s W = 1.9 m/s
ρ = 1.23 Kg/m^3 (T = 15 ºF ±5 ºF) C_{DA} = 0.71 auxP = 29840 Watts (40 HP)

The weights of the two trucks are slightly different, but the difference is small. The rolling resistance coefficient has been approximated for tires with roughly half-tread-life remaining. W is an average wind speed, but the factor $(W/U_T)^2$ is extremely small. The drag coefficient for the tractor-trailer, C_{DA}, is only known approximately. It agrees with the coefficient of drag-in-isolation for the wind tunnel model. Perhaps the greatest uncertainty comes from estimating the auxiliary power. We have chosen 40 hp as being representative, after consultation with Cummins personnel.

Figure 12 presents the comparison between the present field measurements and the fuel consumption savings projected for our trucks if the wind tunnel drag data were used. The large red (blue) circle-symbols are the same data presented in figure 11 for the trail truck (lead truck). The smaller red or blue circles are the trail and lead *estimates*, respectively, for the wind tunnel data. The separation between the model trucks in tandem has been scaled up to full scale (multiplication by the square root of the area ratio). The drag coefficient for the model truck in isolation is about 0.7 (although data is available for models having lower drag coefficients). The value 0.71 is our estimate for the drag coefficient in isolation for the truck(s) utilized in the field test.

With regard to the spacings of 6 meters and greater, the wind tunnel projections are not too bad. The trail vehicle in the field test saves less fuel than anticipated by the wind tunnel test, but the lead vehicle saves slightly more. The average saving for the two trucks would be about the same as predicted.

The dramatic fuel savings—predicted by the wind tunnel test to arise at very short spacings—do not materialize in the field tests. The reason is unknown at present, although some speculation is worthwhile. The first suggestion is that the idealized circumstance in the wind tunnel is not met in the field test, for several possible reasons. There is no control system operating to maintain perfect lateral alignment. That is, the trucks are steered by hand, and so move laterally with respect to one another—destroying or partially destroying the shielding. The lateral motion was observed to be of the order of ± 0.5 meter. Such motion may be of little consequence at larger spacings, but may be important at the shorter spacings—particularly for the trail vehicle. However, earlier wind tunnel measurements for a misaligned platoon of three vehicles performed in our laboratory suggests that the effect would not be large enough to explain the differences in figure 12.

The second concern is that the tight limits on longitudinal position required to maintain the highly accurate relative spacing results in too much throttle motion. (This is a particular problem because of the relatively short averaging time, as remarked upon earlier.) However, the control requirements are similar at all spacings, and no dramatic differences in throttle motion (broadcast fuel rate swing) are noted at the shorter spacings.

