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Effects of Outrigger Design on Vehicle Dynamics

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ABSTRACT

Outriggers are devices that arrest vehicle rollover during handling test maneuvers to protect the test vehicle and/or test driver. Validity of data in these tests has been questioned because the effect outriggers have on vehicle dynamics is not well understood. This research quantifies changes in handling characteristics with outriggers attached to a test vehicle. Three outrigger systems of different masses were developed and tested through various limit and sub-limit handling maneuvers. Analysis of the data generated during testing indicates improvements necessary for future outrigger designs leading to better understanding of vehicle dynamics and potentially reduced injuries from rollovers.

STATEMENT OF PROBLEM

Passenger vehicle handling and roll propensity in limit maneuvers are areas of increasing interest. Recent studies show that 55% of the occupants are injured in single vehicle rollover accidents. Further, rollovers cause the highest injury rate of all accident types.[1] Over the years, various methods to evaluate or predict the performance of vehicles in limit maneuvers have been developed and utilized. These methods include static or quasi-static evaluations, computer models, and dynamic tests. The research described in this work addresses dynamic testing. Specifically, this paper describes a state-of-the-art tool for safe, repeatable test evaluation of vehicles in limit maneuvers.

For many purposes, including design validation and research, it is appropriate to perform full-scale vehicle handling tests in both limit and sub-limit maneuvers. For cases of limit maneuvers in which roll propensity is a concern, the use of outriggers is necessary. Typically, an outrigger is a device attached to the vehicle which extends laterally and arrests roll motion by contacting the ground before rollover can occur.

Outriggers provide the advantage of allowing thorough evaluation of vehicle limit performance without risking driver or test vehicle. Historically, outriggers have been useful in the context described above; however, they have posed some limitation due to their weight and configuration. A problem with using outriggers on vehicles has been understanding and limiting their effect on test vehicle behavior. Vehicles, by their utility, i.e., different load configurations, have a range of inertial properties, and a key design requirement of an outrigger system is to minimize its effect on these properties. Properties of interest are center of gravity (CG) location and roll, pitch, and yaw mass moments of inertia.

LITERATURE SEARCH

Documented outrigger use dates back as far as 1970 when Dugoff, et al.[2], performed limit performance handling tests involving several passenger vehicles. The outrigger system weighed 38.6 kg and contributed 40.7 kg*m^2 to the roll mass moment of inertia (RMMOI). The effect of the outrigger on vehicle handling was a consideration during this effort as demonstrated by calculating the RMMOI of the outrigger system.

In 1973, Ervin, et al.[3], used an outrigger system weighing 40 kg and a RMMOI of 60.3 kg*m^2. Again, the contribution of the outrigger's effect on vehicle handling was given attention as indicated by the RMMOI calculation.

In 1976, a large scale test program involving light trucks, vans, and recreational vehicles was conducted by R.L. Anderson, et al.[4], using an outrigger system. During this effort "a check of the effect of outriggers on the [test vehicle] class "C" motor home was performed during the computer simulation and analysis task of the program." It was claimed that the outrigger system had a negligible effect on the predicted response of a class "C" motor home. It was later noted in the paper that the type of limit handling behavior predicted by the computer model was not always the same as that observed while testing. The mass properties of the outrigger system and its effect on the light truck or van test vehicles were not presented.

Mobility Systems Inc.[5] performed limit maneuver testing of a sport utility vehicle in 1989, and the test results have not been published. The estimated weight and RMMOI are 133 kg and 266 kg*m^2.

RMMOI was not reported during a study of modified suspensions of vehicles in 1990 by Kebschul, et al.[6] The outrigger system used in this study weighed 127 kg.

In 1992, Dr. Nalecz[7] presented a vehicle dynamics software validation effort in which outrigger-equipped vehicles were used. Mass properties of the outrigger system were not disclosed. Mass and inertial properties for all of the above designs are presented in Table 1.

In the published literature there is limited discussion of the instrumentation and modifications made in preparation of test vehicles and their effects on vehicle dynamics. There is also little discussion of the expected or measured effects of the outrigger systems on testing. Although some awareness of outrigger effects on vehicle dynamics was exhibited in earlier test programs, the significance of these effects was not presented.

TABLE 1.

Year	Researcher	Wt. (kg)	RMMOI (kg*m^2)
1970	Dugoff, et al.[2]	38.6	40.7
1973	Ervin, et al.[3]	40.0	60.3
1976	Anderson, et al.[4]	-	-
1989*	Mobility Systems[5]	133	266
1990	Kebschul, et al.[6]	127	-
1992	Nalecz[7]	-	-
1993	Dickerson, et al.	15	32.5

PURPOSE OF RESEARCH

The purpose of this research program is twofold. First, design and build a lightweight outrigger system that could be used on a wide range of vehicle types and sizes for conducting vehicle handling tests. Outrigger designs presented in the literature weigh between 38.6 and 127 kg and have roll mass moments of inertia ranging from 40.7 to 266 kg-m^2. The goal of the design task was to create an outrigger system that was as light as possible with minimum RMMOI. The second task was to determine what effect outriggers have on the handling characteristics of vehicles in limit maneuvers. This was done by conducting a parametric study and a series of limit performance handling tests utilizing three different outrigger systems covering a range of mass properties.

OUTRIGGER MASS PROPERTIES

The range of mass properties for existing outrigger designs was evaluated to determine three outrigger configurations to be analyzed and tested in this study. It was found that the roll mass moments of inertia of the heaviest of the currently-fielded outrigger designs was approximately equal to the roll mass moments of inertia of many passenger cars and sport utility vehicles. Based on this finding, three outrigger configurations were analyzed and tested:

1. Lightweight outrigger designed during this program to minimize its RMMOI.
2. Medium weight outrigger designed to have a RMMOI equal to half the RMMOI of the test vehicle.
3. Heavyweight outrigger designed to have a RMMOI equal to the RMMOI of the test vehicle.

The mass properties of these outrigger configurations are shown in Table 2. The test vehicle was a 1989 Ford Bronco II 4X4 with a curb weight of 1516 kg, a RMMOI equal to 461.2 kg-m^2, and a YMMOI of 2255.3 kg-m^2.

TABLE 2. OUTRIGGER MASS PROPERTIES

Outrigger Design	Weight kg.	RMMOI kg-m^2	YMMOI kg-m^2	% RMMOI of BII 4X4	%YMMOI of BII 4x4
Lightweight	15	32.5	27.1	7	1
Medium weight	60	199.1	189.5	43	8
Heavyweight	106	398.4	388.5	86	17

Analysis was conducted to determine the range of mass properties anticipated for this vehicle when empty and when loaded to its gross vehicle weight rating. This was done to determine an operational envelope for the mass properties of the test vehicle. Additional analysis was conducted to discover effects of adding each of the three outrigger designs to the test vehicle's overall mass properties. The results of this analysis are presented graphically in Figure 1. In this figure, the I-bars represent the anticipated operational envelope for the roll and yaw mass moments of inertia of the test vehicle. Plotted as points on the figure are the roll and yaw mass moments of inertia of the test vehicle in its curb configuration with a 50th percentile male test driver in each of the three outrigger designs. This figure shows that the mass properties of the lightweight outrigger design configuration fall within the anticipated operational envelope. Additionally, it shows the medium weight and heavyweight outrigger designs fall well outside of the anticipated operational envelope for RMMOI and remain inside the envelope for YMMOI.

