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Handling and Stability of 3-Wheeled Electric Vehicles

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ABSTRACT

This project is being sponsored by the Department of Energy's Electric and Hybrid Vehicles Division through Interagency Agreement with the Department of Transportation. The purpose of the project is to determine the conditions under which energy efficient 3-wheel electric vehicles can mix safely with 4-wheeled internal combuslion engine vehicles in urban and suburban traffic.

Analysis and full-scale tests of four 3-wheeled electric vehicles were performed. The test vehicles were selected from an extensive survey of candidates and included both 2 front / 1 rear wheel and 1 front / 2 rear wheel configurations. Two vehicles from each class were selected and tested for handling and braking performance. Results were compared to similar tests performed on small 4-wheel IC vehicles. The results of these tests will also be used to validate and update a computer simulation model whereby other 3- and 4-wheeled vehicle designs could be analyzed for potential handling and stability problems.

PURPOSE

Perhaps the first question we need to ask is, why even consider 3-wheel vehicles? Why not stick with the proven 4-wheel layout? In the first place, there are at least three natural reasons: a 3-wheel vehicle is inherently lighter because there are no chassis torsional stiffness requirements; it allows a more efficient aerodynamic envelope; and cost is reduced by the elimination of a redundant wheel, tire, brake, and suspension assembly. In America there are also two artificial (political) reasons: a 3-wheel vehicle is classified as a motorcycle by the US DOT, which exempts it from many Federal Motor Vehicle Safety Standards; and it frequently qualifies for reduced state license fees and taxes. These advantages which are unique to 3-wheel vehicle design are so desirable to the builders of electric cars that we need to ask what the drawbacks are. Although 3-wheel cars have a reputation for being unstable, it Appears that there is no quantitative vehicle dynamics research anywhere in the public domain (in the English language, at least) to support this assumption. This was the justification for this research program.

Table 1. Test Maneuvers

CATEGORY	RESEARCH OBJECTIVE	NECESSARY MANEUVERS
Handling: Stability	Lateral acceleration limit Steady state yaw gain Stability factor Overturn	Constant radius circle
	Returnability	Free returnability
	External disturbance response	Crosswind disturbance
	External disturbance response	Bump in turn
	Transient yaw reponse Time constant	Step steer
Handling: Control	Math modeling	Steering sweep
	Evasive action response	Single lane change (Emerg. lane change)
Braking	Stopping distance Path maintenance Force gain	Straight line brake
	Path maintenance Overturn	Brake in turn
	Overturn	Brake in turn on slope

The implied question here is: are 3-wheeled vehicles as "safe" as 4-wheeled vehicles? Because such factors as acceleration, top speed, visibility, conspicuity, and crash protection are not related to the number of wheels, they are not considered in this research. But there is still a real problem in determining what "safe" is, because no one has yet determined what is acceptably safe even in 4-wheel vehicles. The best criteria we can use for comparison are the IESV (Intermediate Experimental Safety Vehicle) standards which were established by NHTSA (National Highway Traffic Safety Administration) for vehicles built under contract to them. However, these standards have neither been statistically related to accidenu nor accepted as Federal regulations. Therefore, the first objective was to find whether there in, in fact, any performance difference between 3·wheel vehicles and 4-wheel cars. If there is, then it is a separate problem to determine acceptable limits.

TEST VEHICLE SELECTION

It was felt desirable to test at least two each of the single front wheel configuration and the single rear wheel configuration. An extensive search was made to identify all such 3-wheel electric automobiles that were suitable for our tests. It should be noted that the propulsion system itself (whether electric, internal combustion, or hybrid) has no effect on vehicle dynamics, except perhaps in mass distribution and possibly in flywheel effects. However, the government agency charters were such that electric power was a necessary constraint.

The four 3-wheelers selected were: the H.N. Freeway from Minneapolis (2F/1R), the Gilbert Transelectric from Los Angeles (1F/2R), the Spitri from Tulsa (1F/2R), and the Korff Duo-Delta from Burbank (1F/1R). The vehicles are shown in Figs. 1-4. Though three of these vehicles were not even running prototypes at the time of selection, they were potentially more practical, in terms of speed and overall roadway use, than the majority of 3-wheel golf carts and industrial trucks that were found.

For the four 4-wheel comparison vehicles, a wide range of characteristics was desirable. The most significant handling variables are weight, mass distribution, tires, and driven wheels. Therefore, the selection criteria were fairly well defined by the lightest available vehicles with: rear engine/rear wheel drive (Fiat X1/9); front engine/rear wheel drive (Datsun B210); and front engine/front wheel drive (VW Rabbit). Since none of these was as light as most of the 3-wheel test cars, the fourth vehicle selected was the out-of-production Honda 600 (front engine/front wheel drive) at 1390 pounds. The bar chart in Fig. 5 illustrates the ranges of weight, c.g. location, and mass distribution among these eight cars.

TEST MANEUVERS AND INSTRUMENTATION

Because STI has been testing 4-wheel cars for the DOT for many years, the most relevant tests were fairly well established from the start. These are shown in Table 1. Most of these tests are purely objective, in that the driver's experience or skill is not a factor, and in most cases there are existing performance acceptability limits [handling research and IESV Standards, (1, 2)].

All of these tests are carefully controlled by the use of special test equipment at STI's Edwards Air Force Base facility. For example, 35 mph crosswinds are produced by the NHTSA Crosswind Generators (see Fig. 6), which can reproduce almost any real-world road wind conditions over a 100 ft span (g). All of the tests were performed under the same ambient conditions: still air, 60-80 degrees, and on dry asphalt or concrete.