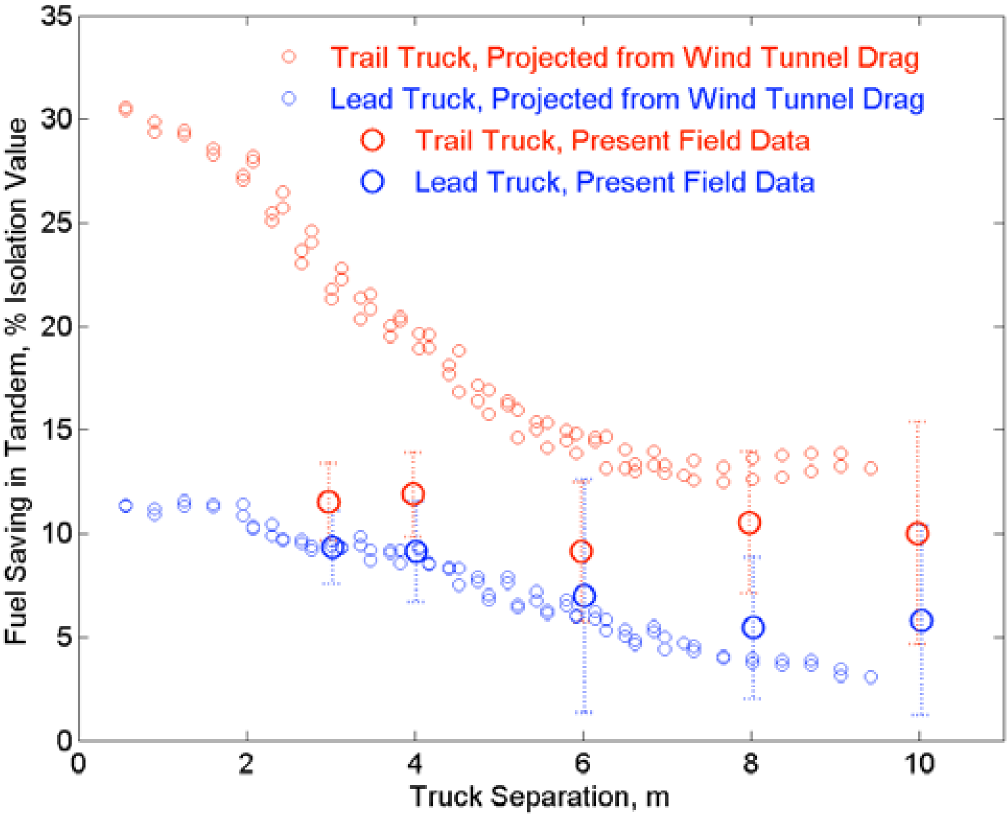

Figure 12. Projected fuel savings based upon wind tunnel tests, compared with the present field measurements.

The more likely explanation is related to the difference between the geometry of the model and the geometry of the full-scale truck. The drag-reducing interaction between the two tandem trucks at short spacing comes in the gap between the trucks. When the trucks are close, the pressure in the gap between the trucks is higher than at the base of the trailer in isolation, but lower than at the nose of the truck in isolation. The lead truck thus has a drag-saving related to the increased pressure over the trailer base—and the geometry of the base is similar for model and full-scale. The trail truck has a drag-saving related to the truck nose shape, and this shape is different in the case of the model test and the full-scale. The Freightliner truck is an engine-forward design having a hood-windshield break about 1.6 meters behind the front bumper. The wind tunnel model is more similar to a cab-over-engine design having a blunt nose and rising almost immediately to full cab height. Because of the long nose, the engine-forward truck is never as close to the base of the lead truck as the wind tunnel model measurements imagine. This explanation would suggest that the trailing Freightliner truck would experience greater fuel saving at even shorter spacing, but would probably not achieve the value approached by the blunter (cab-over) model of our wind tunnel experiments. The difference in geometry is probably not important except at these very short separations.

6.4 OPERATION WITH MERL, OCTOBER 30

The usable fuel consumption results recorded on October 30-31 with MERL are limited indeed. We have a single realization at all spacings for MERL operating as the lead truck with rear door open (exhaust analyzer equipment operating), and a single realization at all spacings for MERL operating as the lead truck with rear door closed. These single realizations are NOT sufficient to establish a stable average performance and confidence intervals for either of the two cases. We would need at least a week of additional test results to provide roughly the same level of confidence as established during the December 4-5 tests just discussed. Nonetheless, the data is presented below to serve as a rough indicator of performance during the time the exhaust gas analysis was being conducted.

In figure 13 below, the results for the empty trailers in tandem operation are plotted for reference purpose as the open circular symbols—blue for lead truck and red for trail truck. MERL is represented by the blue filled triangles and the stars—the filled triangles for the SINGLE realization with open base (exhaust gas analysis operational), and the stars for the SINGLE realization with closed base. The trailing truck (empty) results are marked by corresponding symbols—filled triangles when MERL is operational (open-base), and stars when MERL is closed-base.