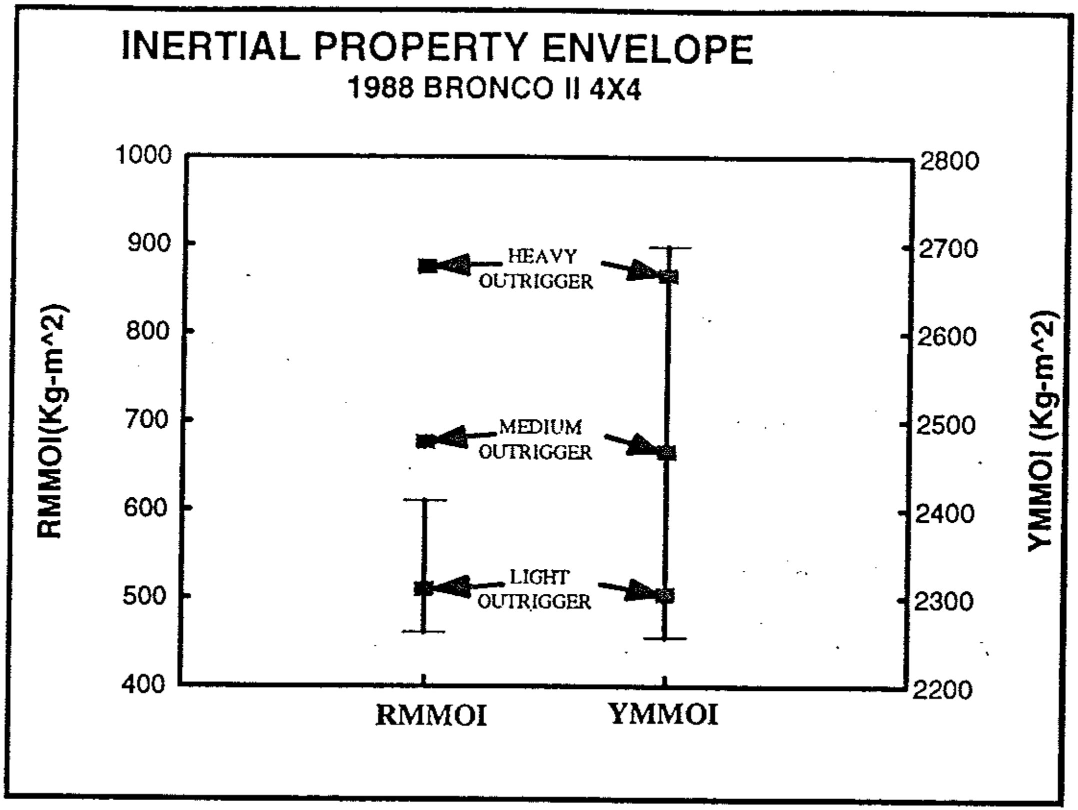


FIGURE 1.

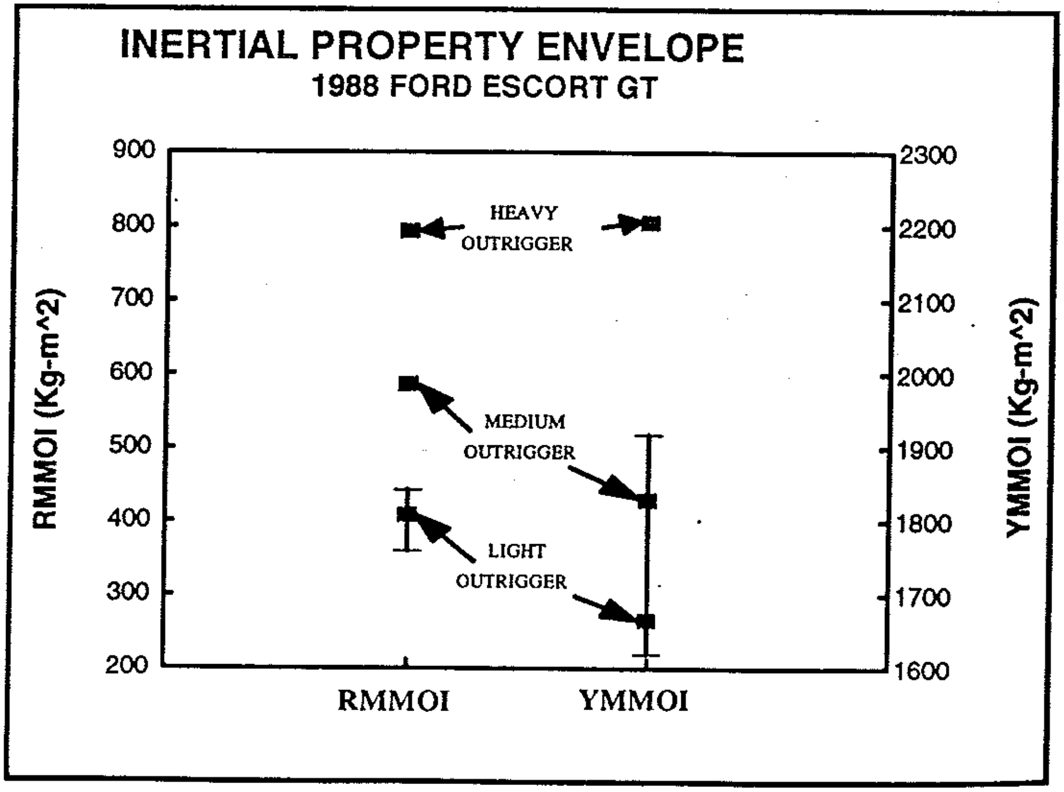


FIGURE 2.

A determination of the operational envelope of the test vehicle CG location also was defined as the range of CG positions anticipated for the test vehicle when empty and when loaded to its gross vehicle weight rating. The CG range for the 1989 Bronco II 4x4 is from 66.7 cm at curb to 70.4 cm at gross vehicle weight. The test vehicle with driver and lightweight outrigger system had a CG height of 67.1 cm. The vehicle with driver and medium weight system had a CG height of 67.0 cm and with the heavyweight system had a CG height of 66.6 cm.

Because the Ford Bronco II 4X4 falls in the middle-to-upper spectrum of the mass properties for passenger cars and sport utility vehicles[8], this analysis was repeated for a vehicle with mass properties at the lower end of the spectrum. The 1988 Ford Escort GT was selected for this analysis. This vehicle has a curb weight of 1105 kg, a RMMOI equal to 338.8 kg*m^2 and a YMMOI equal to 1526.8 kg*m^2. Figure 2 shows the results in graphical form. The I-bars denote the anticipated operational envelope for the roll and yaw mass moments of inertia for the 1988 Ford Escort GT. The three points plotted on the figure denote the roll and mass moments of inertia for the 1988 ord Escort GT and a 50th percentile male driver with each of the three outrigger designs. The 1988 Ford Escort GT with the lightweight outrigger design test configuration falls within the anticipated operational envelope. The medium weight and heavyweight outrigger designs are well outside the operational envelope for RMMOI, and the heavyweight outrigger design falls outside the YMMOI envelope.

OUTRIGGER DESIGN

The outrigger system configuration consisted of upper and lower spars extending from the top and bottom edges of the vehicle. The spars connect away from the vehicle to form a triangular structure, as shown in Figure 3. This outrigger structure was positioned longitudinally at the vehicle's center of gravity. Structural cross members span the top and bottom of the vehicle. Pin joints were used at ch connection of the outrigger spars. This design feature eliminates bending loads on the outrigger spars and allows them to perform as tension and compression members.

The outrigger structures were stabilized longitudinally by means of cables attached from the end of the spars to the front and rear corners of the vehicle.

The lightweight composite outrigger described in this paper is a second-generation design. The first-generation system was made from thin wall steel tubing. For the second-generation system, two improvements were made. The first was a refinement of the geometry while the second was incorporation of lightweight materials.