More esoteric vehicle dynamics analyses are performed by running the data through a computer, but these are primarily for predicting specific effects due to vehicle design changes such as shifting weights or using different tires. In addition, other static tests and measurements were taken for use in predictions. This included measuring the vehicle moment of inertia, center of gravity height (see Figs. 7 and 8), steering ratio, and steering compliance. Although STI has the capability of recording dozens of channels of test data continuously, space and power limitations in these electric cars required a more limited system with four channel capacity. The four most important parameters were determined to be speed, steer angle, yaw rate, and lateral acceleration. These are obtained by the use of a fifth wheel, steering wheel potentiometer, and an inertial measurement unit which contains gyros and accelerometers. In addition, path deviation is recorded by a downlooking camera mounted above the rear bumper and focused on a roadway stripe, and also by a stationary camera in some maneuvers.

Brake pedal force is applied by a mechanical device strapped to the driver’s brake leg, the force being determined by a selection of constant-force springs. Stopping distance is recorded digitally by a counter on the fifth wheel. The recorder is a 10 lb FM cassette recorder which takes data on a standard 4-track cassette. An example of one instrumented car is shown in Fig. 9.

The data are played back immediately in the field onto a strip-chart recorder to insure against dropouts. The final analysis, however, is done by transferring the data to 1 in. magnetic tape, and playing it through a PDP-11 computer onto another strip-chart recorder. In this way relationships between data such as steer angle and yaw rate can be analyzed, as well as scale adjustments, ensemble averaging, and differentiation of signals, such as obtaining longitudinal acceleration from the slope of the velocity curve.

The strip-chart data and movies tell a great deal about the behavior of the driver and vehicle. Figure 10 shows a sample of raw data for the H-M Freeway in the straight brake maneuver. It can be seen that during the hard braking phase the yaw rate starts to rise suddenly, indicating that the rear wheel has locked up and the car is about to spin. A steering correction and brake release can then be seen in the first two channels, while the yaw rate and lateral acceleration return to zero.

RESULTS

The results of the 4-wheel vehicle tests provided no surprises, regardless of the wide range of design characteristics. Obviously, the state of the art is such that proper engineering development can bring any 4-wheel vehicle well within the boundaries of acceptable handling. From this standpoint, it may be unreasonable to compare the available 3-wheeled prototypes to 4-wheeled cars that have been finely developed and produced in at least 10,000-car runs. Because these 3-wheeled vehicles have not been optimized, the results may be more of a product analysis than a concept analysis. To properly determine the ultimate potential of the 3-wheel concept it will be necessary to obtain the "best" example, experiment with various modifications, and retest. However, we should discuss some of the specific results to date.

Subjective evaluations are often valuable when the performance is grossly variant. The first point noted about these electric 3-wheelers is that they were all somewhat overrrated in terms of speed capability. As received, none would reach 40 mph on the level with zero wind, in spite of predictions of up to 55 mph. Although top speed was not a performance test here, this required a revision in test procedures which were originally designed for 50 mph. However, the point is that this true speed limitation may be the overriding factor in safety acceptability for highway use. Another limitation was that, In many cases, vehicle strength, power, or dimensional factors prevented complete testing. For example, the Gilbert Transelectrlc was limited by overstressed wheels and tires, the H-M was limited by an undesirable c.g. location, the Korff had to be run without a body, and the Spitri had a transmission failure.

The first safety criterion we should consider in a 3-wheeled vehicle is its overturn resistance. A great deal has been written about the effect of three versus four wheels in thle respect. However, no one had measured the actual center of gravity height, which is of prime importance, nor had they verified predictions hy full-scale test.

Most of the data necessary for predicting overturn is relatively easy to obtain, except for tire traction capability and center of gravity height. Based on hundreds of automotive tire tests, we can say that the "average" automotive tire has a lateral limit capability of about 0.75 g and a longitudinal limit of about 0.65 g. This creates an elliptical tire limit bouncary for each such car, as shown in Figure 11 (4).

The center of gravity height and other dimensional and deflection characteristics determine the lateral g·level at which the car would overturn. If this level is greater than the tire limit, then the car will skid before turning over. These lateral g-level limits for the four 4-wheel test cars are also shown in Fig. 11. For simplicity, we can calculate a safety margin as the overturn limit divided by the tire traction limit, where percent safety margin is:

$$\% \text{ Safety} = 100 \left[\left(\frac{g_{OT}}{g_{tire}} \right) - 1 \right]$$

In other words, if a vehicle would overturn at twice the lateral g's which the tires can develop, then it has a 100 percent safety margin; and if it overturns before the tires skid, then it has a negative safety margin.

Three-wheeled vehicles have a slightly different situation, in which the overturn limit is affected by longitudinal acceleration, as shown in Fig. 12. Hare wu can see that the overturn safety margin in worse if the vehicle is accelerating or braking in the direction of the single wheel. Fortunately (or unfortunately) we happened to obtain a 3-wheel vehicle for testing that we predicted to have a negative safety margin of about -16 percent (assuming a tire tractive capability of about 0.75 g). This translates to a g-limit of 0.67, or a speed of 25 mph on a 70 ft radius. With great caution, and extra safety equipment, the car was slowly driven up to speed on this radius and, as predicted, at 25 mph the inside wheel lifted off the ground. Anticipation and test driving experience (and, in some cases, the outrigger wheel) prevented the car from going all the way over. It should be noted that most campers, motorhomes, loaded semis, and other tall, narrow vehicles could not pass this test.

However, it is also worth noting that most of these 3-wheelers were not able to reach their tire limit because of a power or braking deficiency limit. The dashed line shows the approximate real-world limit for each of these vehicles as tested. But theoretically, at least, it can be seen that the best 3-wheel car in this test had an overturn safety factor greater than the best 4 wheel car (see Table 2).