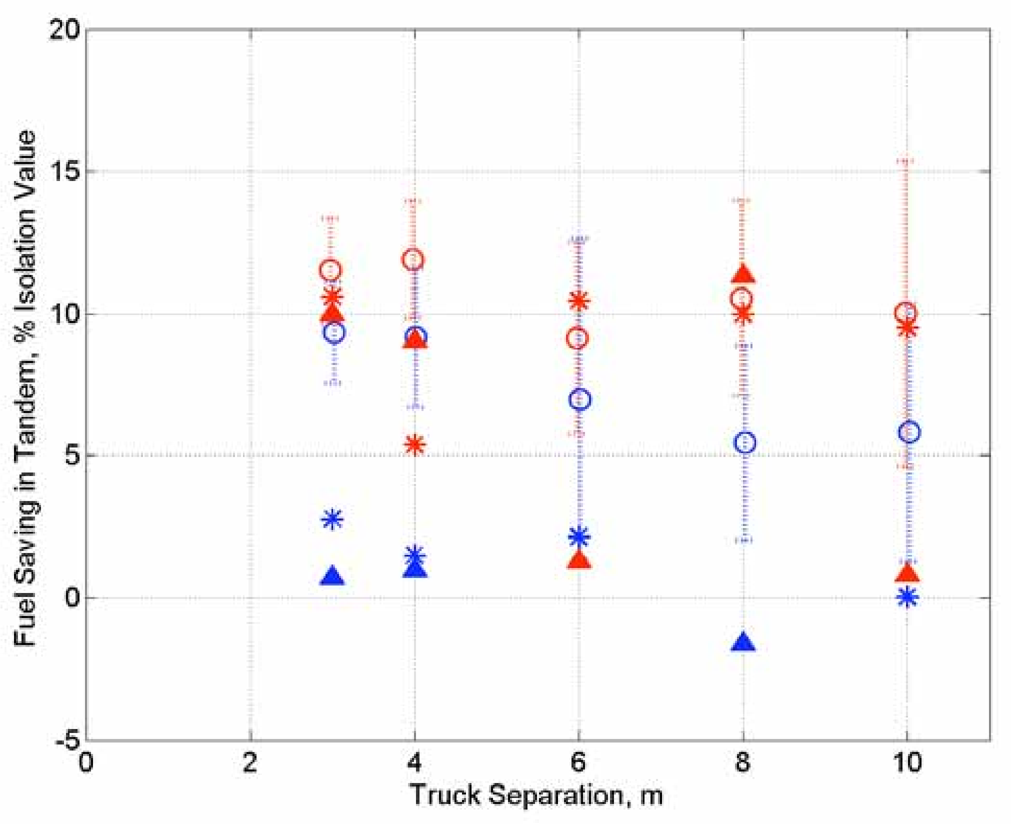

Figure 13. Single realizations utilizing the UCR mobile emissions trailer MERL. MERL in forward position and operating (open-base), and closed, respectively, ▲,*; empty truck in trailing position with MERL open (operating) and closed, respectively, ▲,* . The open circles are the data of figure 11, presented for reference.

From the results of figure 13, it can be seen that the trail truck achieves about the same fuel consumption saving as the results from December 4-5 demonstrate. The several outliers at 6 and 10 meters when MERL is operating are unexplained.

On the other hand, MERL—either operating (open-base) or closed base—appears to develop much less fuel saving than anticipated. These results are not consistent with the results of December 4-5. For example, at three meter spacing on December 4-5, the lead truck has a measured fuel consumption saving of about 9%. Use of equations 5 and 6 as a predictive tool, and using the parameter values suggested earlier, results in a sensitivity factor estimation, $\xi = 0.568$. That is, for the tests of December 4-5, and for the measured fuel consumption saving, we could estimate the drag saving to be $\Delta C_D/C_{DA} = 0.158$, or 15.8%. When the additional weight of MERL and the lower test speed of October 30-31 are accounted for, the sensitivity factor becomes $\xi = 0.434$. If it is assumed that the drag difference, $\Delta C_D/C_{DA}$, is similar for the two tests—as should be the case—then the fuel consumption saving for MERL should be about 7 % at a spacing of 3 meters. The limited data do not show this, and the only reason can be the lack of sufficient data to properly define the results of October 30-31.

Since the drag saving in tandem operation depends upon the spacing of the two trucks and nothing else, the anticipated fuel consumption performance for MERL can be estimated from the fuel consumption data of December 4-5—again using equations 5 and 6, and taking into account the different weights and speeds of the vehicles for the different tests. Figure 14 is such a plot. The blue (red) circles again reproduce the data in figure 11. On the basis of this data, MERL should have recorded the fuel savings marked by the solid triangles.

