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Correlation of Truck Tire Rolling Resistance as Derived From Fuel Economy and Laboratory Tests

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APPENDIX A - ANALYSIS OF WIND EFFECTS

Initial attempts at correlating tire rolling resistance derived from fuel economy tests with laboratory test results were not very successful because wind effects on vehicle aerodynamic sideslip angle and the corresponding increases in vehicle drag coefficient were not considered.

Since the increase of vehicle drag coefficient with sideslip, or yaw, angle is so pronounced, it is of primary importance to include this effect in vehicle aerodynamic analysis. In the subject study, it was assumed for simplicity that the tractor-trailers were operating on a circular track rather than on the actual L-shape of the 8-mile track. Since wind direction was not recorded at the time of the subject fuel economy test, it would be of no value to assume an L-shaped track rather than a circular one. With a circular track, it could be assumed that a steady wind from any direction would cause the test vehicles to go through a cyclic variation of sideslip angle as they traversed the 360 degrees of the track. A "wind-averaged" drag coefficient could then be calculated as a function of wind speed, since the magnitude of wind speed would define the sideslip angle variation through one complete traverse of the track at the constant vehicle ground speed of 60 mph.

The variation of tractor-trailer drag coefficient with aerodynamic sideslip angle was used from (14), instrumented vehicle coast-down tests in a windy environment, see Fig. A-1. The drag coefficient is based on a frontal area of 107 sq ft, measured from the road surface to the top of the trailer.

A vector solution of sideslip angle and resultant air velocity in the presence of winds is given in Fig. A-2.

The variation of vehicle sideslip angle and resulting drag coefficient through a 180 degree cycle from headwind through tailwind was calculated for three wind speeds and is given in Fig. A-3. Integrating the areas under the Fig. A-3 curves and obtaining average values gives the curve of Fig. A-4, where wind-averaged C_D for the tractor-trailer is presented vs wind speed.