The geometry enhancements included moving the outrigger tip closer to the vehicle and the ground. This geometric change significantly reduced the roll mass moment of inertia of the outrigger by moving the mass closer to the CG of the vehicle. During testing of the first-generation outrigger system, too much roll energy was developed before the outrigger tip contacted the ground resulting in unnecessary vehicle and road surface damage. To prevent this from occurring, the outrigger tips were positioned closer to the ground in order to arrest roll excursion earlier.

Weight reduction of the second-generation outrigger system was achieved by constructing many components out of lightweight materials. With the exception of the cables and pins, virtually all of the steel in the system was replaced with aluminum or composite materials.

Continuous fiber reinforced organic matrix composite materials (advanced composites) exhibit very high strength properties at extremely light weights when compared to materials such as steel and aluminum. Material properties are compared in Table 3.

Advanced composites are anisotropic materials consisting of oriented fibers in a resin matrix with mechanical properties dependent on fiber orientation. The design effort for incorporating composite materials into the first-generation outrigger design required sizing the spar section and wall thickness to minimize weight while maintaining structural integrity.

Analysis of the expected loads revealed that the highest forces would be compressive and would occur in the upper strut. Since the strut is attached with pin joints, bending loads would be negligible. The resulting spar tube requirements are shown in Table 4. Examination of these expected forces coupled with the desired geometry revealed that slender tube buckling would be the most likely failure mode.

The composite tube consisted of two general fiber orientations. Most of the layers were aligned predominantly in the longitudinal direction to provide axial stiffness and strength. The remaining layers were oriented transversely to provide stability and damage tolerance. The comparison between design requirements and the tube properties is shown in Table 5.

Fabrication of the outrigger spars was another design consideration. Filament winding is an efficient manufacturing method for producing round tubular structures. This manufacturing method was chosen because the carbon fiber placement could be precisely controlled while minimizing manufacturing costs. Other manufacturing techniques considered were labor intensive or required more elaborate tooling.

The end fittings that mated with the composite spars were machined from 2024 T-4 aluminum then anodized and adhesively bonded to the inside of the composite tubes using an aerospace-grade epoxy.

Due to the distance of the skid assembly from the CG of the test vehicle, the weight of the skid assembly was especially critical. The design shown in Figure 4 consists of a monolithic fiberglass shoe that houses the end fitting with a small replaceable steel disk attached to it. The weight of this design is approximately .44 kg. This is 2.74 kg less than the first-generation skid design.

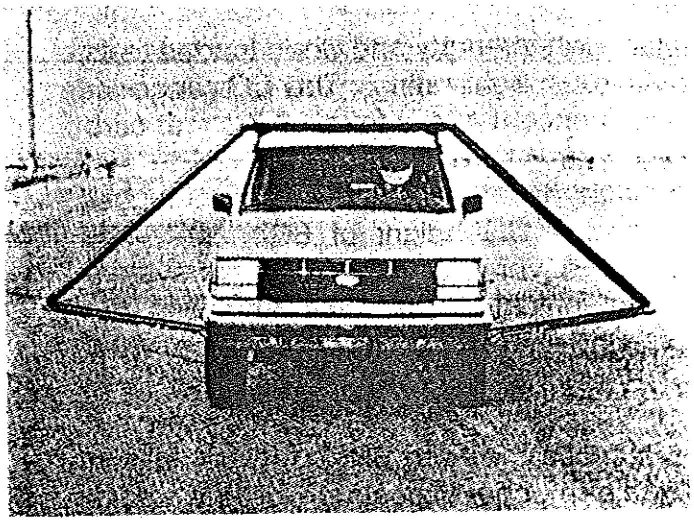


FIGURE 3.
TEST VEHICLE WITH OUTRIGGERS

The cross members that span the roof and undercarriage to connect the outrigger spars were made of 6061 T-6 aluminum. These cross members consist of 7.62 cm diameter round tubing with .165 cm wall thickness. The

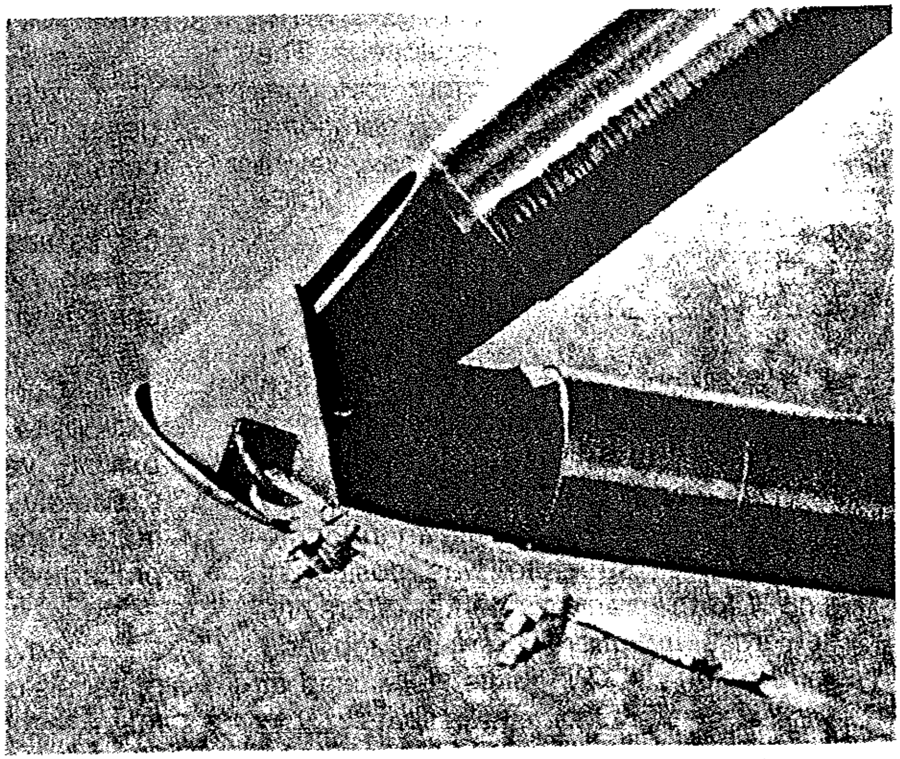


FIGURE 4. OUTRIGGER SKID ASSEMBLY

material properties of the 6061 T-6 aluminum are included in Table 3.

TABLE 3.

MATERIAL PROPERTIES

MATERIAL	TENSILE STRENGTH (MPa)	COMPRESSIVE STRENGTH (MPa)	DENSITY (gm/cc)
ASTM A500 STEEL	310	310	7.86
6061 T-6 ALUMINUM	289	289	2.68
2024 T-361 ALUMINUM	496	496	2.77
INTERMEDIATE MODULUS CARBON FIBER	2853	1447	.066

TABLE 4.

TUBE REQUIREMENTS

TUBE LENGTH	2 M
WALL THICKNESS	0.160 CM
OUTSIDE DIAMETER	7.62 CM
COMPRESSIVE LOAD	35,500 N
TENSILE LOAD	35,500 N
MAXIMUM OPERATING TEMP.	85 DEGREES C

TABLE 5.

DESIGN AND TUBE PROPERTIES

	DESIGN REQUIREMENTS	TUBE PROPERTIES	FACTOR OF SAFETY
TENSILE STRENGTH	90 MPa	640 MPa	7.11
COMPRESSIVE STRENGTH	90 MPa	775 MPa	8.61
AXIAL MODULUS	49 GPa	125 GPa	2.55

TEST CONFIGURATION

The vehicle used in this effort was a 1988 Ford Bronco II four-wheel drive sport utility vehicle. Prior to testing, the test vehicle was restored to original factory specifications. The test vehicle was then weighed and CG location easured. All subsequent changes to the test vehicle were documented and its weight and CG measured again in the final test configuration. The only modifications made to the vehicle were those necessary for driver protection and data acquisition.