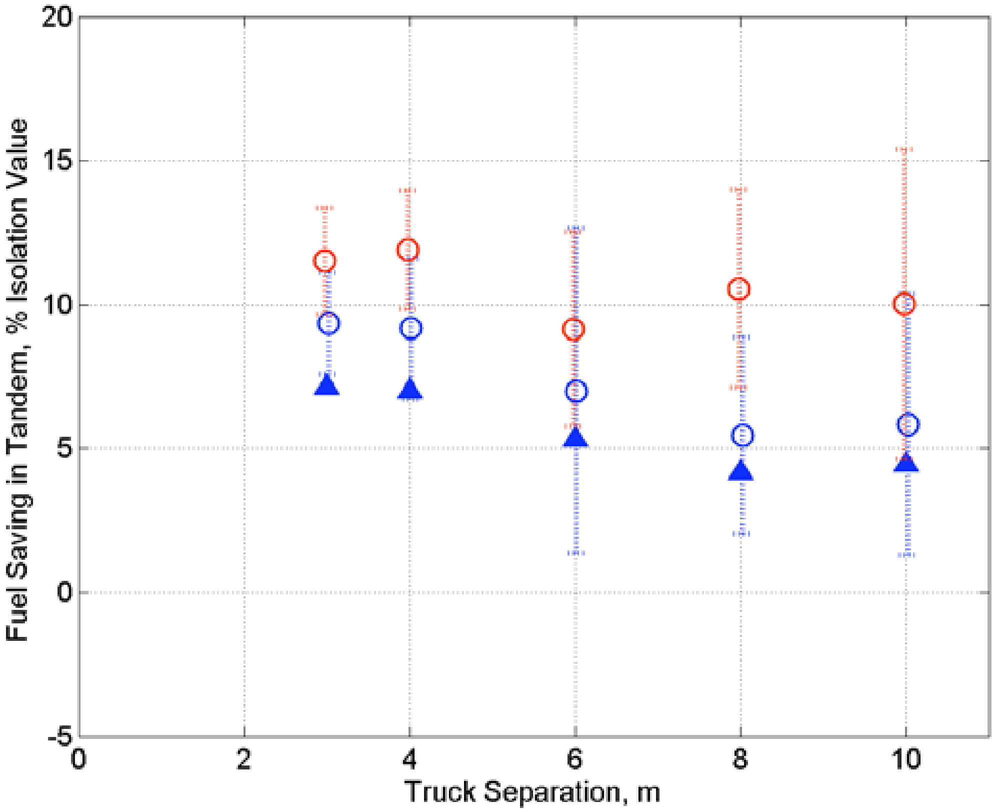

Figure 14. Predicted performance for MERL on October 30, based upon the data of December 4-5. Open symbols reproduce data of figure 11 (December 4-5); filled symbol ▲ is prediction for MERL.

7. CONCLUDING REMARKS

The run schedules, wind and temperature data, and the fuel consumption values derived from the broadcast fuel rate and discussed in this report, are made available in the Appendix. We believe the data of December 4-5 is reliable (but it is not of particularly high quality). We demonstrate our confidence in the specific values by providing confidence level estimates and standard deviations as error bars.

Conclusions about fuel consumption savings can be made from figure 11. Another way to present the result is simply to give the difference in fuel consumption for tandem travel versus travel in isolation. The fuel consumption for the trucks in isolation is the average value, 0.3948 liters/kilometer. The average saving in the spacing range 6-10 meters is about 8%, or 0.0316 liters/kilometer. Thus the aggregate fuel saving for both trucks would be 0.0632 liters/kilometer, or

6.32 liters per 100 kilometers. This number would be the appropriate saving while the trucks are in tandem formation on the highway at 24.6 m/s (55 mph). For an average yearly highway travel of 75,000 miles (120,000 kilometers) and a diesel fuel price of $2.00 per gallon, the average yearly saving for the truck-pair would be about $4,007. This is a significant saving. Since aerodynamic drag is proportional to the square of the forward speed, the savings would be greater at highway speeds above 55 mph in proportion to the square of the speed ratio. Thus at an operating speed of 75 mph, the savings would be greater by a factor of 1.86, or $7,453.

The data (figure 11 or the corresponding data in the appendix) could also be used to infer delta drag values for tandem operation by utilizing equations 5 and 6 and our truck operation parameters. Estimating delta drag would allow the projected fuel savings to be made for other driving scenarios—for example, to project savings for higher truck speeds, or other trailer loading conditions.

The formulation of a control law for two trucks in tandem operation involves—among other steps—the solution of the equations-of-motion for each truck. Since the equations-of-motion (Newton's law) include the drag, the proper formulation should include the drag of each truck while in tandem operation at the target spacing. The differences in drag, as determined from the differences in fuel consumption by utilizing equations 5 and 6, could easily be incorporated into the control law.