Table 2. Calculated Overturn Safety Margin for 4- and 3-Wheeled Vehicles

4-Wheeled	
Datsun	41%
VW Rabbit	49%
Honda 600	47%
Fiat X1/9	73%
3-Wheeled	
H-M Freeway	(-)23%
Structural Plastics Spitri	20%
Gilbert Transelectric	27%
Korff Duo-Delta	80%

To drastically simplify the analysis, we can say that for a given ratio of c.g. height and effective track width it does not matter whether three or four wheels are involved. In other words, it is possible, by shifting the c.g. lower or closer to the pair of wheels, or by widening the track, to make a 3-wheeled car as resistant to overturn as a 4-wheeler. However, for more precise predictions, it is also necessary to consider other factors such as ultimate tire traction capability, and tire and suspension deflections.

If a vehicle has adequate overturn resistance, then the next most important question is whether it understeers or oversteers at the limit of adhesion. .In other words, oversimplifying again, do the front or rear wheels lose lateral traction first? Essentially all automobiles built today are designed for the front wheels to skid first, since a rear wheel skid is somewhat more difficult for the average driver to control.

Figure 13 is a plot of steering wheel angle versus lateral acceleration in g's in a steady state turn. To simplify the explanation, the Ackermann steer angle (zero speed steer angle) has been subtracted out, and steering gear ratio effect has been ignored. If the steering angle continues to increase, up to the cornering limit, then we can say that the car has steady state understeer. However, if the steering angle curves downward, then it indicates an oversteer condition, in which countersteering is necessary to prevent the rear wheels from breaking away.

As expected, all cars tested show some degree of understeer, and some cars have a rather extreme amount. A few cars, however, are very close to neutral steer, which is uncomfortably close to oversteer, and could actually oversteer in a transient maneuver. The analysis is clouded by the fact that the 3-wheel electrics had too little power to approach the cornering limit, where the most interesting data are obtained. It is not unusual for a curve to show understeer up to 0.5-0.6 g, and then break sharply down into oversteer. Two 3-wheelers, which were judged to be safe in such a maneuver, were driven at speed on a tangent into the turn circle where the steering wheel was turned over into the approximate necessary angle. Both of these cars, a single rear and a single front wheel configuration, oversteered drastically, or spun out. Most production cars will not do this, but the results are inconclusive since the other six cars were not put to such a test. So again we can say that the 3-wheel cars we tested were within safe boundaries, but perhaps only because they were power limited.

If we look at the known state-of-the-art vehicle factors which affect oversteer / understeer, in Table 3, we can see that regardless of the test results, or lack of them, there are only two factors which are a function of the difference between three and four wheels, and these factors are not of critical importance. In other words, a lack of variability in camber and roll rate distribution should be compensatable through the remaining factors, given proper engineering development.

Table 3. Factors Affecting Understeer and Oversteer

Tire Sizes and Characteristics
Tire Pressures
Camber Characteristics (not applicable at a single wheel)
Roll Resistance Distribution (not available on 3-wheeler)
Steering Compliance
Power Application
Weight Distribution

Although these were the key safety-related tests, other tests have shown some significant differences between the 3- and 4-wheel vehicles tested. However, these differences appear to be primarily dependent on the early stage of development of the 3-wheelers and, at any rate, not particularly hazardous. Some 3-wheelers had poor free returnability, but only because the steering was tight or not aligned properly. One car did poorly in the bump in turn, because its spring rates were too high. And most cars had poor braking merely because the front / rear brake ratio was bad or there simply was not enough pedal force gain. On the other hand, there were no significant differences in the crosswind disturbance, step steer, or single lane change results.

It appears that traditional state-of-the-art vehicle dynamics knowledge applies to 3-wheelers also. The handling characteristics are still primarily a function of suspension geometry, weight distribution, steering and suspension compliance, tire properties, etc. The only obvious exception is that anti-roll bars are of lesser significance because the front / rear roll rate distribution is not a variable in 3-wheel vehicles.

CONCLUSIONS

Based on the research done to date, we believe that it is possible to build a 3-wheeled car with essentially the same handling and overturn characteristics as any given 4-wheeled car. All the laws of physics and vehicle dynamics engineering apply to both, with some special considerations. It is possible for inexperienced designers to produce a 3-wheeler with undesirable characteristics in overturn or oversteer, but the same could be said for is-wheel cars. None of the 3-wheeled prototypes we tested was completely acceptable as received, but we assume that all of the cars we tested could be modified so as to conform to all known automotive handling and braking recommendations.