Safety modifications were made for safe exploration of the limit handling behavior by adding the outrigger system for the protection of both driver and vehicle. Also, a roll bar, five-point restraint, and driver's door window webbing were added for the protection of the test driver.

In order to mount the instrumentation package, removal of vehicle interior components was necessary, A complete log of all changes including weight and CG location of the added and removed items was kept. This accounting process provided a means for analytically determining the effect of the modifications on e inertial properties of the vehicle. The modifications did not significantly affect the inertial properties or mass of the vehicle.

To record vehicle behavior throughout the test maneuver, a sixteen-channel data acquisition package was installed. Table 6 describes the channels recorded. In this system, an analog transducer signal was filtered, conditioned, digitized, and finally stored on floppy disk in a standard IBM PC compatible DOS format. The acquisition system sampled data at 1000 Hz and had a pre-amplification three-pole filter with a 3dB cutoff at 10 Hz. All of the signal conditioning and acquisition equipment resides in the vehicle making it completely self-contained.

TABLE 6.

Channel Description

1 - 33	axis acceleration
4	roll angle
5	roll rate
6	heading angle
7	heading angle rate
8	pitch angle
9 - 10	left and right front wheel steer angle
11	steering wheel angle
12	vehicle velocity
13 - 16	vertical suspension deflection

DISCUSSION

MANEUVER DESCRIPTION - Open loop maneuvers were performed to study outrigger effect(s) on vehicle dynamics. This allowed the data to be examined objectively and independent of driver skill or behavior. The two maneuvers used were a step steer input and a double-step steer input. For each maneuver the primary variables were vehicle velocity at the beginning of the maneuver and steer input magnitude. Throttle and brakes were not used during the maneuver.

The step steer input maneuver is commonly referred to as a J-turn. It was performed by bringing the vehicle to a desired velocity, removing throttle input, then rapidly turning the steering wheel to the desired magnitude. The steer input was then held constant until the vehicle reached steady state or limit behavior was observed. For the outrigger characterization series, steer input was fixed and vehicle velocity was increased in each subsequent run until outrigger contact was achieved. A series of 180 and 270 degree step steers with speeds ranging from 40.3 km/h to 91.2 km/h were made with each outrigger configuration.

The double-step maneuver was developed to create a more severe steer input. It is performed by inputting a step in one direction and allowing lateral acceleration to build up to a maximum before inputting a step steer in the opposite direction. The second step results a final magnitude equal and opposite the first. Similar to the J-turn, the throttle is released before performing the maneuver. This maneuver was chosen over a sinusoid input because of its broader spectral content. It was desired to use a maneuver that could be applied to a wide variety of vehicles without inadvertently matching the input sinusoid frequency to the natural frequency of one of them. In this test series, the steer inputs were limited to a 180 degree left input followed by a 360 degree right input resulting in an absolute input of 180 right at the end of the maneuver. The speeds ranged from 48.3 km/h to 80.0 km/h.

RESULTS - The outrigger characterization test series consisted of 52 runs which resulted in 19 runs with wheel lift and 9 runs with outrigger contact. Thirty-five of the runs were step steer inputs and 17 were double-step steer inputs. Scatter plots showing the overall results of the 180 degree right step steer, the 270 degree right step steer, and the 180 degree left-180 degree right double step steer for all three outrigger configurations are shown in Figures 5

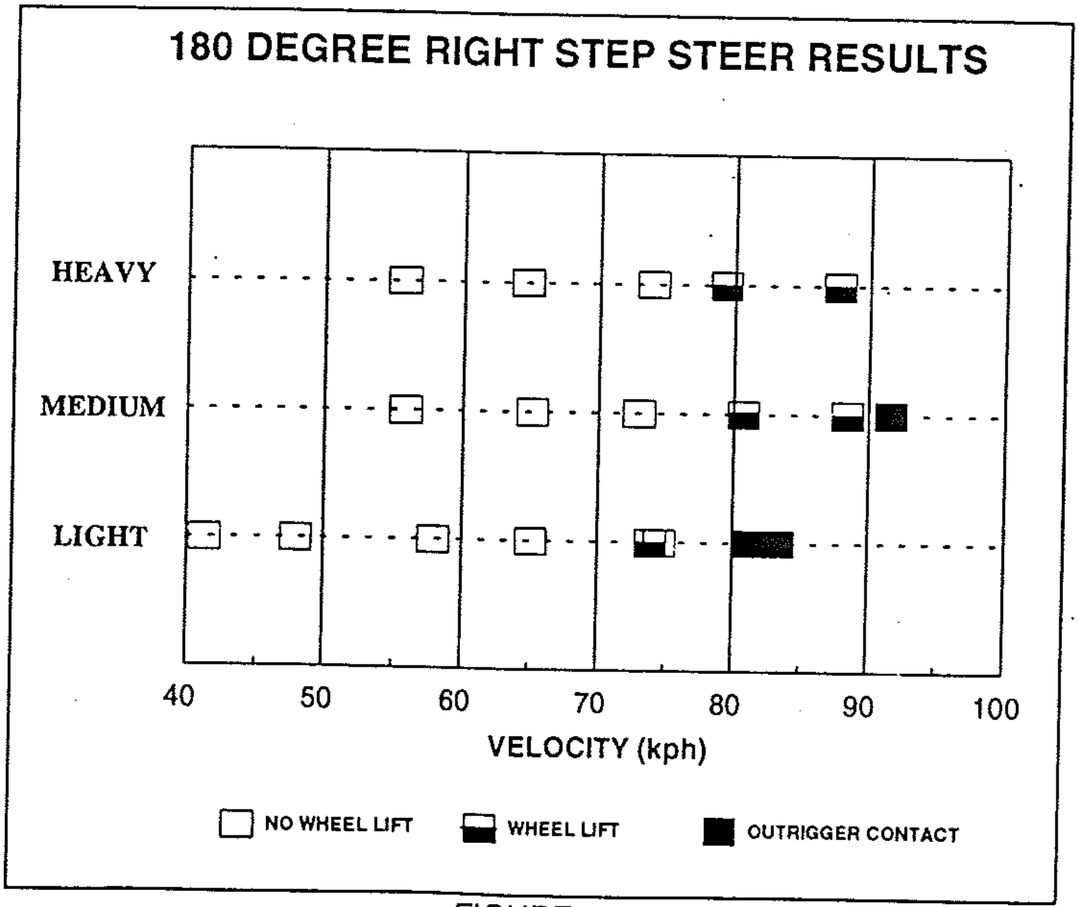
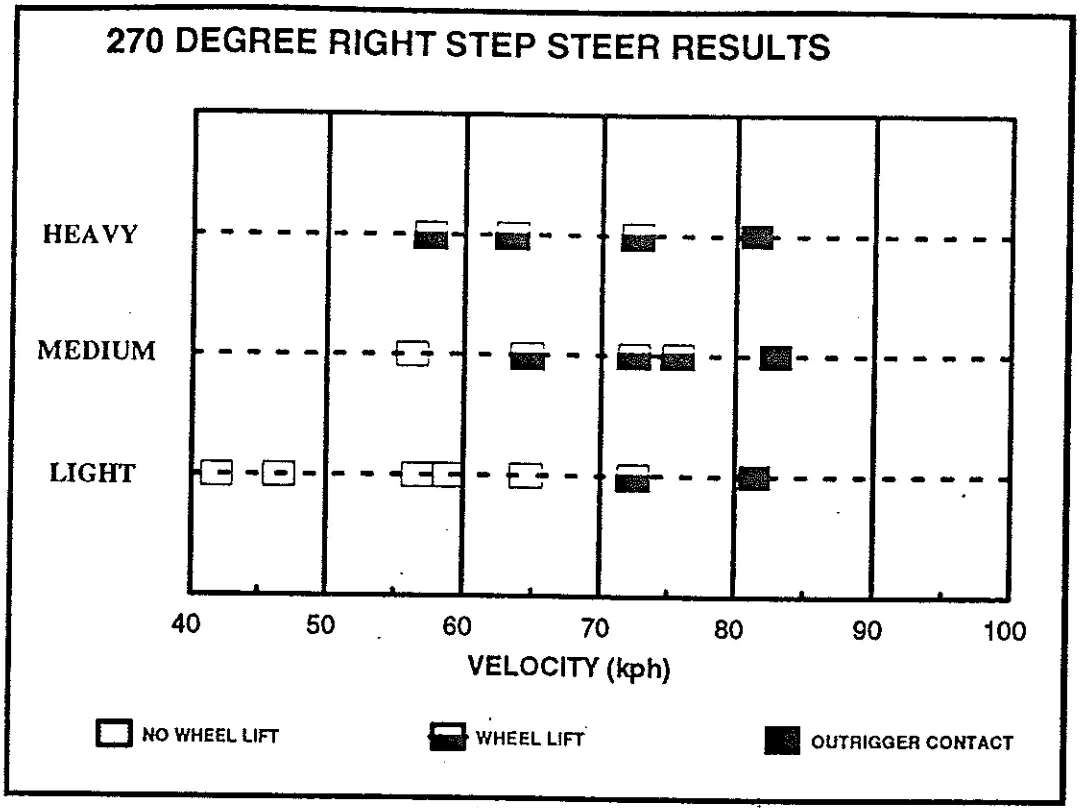