The major difficulty we encountered is that the Crows Landing runway is too short to test two trucks in tandem operation. The trucks must accelerate and decelerate (in tandem) to zero speed at either end of the runway—limiting top speed as well as the length of the central overlap region required to cancel out wind and runway elevation.

A test of drag-saving devices on a *single truck* would not suffer the limitations at Crows Landing so severely. A single truck could negotiate turns at either end of the runway rather than slowing to a stop. With 20-25 mph turns, the top speed could be increased to 60-65 mph within a constant speed overlap region of the order of 700 meters in the central section of the runway. Repeating each configuration test 10-12 times (with interlaced reference-condition runs) would improve the accuracy of the fuel consumption estimates by a factor of two or greater.

The test results of October 30-31 are not reliable. Rain cancelled most of the data taken on October 31. There was insufficient data taken on October 30 to obtain stable, reliable averages. Crows Landing is much too short for MERL. The acceleration from standing start of the heavier trailer limited the attainable top speed to 50 mph in an overlap region that is only 200 meters in length.

Any further tests using MERL would have to be performed at higher speeds—preferably 70-75 mph—on a test oval. One or both test straight-aways could be used for data recording. The track could be traversed a specified number of times in each direction to remove the effects of elevation change, and wind (to lowest order).

8. ACKNOWLEDGEMENTS

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9. REFERENCES

Bonnet, C. & Fritz, H., 2000, “Fuel Consumption Reduction in a Platoon: Experimental Results with Two Electronically Coupled Actros Trucks at Close Spacing”, SAE 2000 Future Transportation Technology Conference, Costa Mesa, CA, August 21-23, 2000.

Browand, F. & Hammache, M., 2004, “The Limits of Drag Behavior for Two Bluff bodies in Tandem”, SAE paper No. 2004-01-1145, reprinted from SP-1874, 2004.

Michaelian, M. & Browand, F., 2001, “Quantifying Platoon Fuel Savings: 1999 Field Experiments”, SAE paper No. 2001-01-1268, reprinted from SP-1600, 2001.

APPENDIX A
Run Log for 10/30 – 10/31/2003 Tests

NOTES

1 The Blue truck always led the Gold truck.
2 The trailers were switched between trucks as noted.
3 The Emissions trailer was either opened or closed as noted.
4 *Wind Magnitude is the effective wind speed; accounts for driving direction and wind direction with respect to the runway heading.