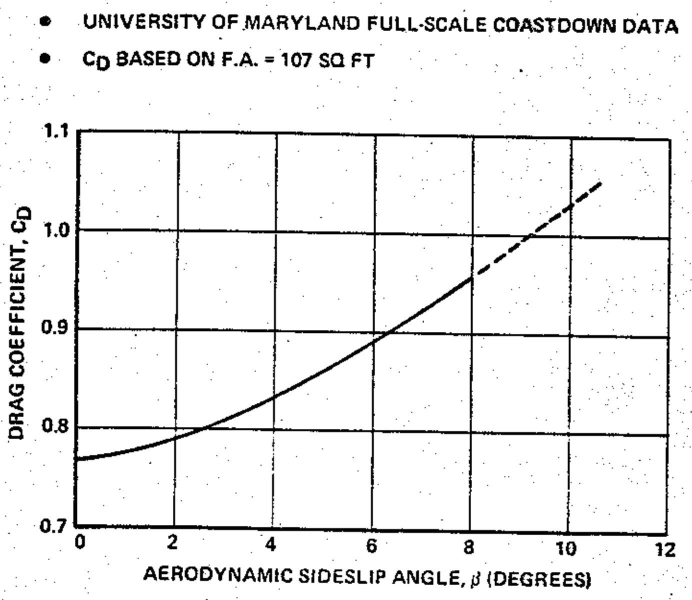

Figure A-1 – Tractor-Van Trailer Drag Coefficient Versus Sideslip Angle

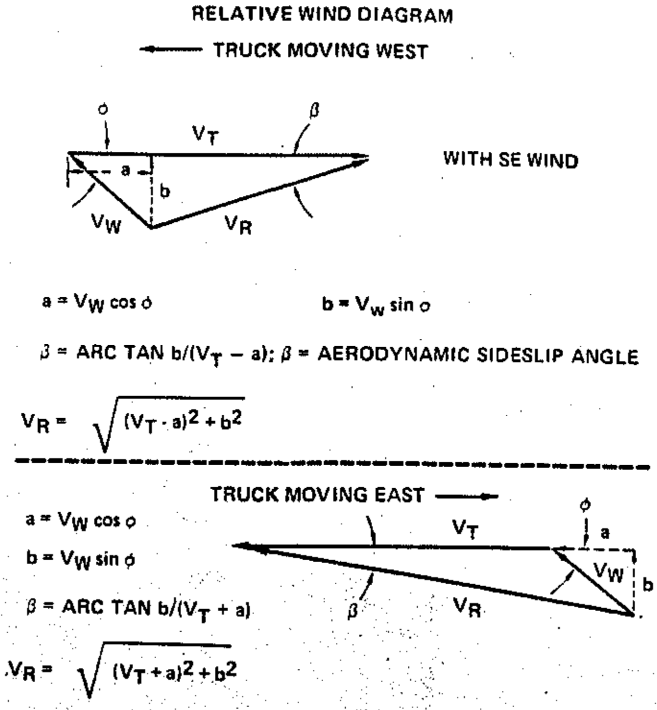

Figure A-2 – Analysis of Wind Effects

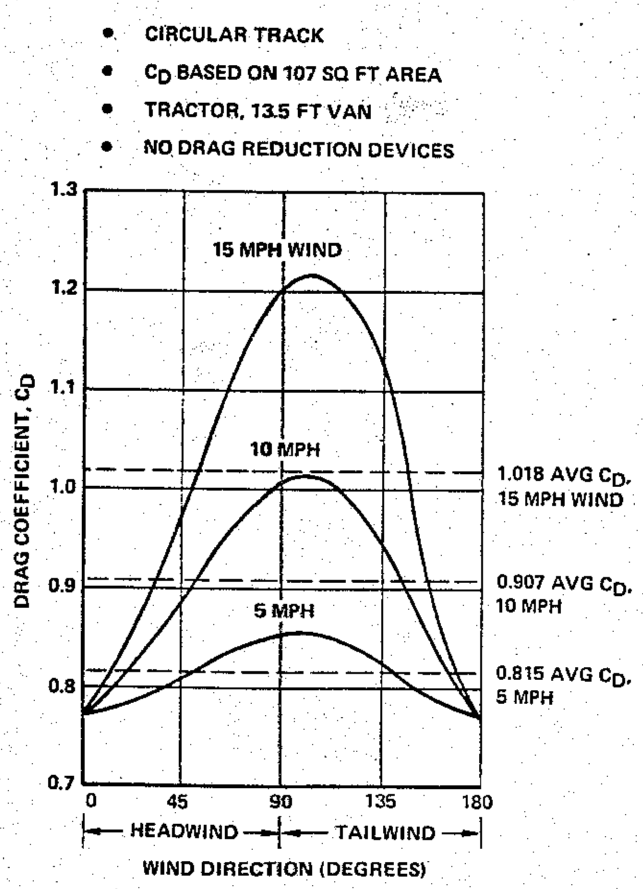

Figure A-3 – Tractor-Trailer Aerodynamic Drag Coefficient Versus Wind Direction and Speed

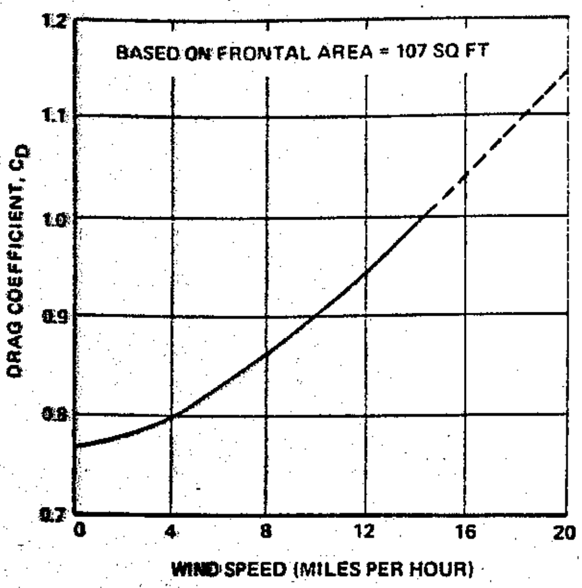

Figure A-4 – Wind Averaged Drag Coefficient for Tractor and Van Trailer

Strictly speaking, wind should be measured at about half the height of the truck because of wind gradient effects; wind velocity increases speed and changes direction with altitude in a fashion that depends on whether laminar or turbulent (with vertical mixing) atmospheric flow is present.