FIGURE 5.

through 7. In the plots, an empty marker indicates no observed wheel lift, a half-filled marker indicates either 1 or 2 wheels were observed to lift, and a completely filled marker indicates that outrigger contact occurred.

In the 180-degree right step steer, contact occurred, with use of the lightweight outrigger system, at a speed of 80.6 km/h. Outrigger contact occurred while using the medium weight system at 91.8 km/h, 11.2 km/h faster. Wheel lift was observed at 74.1 km/h with the lightweight system, 6.8 km/h slower than the medium weight system and 5.3 km/h slower than the heavyweight system. Wheel lift occurred at approximately the same speeds for both the medium weight system and the heavyweight system. The heavyweight system was not tested beyond 87.9 km/h due to limitations of the test track.



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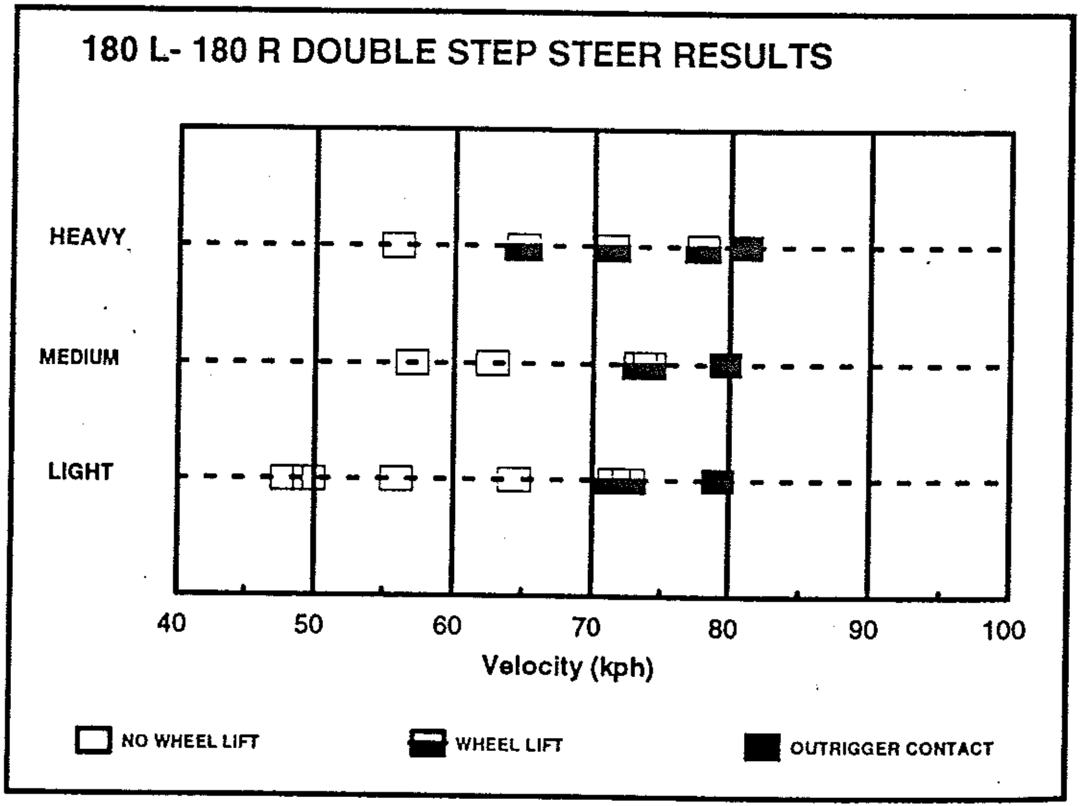

FIGURE 7.

A method for examining the rollover propensity of a vehicle that has been commonly used is the static stability factor. This method generates a parameter based on track width and CG height. In the 180 degree right step steer maneuvers, a 14% change in rollover speed was observed between two of the outrigger system configurations. This occurred without any modification of the CG height or