Run	Time	File names	Spacing (m)	Blue Trailer	Gold Trailer	Driving Direction	Temp. (°F)	*Wind Magnitude (m/s)	Mean Fuel Consumption (L/km)		Notes
									BLUE	GOLD	
1	2:01:00 PM	B_01 G_01	10	Emission (open)	empty	N	75.7	0.5	0.5070	0.3535	**THURSDAY 10/30/2003** 2 runs aborted before run 1
2	2:06:00 PM	B_02 x	10	Emission (open)	empty	S	76.1	-0.6	n/a	n/a	Forgot Emmissions Tests Gold Truck data not saved
3	2:18:00 PM	B_03 G_03	8	Emission (open)	empty	N	76.5	0.0	n/a	n/a	Spacing was incorrect
4	2:29:00 PM	B_04 G_04	10	Emission (open)	empty	S	75.4	-2.3	0.6203	0.3892	Repeat of Run 2
5	2:34:00 PM	B_05 G_05	8	Emission (open)	empty	N	75.4	1.6	0.4745	0.3375	Repeat of Run 3
6	2:38:00 PM	B_06 G_06	8	Emission (open)	empty	S	75.4	0.2	0.5248	0.3809	
7	2:42:00 PM 2:42:30 PM	B_07 G_07	∞	Emission (open)	empty	N	75.2	-1.1	0.4130	0.3752	
8	2:46:00 PM 2:47:00 PM	B_08 G_08	∞	Emission (open)	empty	S	75.2	-0.3	0.5499	0.4271	
9	2:53:00 PM	B_09 G_09	6	Emission (open)	empty	N	75.0	-1.0	0.4861	0.3932	
10	2:58:00 PM	B_10 G_10	6	Emission (open)	empty	S	74.8	-2.8	0.6024	0.4059	
11	3:04:00 PM	B_11 G_11	4	Emission (open)	empty	N	74.7	-0.1	0.4527	0.3253	
12	3:09:00 PM	B_12 G_12	4	Emission (open)	empty	S	74.7	-0.1	0.5210	0.4114	1 run aborted before run 12
13	3:16:00 PM	B_13 G_13	3	Emission (open)	empty	N	74.5	0.0	0.4594	0.3169	
14	3:21:00 PM	B_14 G_14	3	Emission (open)	empty	S	74.3	0.0	0.5178	0.4055	Went way past the end cone
15	3:25:35 PM 3:26:08 PM	B_15 G_15	∞	Emission (open)	empty	N	74.3	0.1	0.4016	0.3602	
16	3:30:29 PM 3:31:25 PM	B_16 G_16	∞	Emission (open)	empty	S	74.3	-1.1	0.5902	0.4666	
17	4:25:26 PM	B_17 G_17	3	Emission (closed)	empty	N	72.0	0.8	0.4039	0.3404	Closed Emissions Trailer
18	4:29:34 PM	B_18 G_18	3	Emission (closed)	empty	S	71.4	-0.8	0.5089	0.3837	
19	4:35:20 PM	B_19 G_19	4	Emission (closed)	empty	N	71.1	0.2	0.4061	0.3876	
20	4:39:40 PM	B_20 G_20	4	Emission (closed)	empty	S	70.7	0.0	0.5185	0.3788	
21	4:44:50 PM	B_21 G_21	6	Emission (closed)	empty	N	70.3	-0.3	0.3997	0.3608	
22	4:48:45 PM	B_22 G_22	6	Emission (closed)	empty	S	70.0	-0.3	0.5189	0.3644	
23	4:55:25 PM	B_23 G_23	8	Emission (closed)	empty	N	69.4	1.5	0.4461	0.3655	
24	5:05:15 PM	B_24 G_24	8	Emission (closed)	empty	S	68.4	1.1	0.5859	0.3637	Turned on headlights before run 24
25	5:10:15 PM	B_25 G_25	10	Emission (closed)	empty	N	67.6	-0.3	0.4488	0.3702	
26	5:14:22 PM	B_26 G_26	10	Emission (closed)	empty	S	67.3	0.4	0.4897	0.3577	
27	5:18:16 PM 5:19:10 PM	B_27 G_27	∞	Emission (closed)	empty	N	66.7	-0.5	0.4539	0.4079	
28	5:21:52 PM 5:26:15 PM	B_28 G_28	∞	Emission (closed)	empty	S	66.4	0.2	0.4849	0.3931	End of Thursday Testing
29	7:59:48 AM	B_29 G_29	10	empty	Emission (closed)	S	55.4	-1.0	0.4442	n/a	**FRIDAY 10/31/2003** Wet Track, Slight Rain Trailers switched between trucks
30	8:04:05 AM	B_30 G_30	10	empty	Emission (closed)	N	55.2	1.2	0.3665	0.4200	
31	8:09:08 AM	B_31 G_31	8	empty	Emission (closed)	S	55.0	-2.2	0.4528	0.6376	LIDAR problem due to dirty lens cover (rain and dirt)
32	8:15:25 AM	B_32 G_32	8	empty	Emission (closed)	N	54.9	1.4	0.3812	0.4120	Rain inceased. Begin to clean LIDAR lens before each Run
33	8:20:25 AM 8:21:12 AM	B_33 G_33	∞	empty	Emission (closed)	S	54.7	-0.5	0.4750	0.5973	
34	8:24:04 AM 8:25:06 AM	B_34 G_34	∞	empty	Emission (closed)	N	54.5	1.3	0.4027	0.4600	