ACKNOWLEDGMENTS

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Fig. 1 H-M Freeway

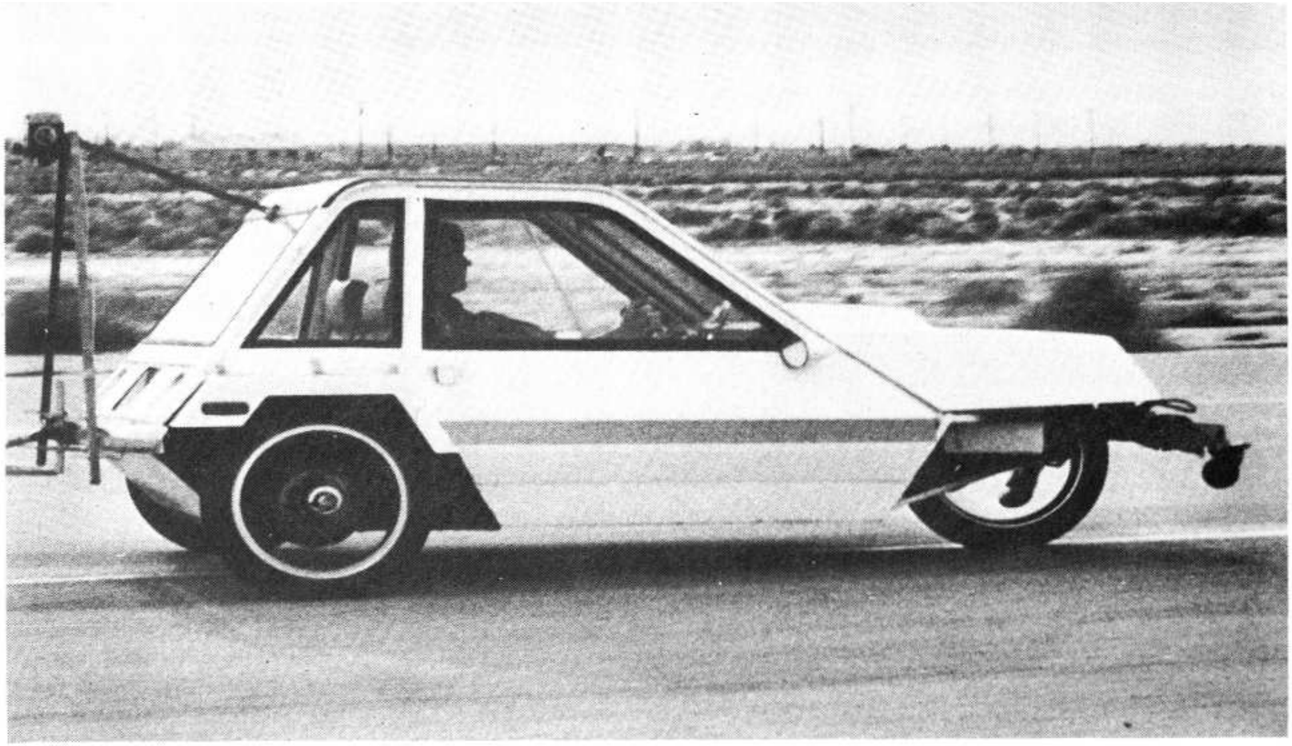

Fig. 2 Gilbert Transelectric

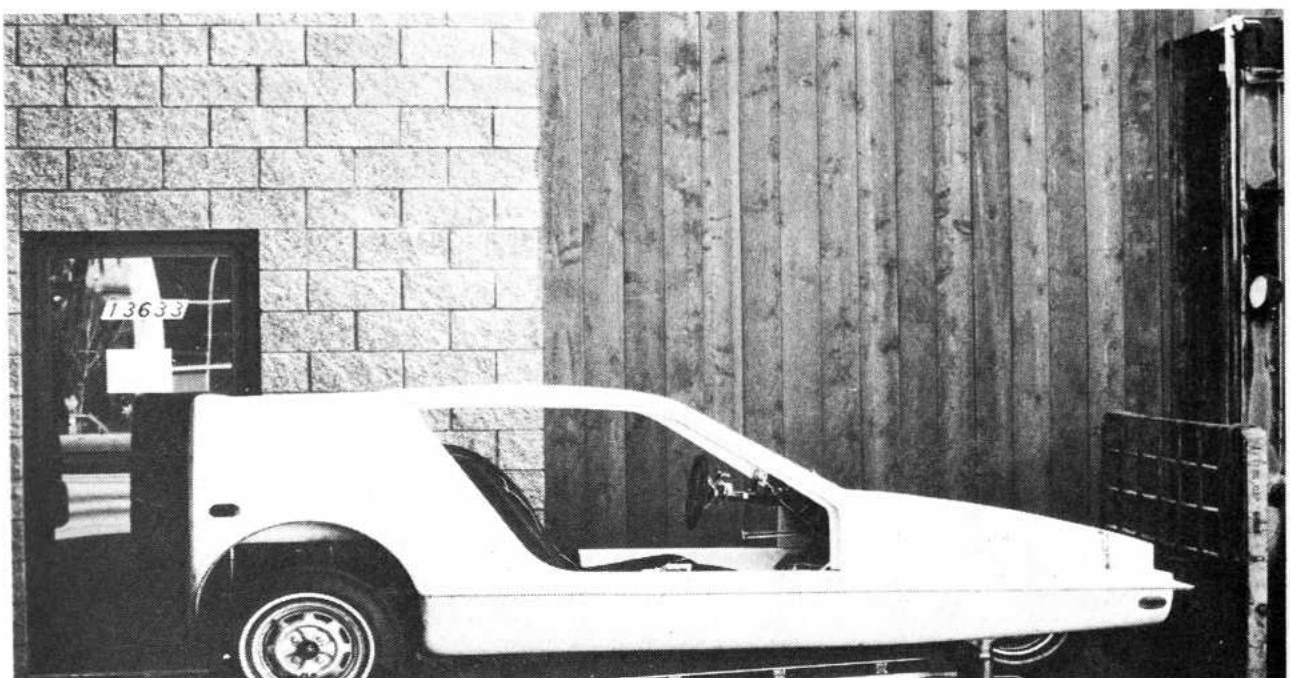