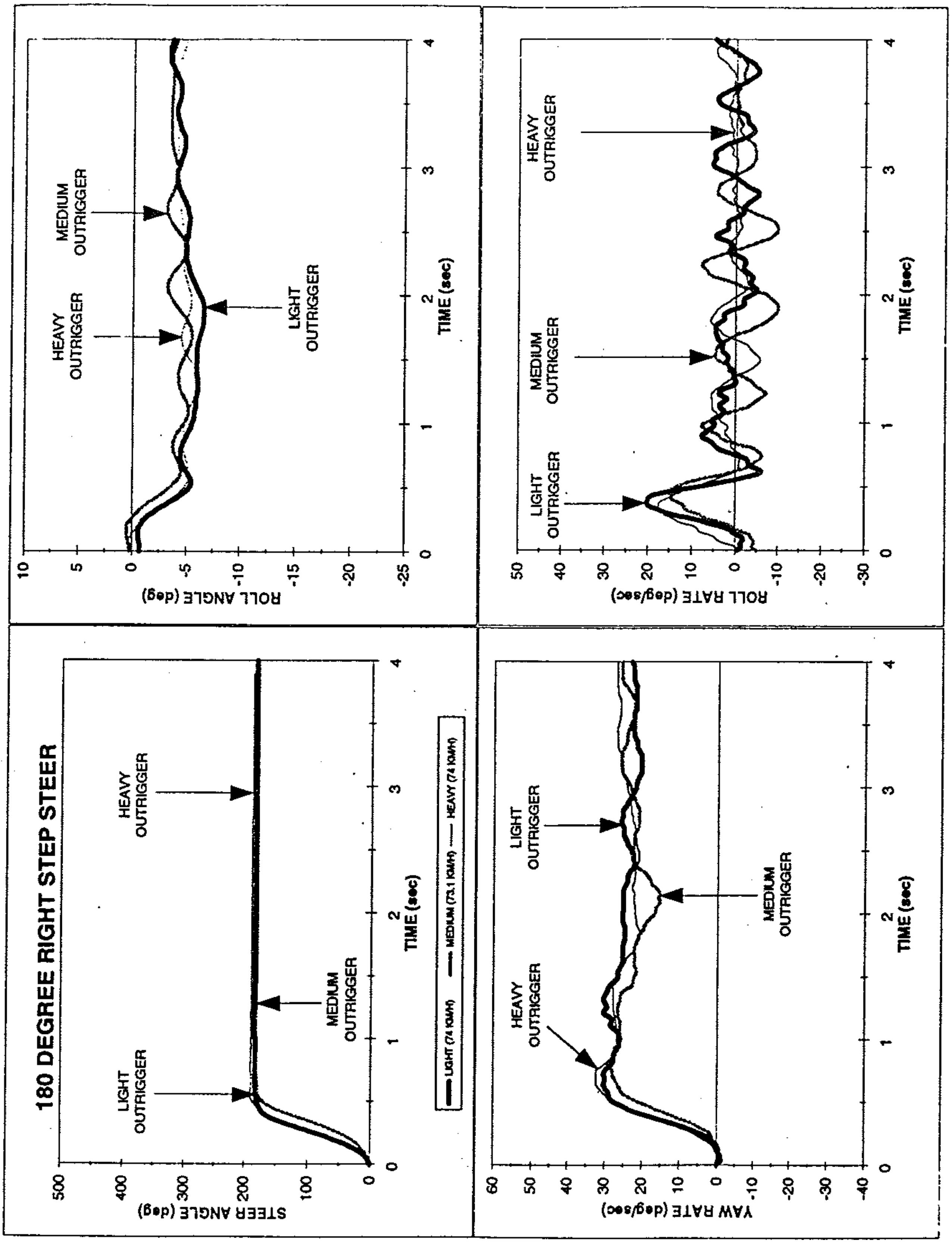

FIGURE 8. 180 DEGREE RIGHT STEP STEER DATA, NO OUTRIGGER CONTACT

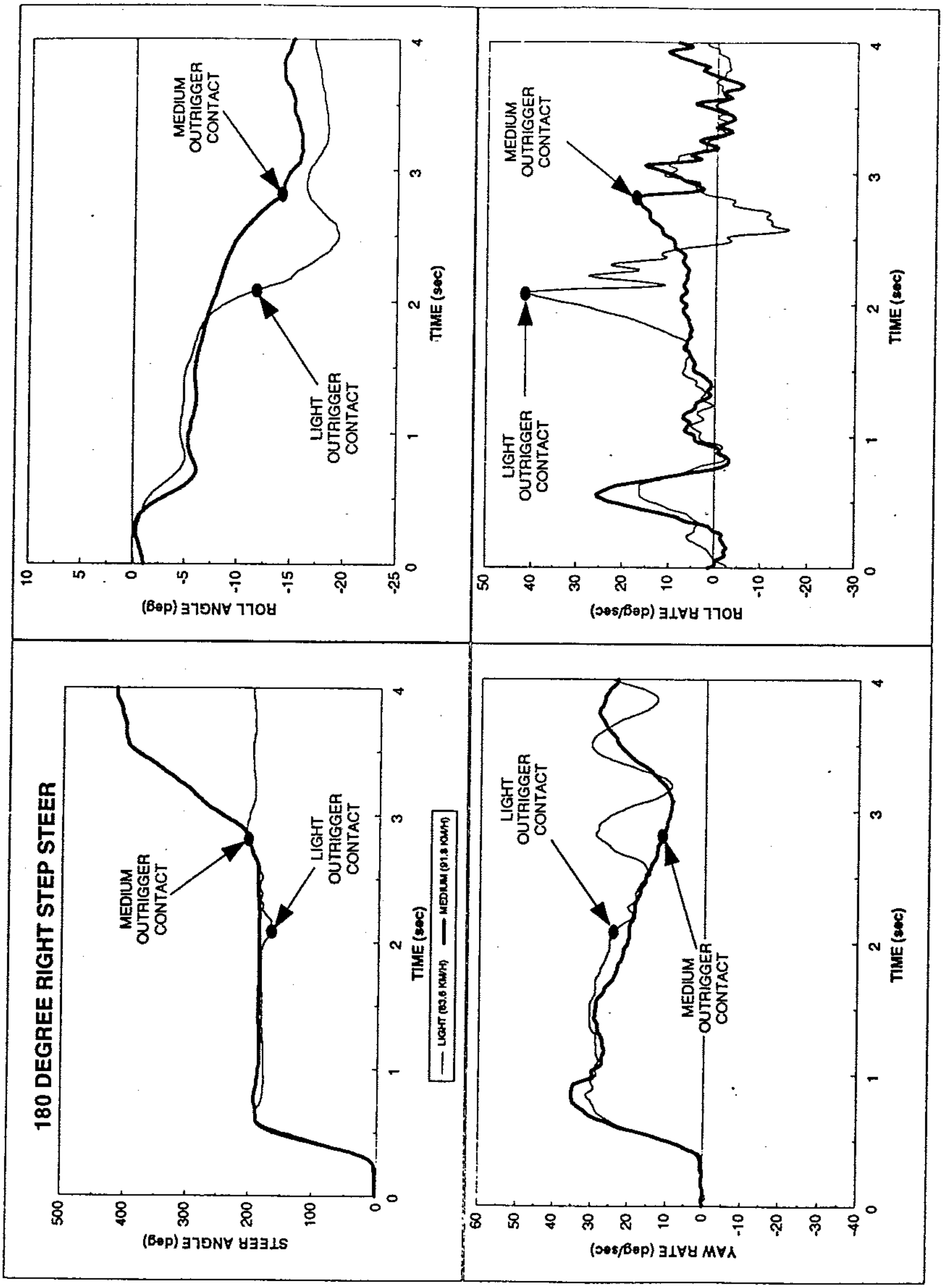

FIGURE 9. 180 DEGREE RIGHT STEP STEER DATA, OUTRIGGER CONTACT

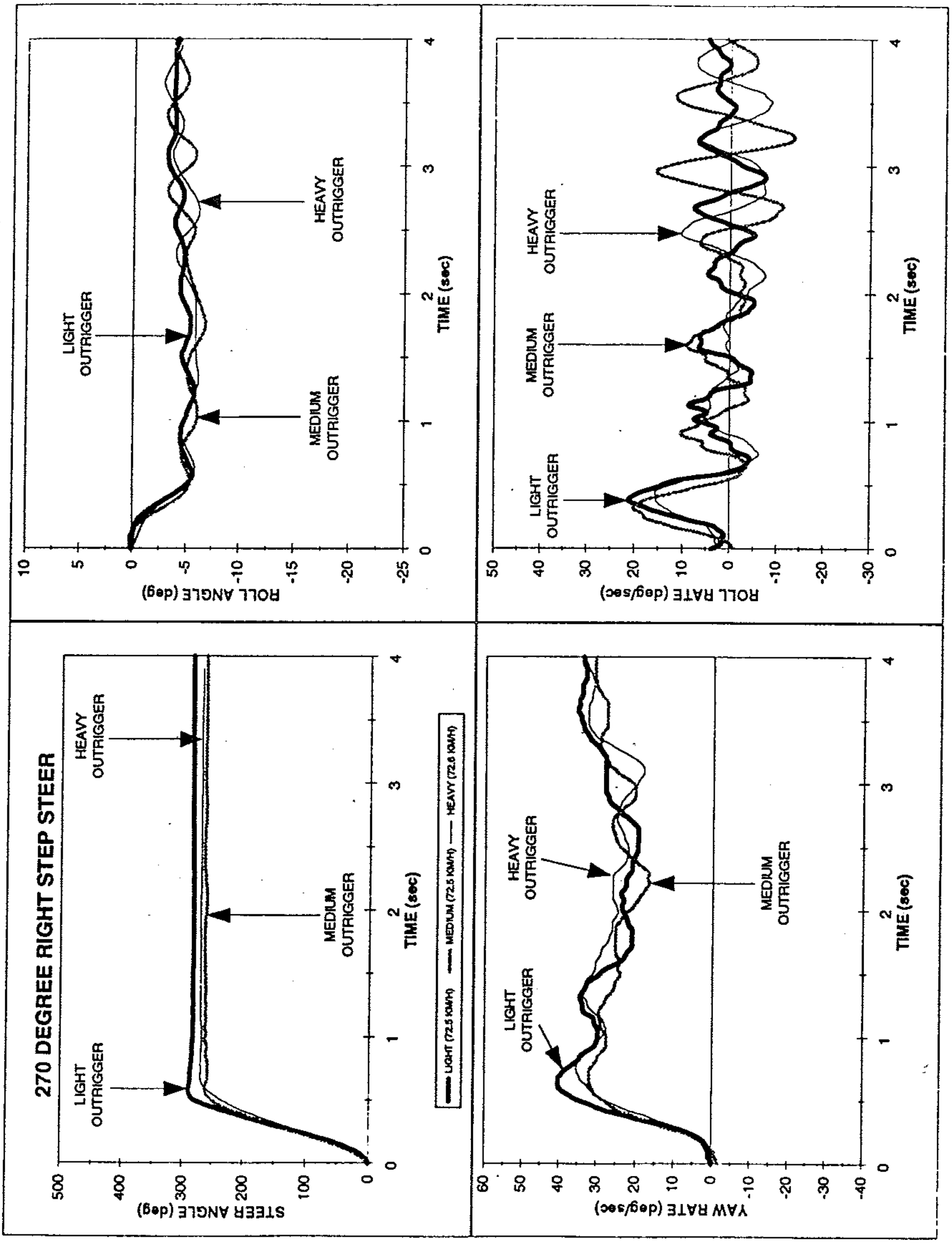

FIGURE 10. 270 DEGREE RIGHT STEP STEER DATA, NO OUTRIGGER CONTACT

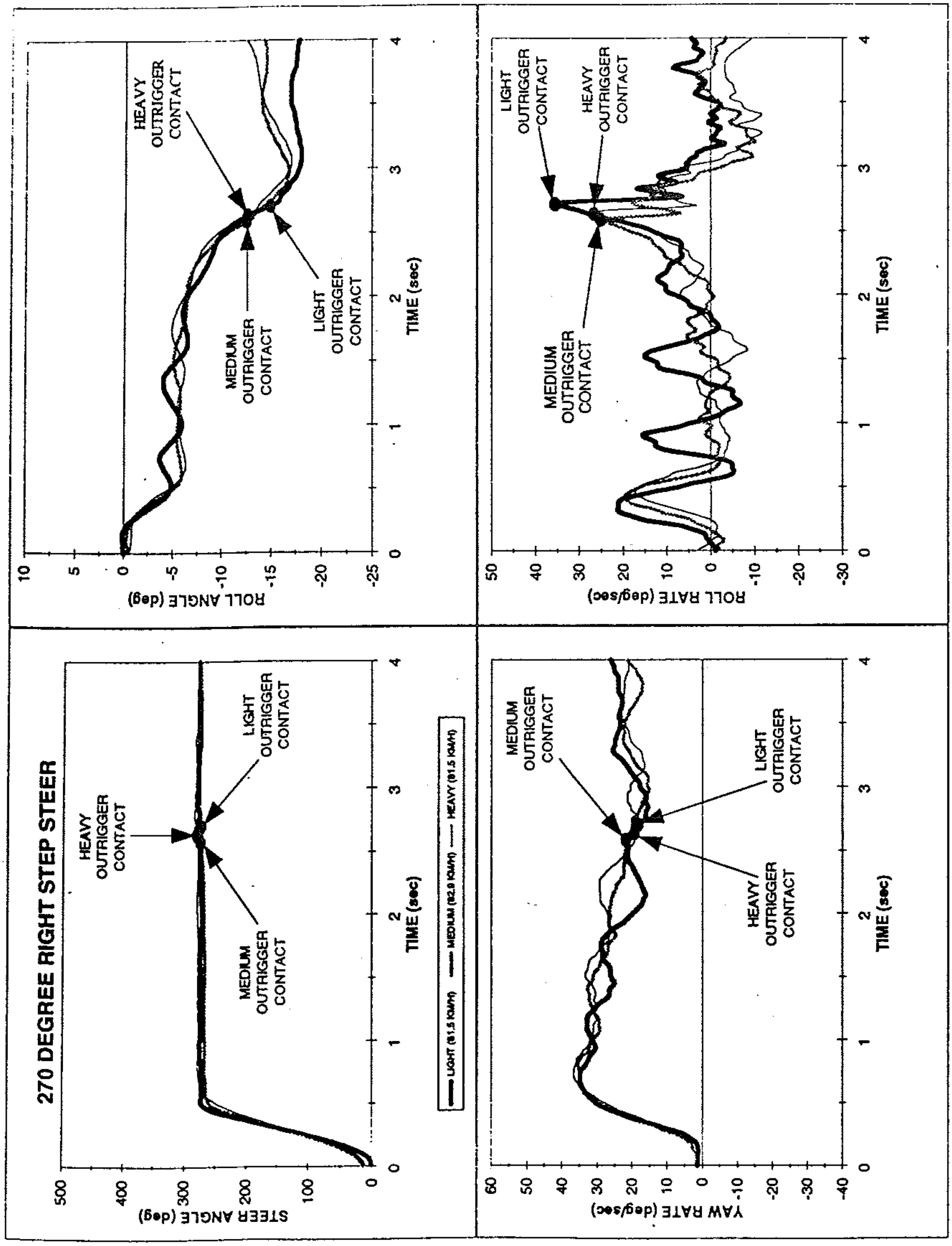

FIGURE 11. 270 DEGREE RIGHT STEP STEER DATA, OUTRIGGER CONTACT

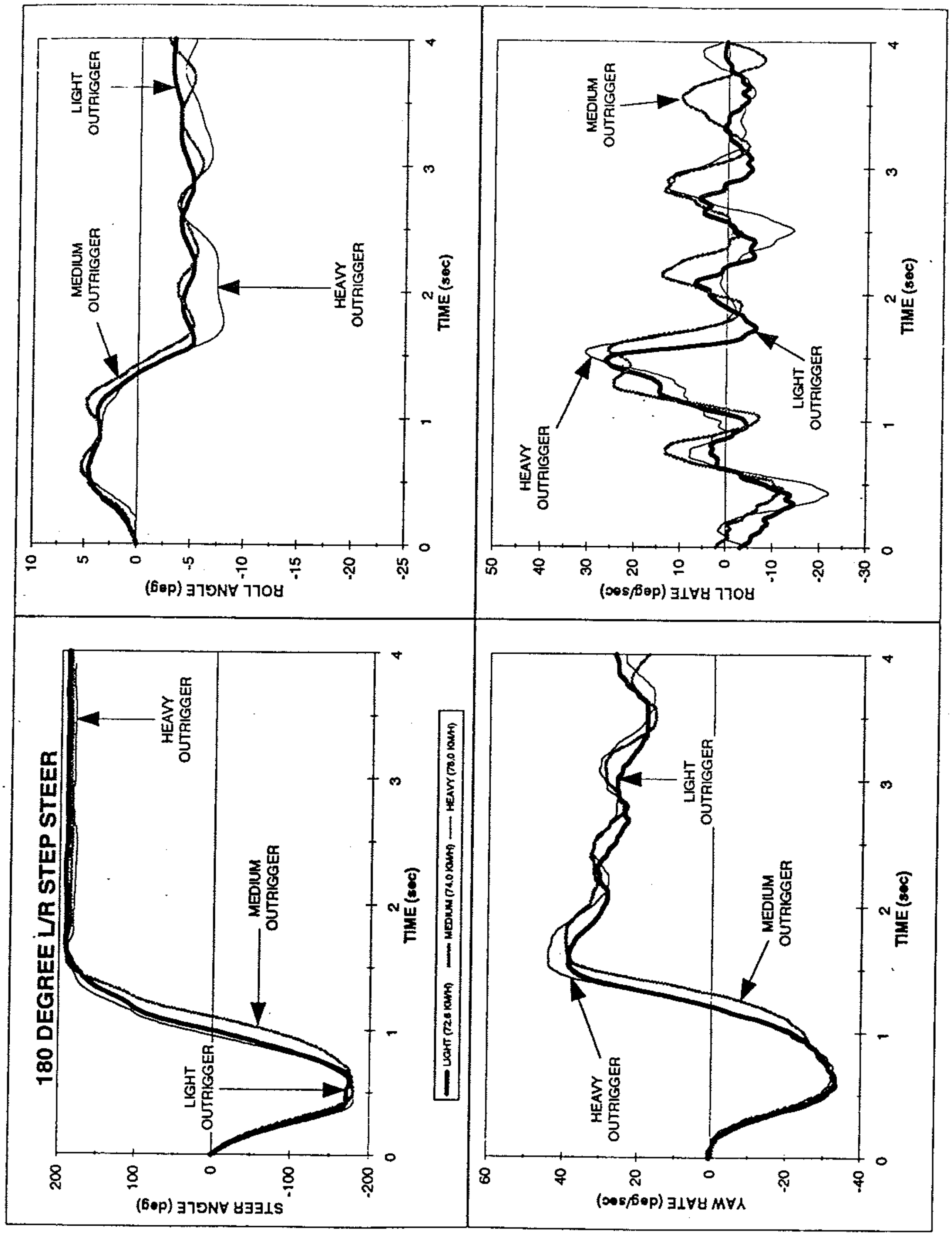

FIGURE 12. 180L / 180R DOUBLE STEP STEER DATA, NO OUTRIGGER CONTACT

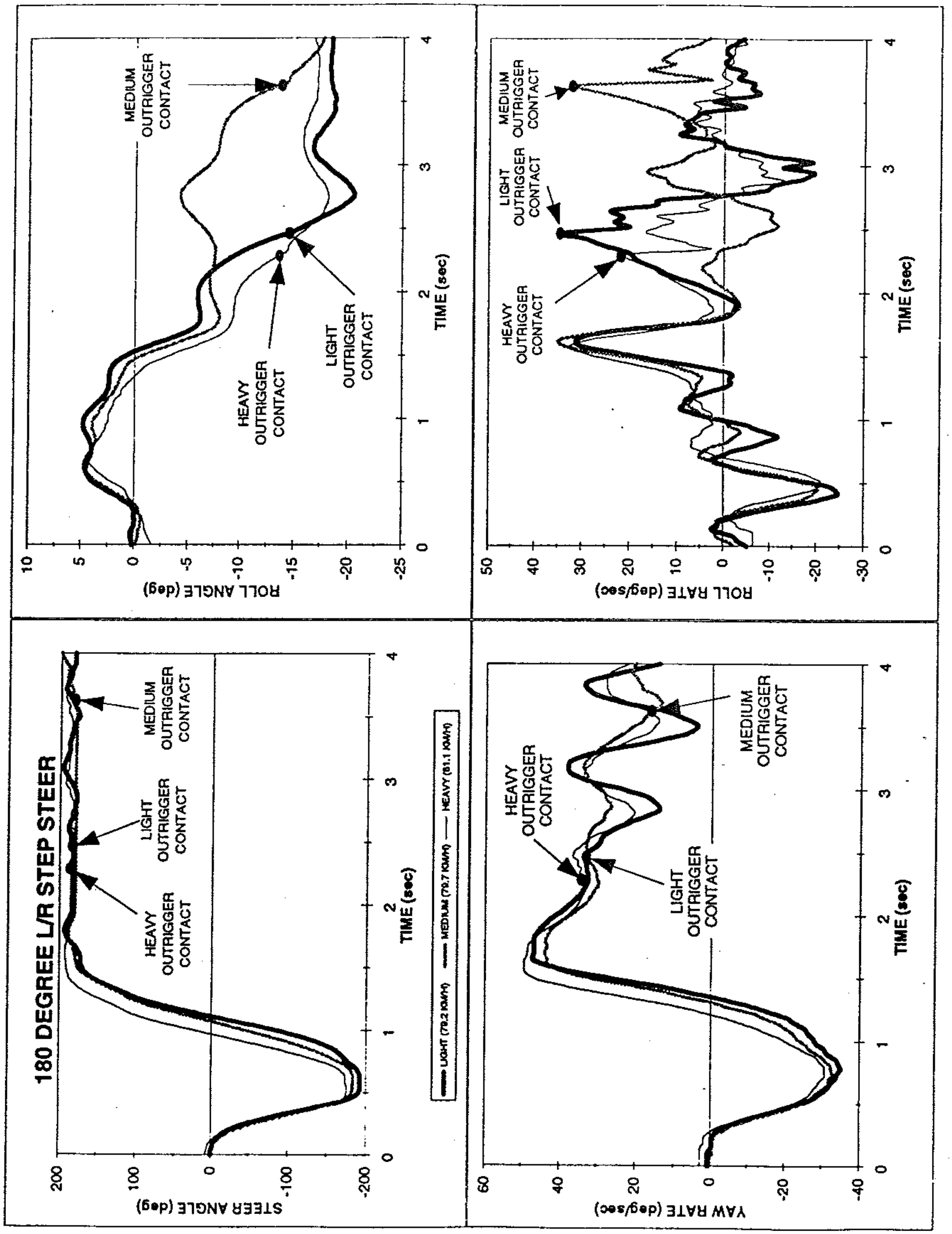

FIGURE 13. 180L / 180R DOUBLE STEP STEER DATA, OUTRIGGER CONTACT

track width of the test vehicle.

The 270-degree right step steer series resulted in all three outrigger systems contacting e ground at approximately 82.0 km/h. Wheel lift occurred at 64.4 km/h for the lightweight and medium weight outrigger systems and 57.5 km/h for the heavyweight outrigger system.