APPENDIX A – continued

35	8:30:29 AM	B_35 G_35	6	empty	Emission (closed)	S	54.3	-1.6	0.4792	0.5686	
36	8:38:19 AM	B_36 G_36	6	empty	Emission (closed)	N	54.0	2.5	0.4273	0.4473	
37	8:44:05 AM	B_37 G_37	4	empty	Emission (closed)	S	53.8	-2.9	0.4707	0.5470	Rain stopped but track still wet.
38	9:12:00 AM	B_38 G_38	4	empty	Emission (closed)	N	53.6	1.0	0.3867	0.4256	Aborted due to Doppler Radar problem but repeated after run 41 and saved as run 38
39	8:52:31 AM 8:55:59 AM	B_39 G_39	∞	empty	Emission (closed)	S	53.6	-0.7	0.4484	0.5844	No spray from trucks.
40	8:58:28 AM 9:00:03 AM	B_40 G_40	∞	empty	Emission (closed)	N	53.6	1.0	0.3964	0.4347	
41	9:04:14 AM 9:04:16 AM	B_41 G_41	∞	empty	Emission (closed)	S	53.6	0.3	0.4662	0.5634	Trucks were close during this isolated run
42	10:56:15 AM	B_42 G_42	10	empty	Emission (open)	N	59.4	-0.1	0.3603	0.4145	Turned on headlights before run 42 Emissions trialer opened. Still rainy conditions.
43	11:01:34 AM	B_43 G_43	10	empty	Emission (open)	S	59.4	-0.8	0.4705	0.6094	Never came to a complete stop, rolled way past the cone
44	11:06:32 AM	B_44 G_44	8	empty	Emission (open)	N	59.2	-0.1	0.3461	0.3781	1 run aborted before run 44
45	11:14:30 AM	B_45 G_45	8	empty	Emission (open)	S	58.6	1.8	0.4498	0.6138	
46	11:20:42 AM 11:21:11 AM	B_46 G_46	∞	empty	Emission (open)	N	58.3	-2.1	0.3575	0.4176	
47	11:24:28 AM 11:25:24 AM	B_47 G_47	∞	empty	Emission (open)	S	58.1	1.7	0.4514	0.5882	
48	11:30:26 AM	x G_48	6	empty	Emission (open)	N	57.9	-2.3	n/a	0.3449	This one may not have saved correctly --- Stopped right at cone
49	11:35:24 AM	B_49 G_49	6	empty	Emission (open)	S	57.7	1.6	0.4347	0.5619	
50	11:40:25 AM	B_50 G_50	4	empty	Emission (open)	N	57.7	-2.0	0.3365	0.3612	Stopped right at cone
51	11:46:08 AM	B_51 G_51	4	empty	Emission (open)	S	57.7	2.0	0.4194	0.5534	
52	12:10:54 PM	B_52 G_52	3	empty	Emission (open)	N	58.5	-2.2	0.3548	0.3704	Many runs aborted before run 52
		x x	3	empty	Emission (open)	S					Many runs attempted, none completed
53	12:23:17 PM 12:21:20 PM	B_53 G_53	∞	empty	Emission (open)	S	59.0	0.1	0.4714	0.5841	
54	12:26:38 PM 12:27:06 PM	B_54 G_54	∞	empty	Emission (open)	N	59.4	-0.3	0.3398	0.3901	
55	12:45:00 PM	B_55	∞	empty	Emission (open)	S					Blue Truck ONLY; used to determine the distance between the cones. Max speed of 25 mph, started at the North cone, went to Northern "Engine Cut-off Point" and stopped momentarily, then went to the South cone and stopped the control program.

APPENDIX B

Run Log for 12/4 – 12/5/2003 Tests

NOTES

1 The Blue truck always led the Gold truck.
2 The trailers were identical and were empty.
3 *Wind Magnitude is the effective wind speed; accounts for driving direction and wind direction with respect to the runway heading.