Fig. 3 Structural Plastics Spitri

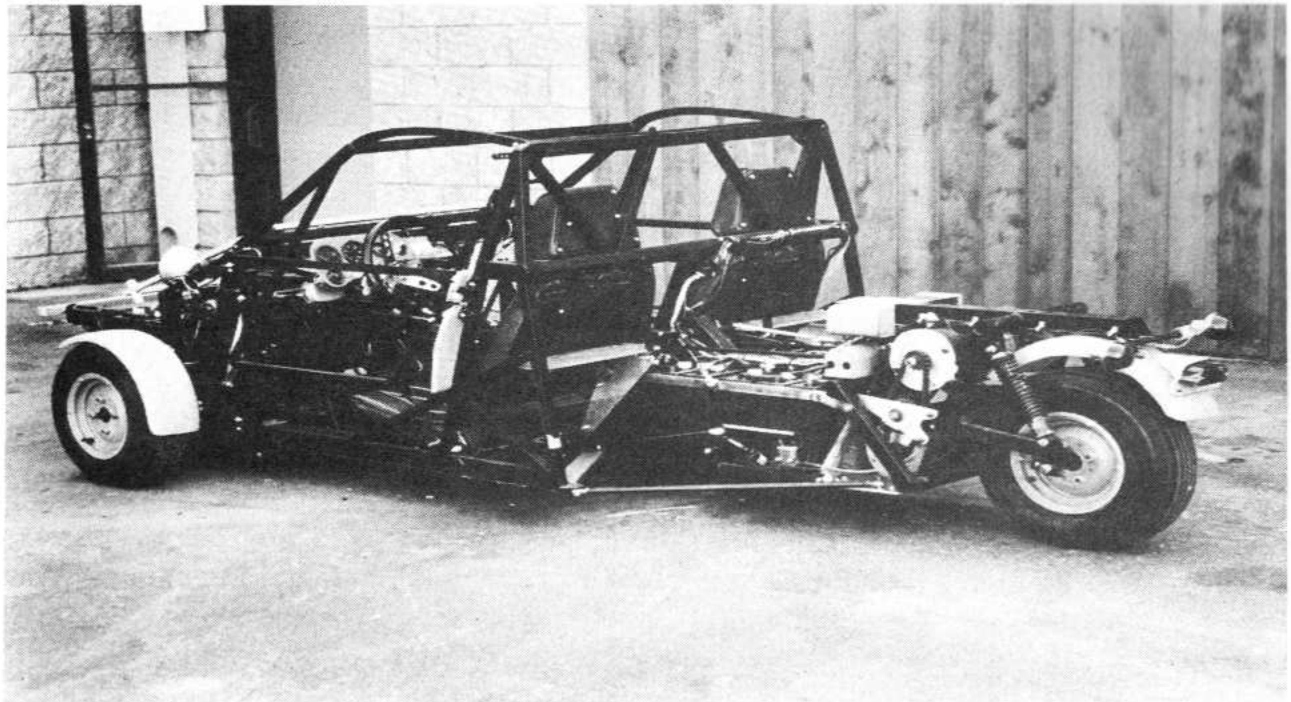

Fig. 4 Korff Duo-Delta

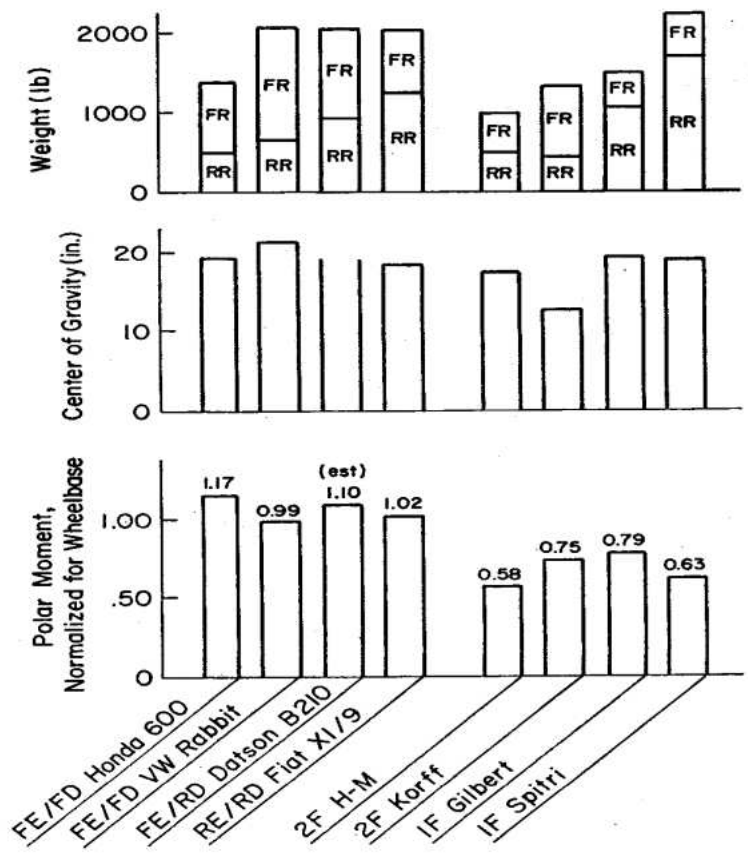

Fig. 5 Ranges of Vehicle Characteristics for Eight Test Vehicles

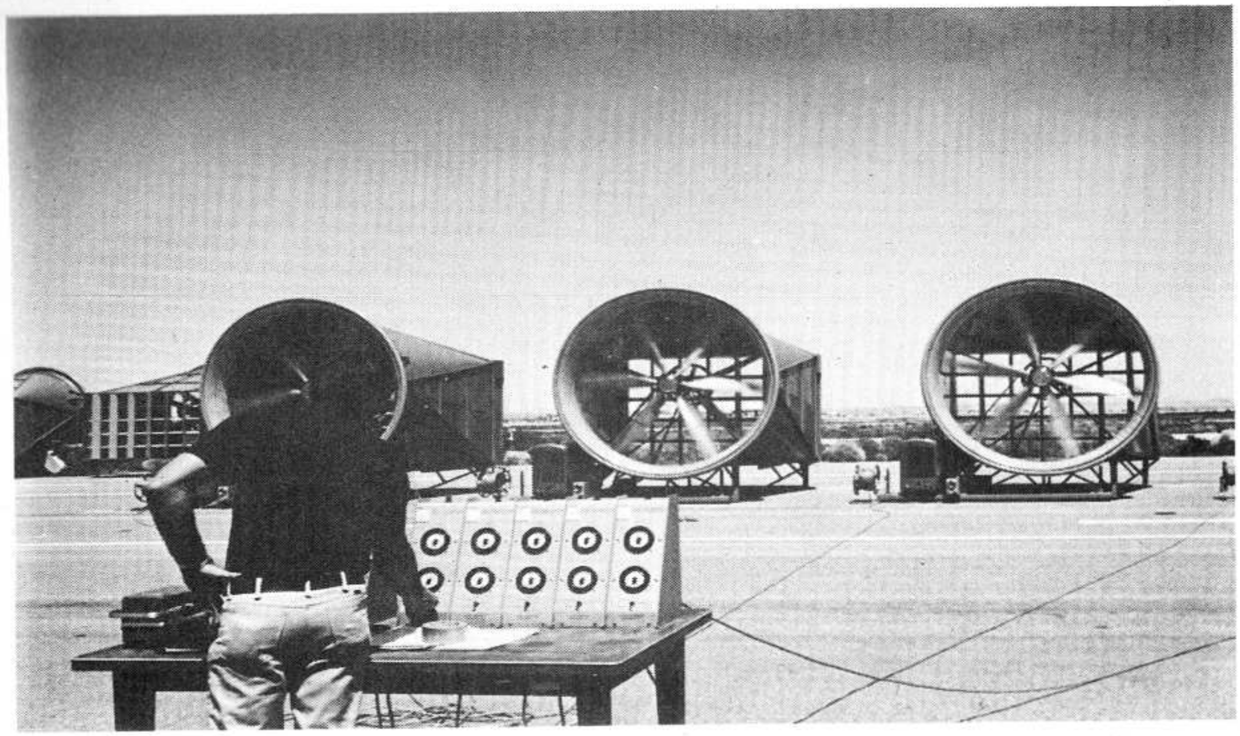