Since the subject wind data were taken with meteorological instruments mounted at about 25 feet above the ground, a correction was applied to the measured winds using the method and gradient parameters described under "National Wind Statistics" in (15). The correction factor was calculated to be 0.81. This factor was applied to the wind values measured at a 25-ft height to obtain wind values at a truck half-height of 7 ft above ground. These corrected wind values were used to determine vehicle wind-averaged C_D, using Fig. A-4.

Maximum average corrected wind during a 24-hour test period was 11.5 mph with a minimum average value of 0.6 mph; maximum wind-averaged C_D was 0.94, while minimum was 0.77. Overall average wind speed for all test conditions was 4.8 mph, while overall average wind-averaged drag coefficient was 0.82.

Maximum average effective aerodynamic sideslip angle encountered during a given set of test runs was 7.5°, and minimum was 0.4°. The overall average value for all tests was 3.2°.

Any effect of aerodynamic sideforce on the tires that may exist due to the sideslip angle, was neglected in this study. Such sideforces will affect tire operating slip angle and increase tire rolling resistance. However, the actual tire slip angles are not known and their mathematical solution would be complex.

APPENDIX B - ERROR STUDY

Of the potential sources of error in the subject study, some are random and will average out over a sufficient number of samples. Others are systematic and must be recognized as such even if they cannot be corrected within the current state of the art.

In Fig. 9, a comparison of ti[illegible] of regression with the line of equal correlation sh[illegible] that the absolute values of rolling resistance derive[illegible]om mile-per-gallon data are on the average higher th[illegible]hose derived from laboratory data by 0.4 to 1.2 lb [illegible] one to seven percent, going from the highest to the [illegible]west rolling resistance test point. This percentage difference is accounted for by four probable factors:

1. Inacurracy in basic data (random)
2. Errors in methods and assumptions (random)
3. Torque effects (systematic)
4. Surface roughness effects (systematic)

INACCURACY IN BASIC DATA -The first item above consists of random errors, and it is believed that sufficient data samples and test points are available to make the averaging process valid. Data samples consisted of two tractor-trailers for the fuel economy test points and four tires for the laboratory rolling resistance test points. Data points available from the fuel economy tests consisted of 14 different tire designs or combinations thereof, with an additional 2 duplicated runs, for a total of 16 points for each of the two vehicles, making a total of 32 points used in the correlation study.

Data points available from the laboratory rolling resistance tests consisted of eight different types of tires, with four tires tested of each type except for the bias ply Super Hi-Miler rib sample of two tires, for a total of 30 tires tested. Three load points were tested for each tire and used for interpolation purposes, so a total of 90 test points entered into the determination of laboratory tire rolling resistance values.

ERRORS IN METHODS AND ASSUMPTIONS -The second source of mostly random errors can certainly be present, particularly since the knowledge of methods to correct laboratory data to road conditions is rather limited at this time. Wind effects in the fuel economy data are also of primary importance, and the techniques used herein for correction of vehicle drag coefficient for a time-averaged as well as a direction-averaged wind may not be completely adequate.

The basic curve of tractor-trailer drag coefficient vs sideslip angle as used from Ref. (14), while representative of the vehicles used in the subject test, is not precisely applicable. An accuracy of ± three to four percent is estimated.

The wind-caused side forces on the tractor-trailers and resultant operation of tires at a slip angle were neglected in analysis of the fuel-economy-derived tire rolling resistance values due to lack of data. This effect is an unknown and must be considered to be included in the applicable tire rolling resistan[illegible] values.

In some cases, the tires as[illegible]ted in the laboratory had accrued more miles of tread[illegible]r and hence had lower tread depth than the same tire[illegible]s tested on the track. The effect of this difference in [illegible]ad depth on tire rolling resistance was considered to be [illegible]all and was ignored. In the cases where these diffe[illegible] existed, the laboratory rolling resistance value we[illegible]end to be slightly lower than that derived from fue[illegible]nomy tests.

While the magnitudes [illegible] the above error factors are not known, it is estimated t[illegible] in total they may be worth

,out ±1.5 lb of rolling resistance, or perhaps ± four to ight percent over the measured range of rolling resistance values.