Run	Time	File names	Spacing (m)	Driving Direction	Temp. (°F)	*Wind Magnitude (m/s)	Mean Fuel Consumption (L/km)		Notes
							BLUE	GOLD	
1	8:17:00 AM	blue_01 gold_01	?	S	52.2	-8.1	0.4586	0.4607	**THURSDAY 12/4/2003** runway heading 197 degrees looking south
2	8:24:00 AM	blue_02 gold_02	?	N	52.0	8.0	0.3032	0.2873	gold truck running too close --perhaps two truck lengths apart
3	8:31:00 AM	blue_03 gold_03	10 m	S	52.2	-7.6	0.4359	0.4289	
4	8:36:00 AM	blue_04 gold_04	10 m	N	52.3	8.7	0.2749	0.2602	
5	8:42:00 AM	blue_05 gold_05	8 m	S	52.5	-8.0	0.4279	0.4026	
6	8:48:00 AM	blue_06 gold_06	8 m	N	52.5	7.6	0.3026	0.3195	
7	8:53:00 AM	blue_07 gold_07	?	S	52.3	-7.8	0.4625	0.4592	
8	8:59:00 AM	blue_08 gold_08	?	N	52.7	7.7	0.2950	0.3354	very foggy not much light
9	9:07:00 AM	blue_09 gold_09	6 m	S	53.1	-8.1	0.4416	0.4146	
10	9:11:00 AM	blue_10 gold_10	6 m	N	53.2	8.1	0.2865	0.2759	
11	9:17:00 AM	blue_11 gold_11	4 m	S	53.4	-8.3	0.4242	0.4097	early braking
12	9:28:00 AM	blue_12 gold_12	4 m	N	52.9	7.6	0.2928	0.2667	
13	9:34:00 AM	blue_13 gold_13	?	S	52.9	-8.2	0.4707	0.4597	
14	9:41:00 AM	blue_14 gold_14	?	N	53.1	8.0	0.3081	0.3268	
15	9:51:00 AM	blue_15 gold_15	3 m	S	53.2	-8.0	0.4257	0.4313	too colse??? Possibly 2.5 m
16	10:03:00 AM	blue_16 gold_16	3 m	N	53.4	7.2	0.3106	0.2896	
17	10:11:00 AM	blue_17 gold_17	3 m	S	53.6	-7.3	0.4322	0.4032	
18	10:16:00 AM	blue_18 gold_18	3 m	N	54.3	7.1	0.2934	0.2818	
19	10:28:00 AM	blue_19 gold_19	?	S	53.8	-6.8	0.4605	0.4591	
20	10:33:00 AM	blue_20 gold_20	?	N	54.0	7.8	0.3043	0.3247	
21	10:41:00 AM	blue_21 gold_21	4 m	S	54.1	-6.2	0.4373	0.4207	
22	10:45:00 AM	blue_22 gold_22	4 m	N	54.1	7.2	0.3023	0.2881	
23	10:49:00 AM	blue_23 gold_23	6 m	S	54.5	-7.9	0.4374	0.4342	
24	10:53:00 AM	blue_24 gold_24	6 m	N	54.9	7.4	0.2889	0.3009	
25	10:59:00 AM	blue_25 gold_25	?	S	54.9	-8.6	0.4752	0.4651	
26	11:04:00 AM	blue_26 gold_26	?	N	55.4	5.3	0.3268	0.3449	
27	11:10:00 AM	blue_27 gold_27	8 m	S	55.8	-8.7	0.4482	0.4089	
28	11:14:00 AM	blue_28 gold_28	8 m	N	55.6	7.1	0.2797	0.2644	
29	11:19:00 AM	blue_29 gold_29	10 m	S	56.1	-6.1	0.4433	0.4609	
30	11:23:00 AM	blue_30 gold_30	10 m	N	57.0	7.6	0.2895	0.2746	

APPENDIX B – continued

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APPENDIX B – continued

66	1:23:00 PM	blue_66	8 m	S	58.8	-0.8	0.4457	0.4039	
		gold_66							
67	1:28:00 PM	blue_67	6 m	N	58.8	2.4	0.3474	0.3341	
		gold_67							
68	1:38:00 PM	blue_68	6 m	S	58.6	-1.5	0.4569	0.4199	Bill Stone riding in Gold
		gold_68							
69	1:49:00 PM	blue_69	4 m	N	58.8	3.8	0.3059	0.3196	Bill Stone x 2 riding in Gold
		gold_69							
70	1:57:00 PM	blue_70	4 m	S	59.0	-3.9	0.4165	0.3939	Bill Stone x 2 riding in Gold, Steve riding in Blue
		gold_70							
71	2:04:00 PM	blue_71	?	N	59.2	3.3	0.3085	0.3084	Bill Stone x 2 riding in Gold
		gold_71							
72	2:09:00 PM	blue_72	?	S	59.4	-5.3	0.4441	0.4361	Bill Stone x 2 riding in Gold
		gold_72							
73	2:16:00 PM	blue_73	3 m	N	59.4	6.1	0.2770	0.2927	Bill Stone x 2 riding in Gold, Steve riding in Blue
		gold_73							
74	2:27:00 PM	blue_74	3 m	S	59.4	-7.9	0.4280	0.4068	chase car front left Bill Stone, Steve riding in Gold
		gold_74							
75	2:38:00 PM	blue_75	3 m	N			0.3074	0.2942	
		gold_75							
76	2:46:00 PM	blue_76	3 m	S			0.4019	0.3935	
		gold_76							
77	2:51:00 PM	blue_77	3 m	N			0.3224	0.3051	
		gold_77							