Fig. 6 Three of Eight Units of the NHTSA Crosswind Generator

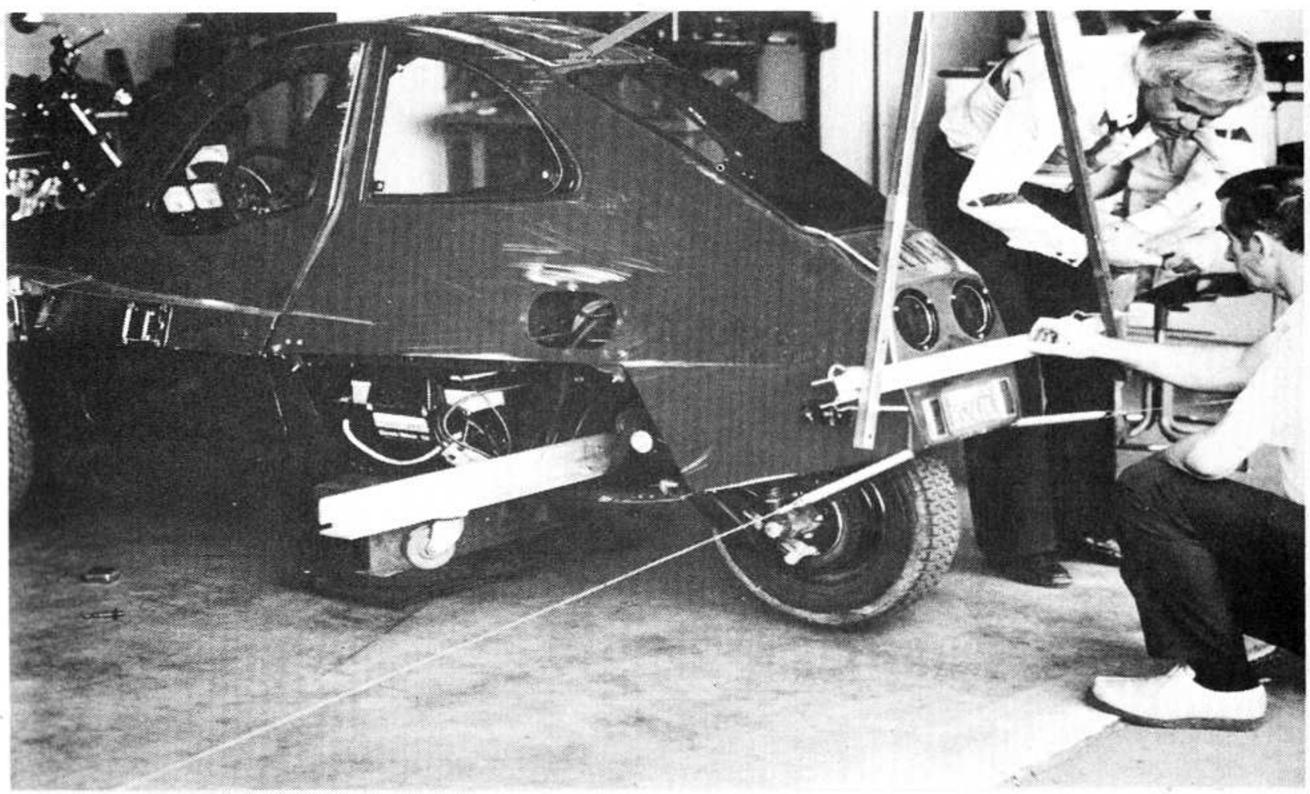

Fig. 7 Measurement of the Vehicle Polar Moment Using the Torsional Pendulum Frequency Method