TORQUE EFFECTS - At steady highway speeds, torque effects can be estimated to systematically reduce rolling resistance of the eight drive tires by 10 to 20 percent, based on Ref. 9 data. On an overall weighted average basis for the 18-wheel tractor-trailer, the torque effects may reduce values of the fuel-economy-derived rolling resistance by four to nine percent (8/18 times 10 to 20 percent).

ROAD SURFACE ROUGHNESS - When changed from the sometimes worn medium grit of the laboratory test wheel to an actual road surface, roughness effects may systematically increase tire rolling resistance by zero to about three percent for typical asphalt/mixed aggregate surfaces, and by up to 27 percent for a newly applied chip-and-seal surface, as given in Ref. (11). The Ref. (11) paper tested radial passenger car tires, but the results are believed to be generally applicable to truck tires as well. For a worn chip-and-seal surface representative of average conditions that existed during the fuel economy tests reported herein, an estimate might be midway between the three and 27 percent values, or a 15 percent increase in rolling resistance going from laboratory to track conditions.

With regard to contour irregularities, the test track had a newly paved, smooth surface. When truck travel is over roads with appreciable contour roughness (aside from surface texture effects), additional rolling resistance will occur, as reported in Ref. (12) based on tests with passenger cars. A general conclusion from Ref. (12) is that rolling losses as large as 20 percent may be sustained by traveling on rough roads, with additional losses resulting from increased aerodynamic drag due to vehicle pitch and yaw activity.

COMBINED TORQUE AND SURFACE ROUGHNESS EFFECTS - Given certain random inaccuracies in basic data and errors in methods and assumptions that might cause errors in either a plus or minus direction, the drive tire torque may cause a systematic reduction in average tractor-trailer tire rolling resistance of four to nine percent, while the track surface roughness may cause a systematic increase in tire rolling resistance of about 15 percent. These two factors tend to cancel each other, and a net increase in rolling resistance of six to 11 percent might be expected for the fuel economy test results as compared to the laboratory results. These values show fair agreement with the corresponding values found in this study of one to seven percent.

APPENDIX C - DIFFERENCES WITHIN TEST SAMPLES

During the correlation process, average per-tire rolling resistance was calculated independently for a given set of tires as mounted on each of the two trucks used in the fuel economy tests, and the results were averaged as shown in Table 1. A study was made of the differences in calculated tire rolling resistance between trucks, with the result that Truck 845 generally indicated higher values of tire rolling resistance than Truck 844. Of the 16 test runs considered valid, Truck 845 showed average per-tire rolling resistance values ranging from 8.6 pounds greater to 3.0 pounds less than truck 844. The average value was 2.8 pounds or 10 percent.

This difference is due to the individual characteristics of engine, vehicle, and drivers, and can reflect such factors as slightly different engine tuneup conditions including fuel pump adjustments, brake adjustments, alignment of all axles, and driver techniques (a given driver stayed with a given truck) in otherwise identical vehicles. This shows the need to average the test data from at least two "identical" vehicle-driver combinations in order to separate tire rolling resistance from aerodynamic drag by means of detailed performance analysis.

Laboratory rolling resistance was measured on each of four tires of a given type except for the Super Hi-Miler bias ply tire, which used a two-tire sample. The rolling resistance measurements for all tires in a given sample were averaged for use in the subject correlation study. However, a review was made of the individual tire rolling resistance measurements within a given sample (all corrected to the same ambient temperatures) to determine differences between otherwise identical tires.

Of the seven different four-tire sample sets tested, an experimental radial rib tire (test combinations No. 10 and 10R) showed the greatest range of values within the sample, amounting to 7.5 percent, while the lowest range of values was found for the production Custom Cross Rib bias ply drive tire at 0.8 percent. The average range of values existing in all four-tire samples was 3.5 percent.

Differences in rolling resistance measurements of individual tires can be attributed to variations in uniformity of construction and compounding that are measurable also as radial and lateral runouts and force variations.

Because of these differences in uniformity between otherwise identical tires, it is necessary to measure the rolling resistance of more than one tire of the same design and average the results. A minimum of two tires is evident, and it is recommended that a sample size of four tires be tested and results averaged for better accuracy.