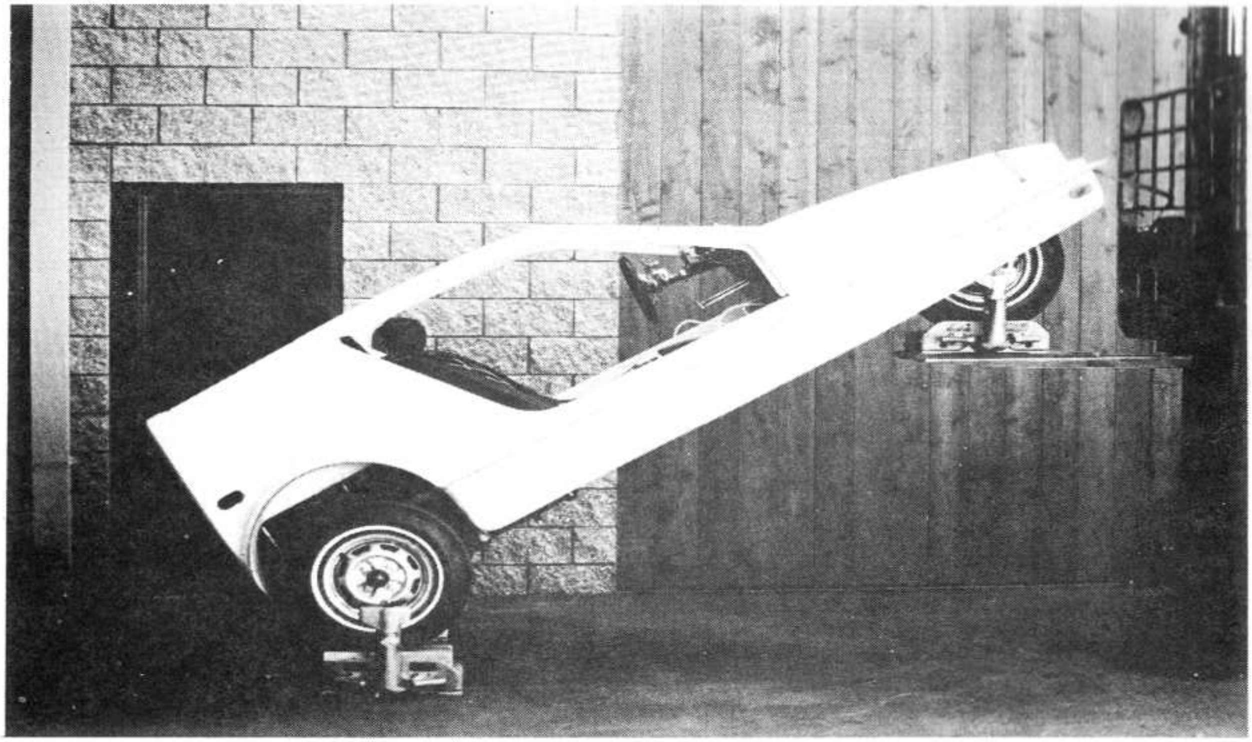

Fig. 8 Measurement of the Center of Gravity Location by Taking Wheel Weights in Different Positions

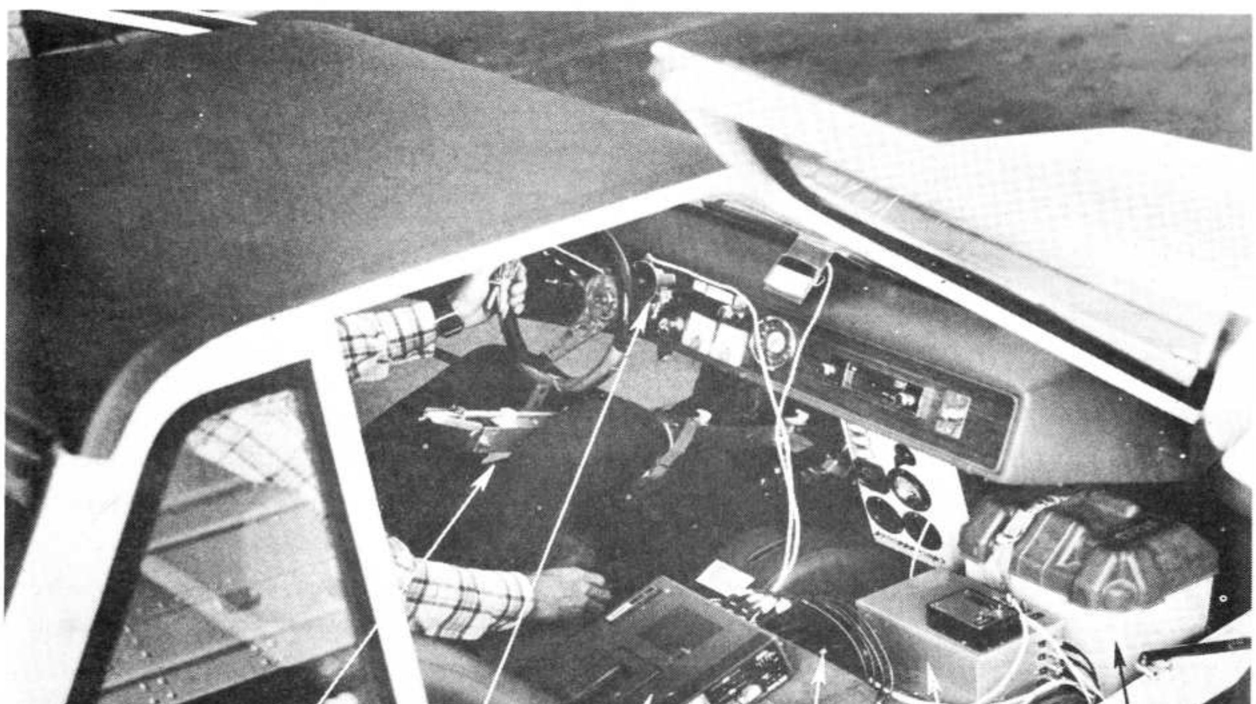

Fig. 9 Placement of Instrumentation in Test Vehicle

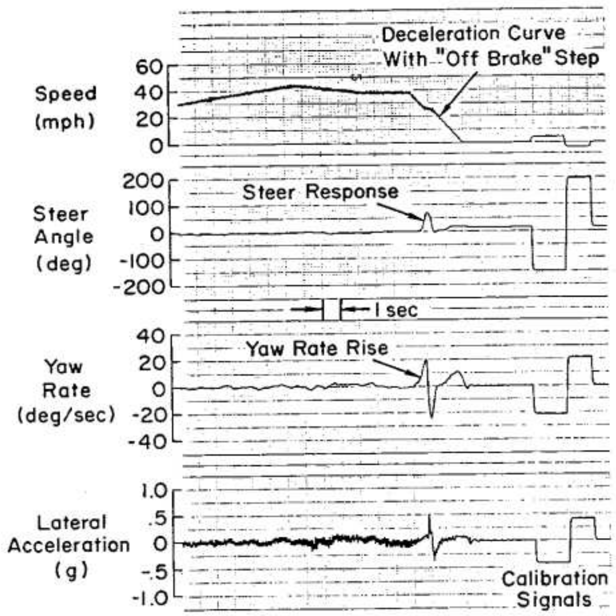

Fig. 10 Example of Strip Chart Data, Straight Brake with Rear Lockup

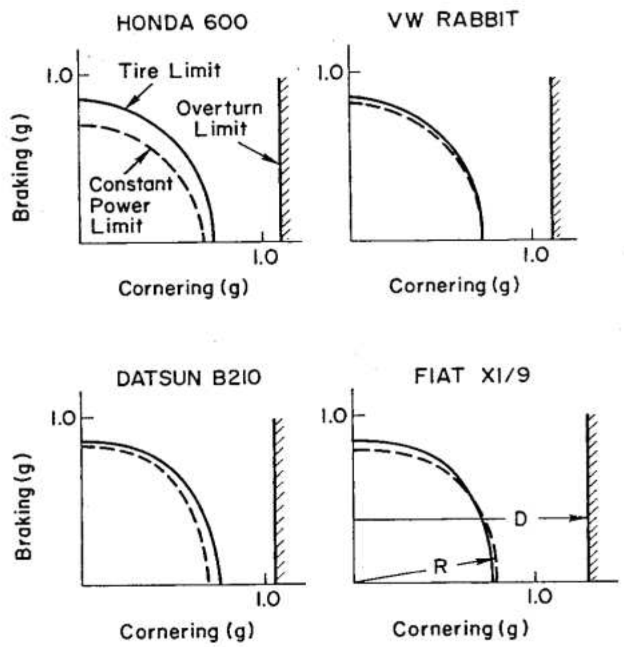

Fig. 11 Prediction of Overturn Limits for 4-Wheeled Vehicles

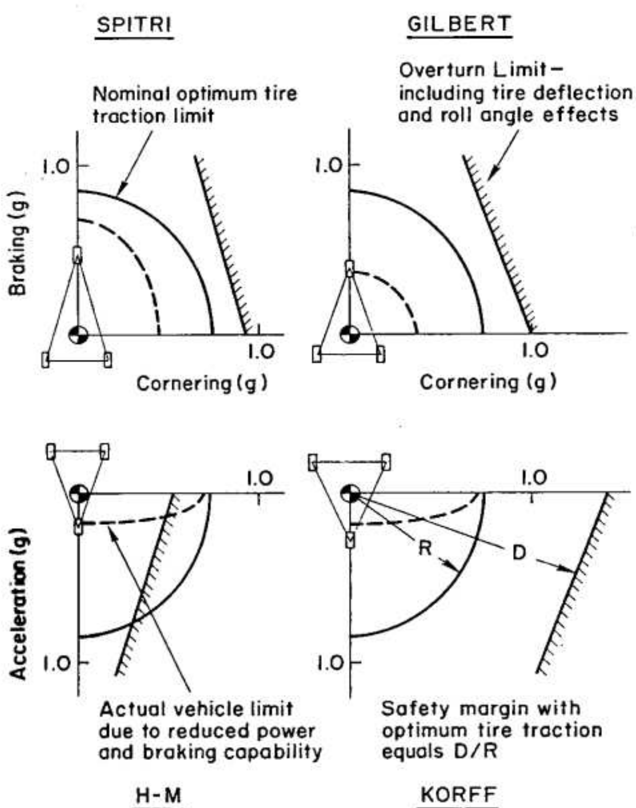

Fig. 12 Prediction of Overturn Limits for 3-Wheeled Vehicles

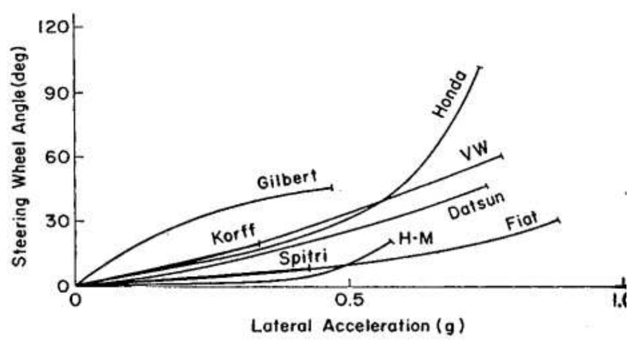

Fig. 13 Understeer Curves for All Test Cars