The 180 left-180 right double-step steer series results were similar to the 270 right step steer results. The heavyweight configuration exhibited wheel lift at a lower speed than the medium weight and lightweight systems with wheel lift occurring at 64.4 km/h for the heavyweight outrigger and 72.4 km/h for the lightweight and medium weight outriggers. Wheel lift for all three systems occurred during the 180 degree right step steer portion of the maneuver. Outrigger contact occurred at approximately 80.5 km/h in all three configurations.

Figures 8 through 13 show the actual ta for four of the channels: steer angle, roll angle, roll angle rate, and yaw angle rate. On each graph the response of the vehicle with each of the outrigger systems is plotted. A set of plots for runs that result in outrigger contact and a set of plots for runs that do not result in outrigger contact are presented for each maneuver. These plots provide an example of the data set that has been collected and a means for comparison of the individual dynamic responses. Differences in the vehicle behavior with the three outrigger configurations can be seen in these plots.

CONCLUSIONS

Outrigger systems can affect vehicle behavior in limit maneuvers. The magnitude of the effect is dependent on the mass and inertial properties of the outrigger as well as the maneuver being performed. The outrigger mass properties must be reduced to minimize their ect on vehicle behavior.

The test data shows that the effect of adding mass to the outrigger system is more pronounced in maneuvers with higher speeds and smaller steer angles.

The static stability factor does not adequately describe the observed differences in performance.

RECOMMENDATION FOR FURTHER WORK

The work presented in this paper is ongoing and additional effort is necessary. A more thorough analysis of the data to better quantify the effects of the outrigger system on vehicle parameters such as vehicle natural frequency, damping factor, and dynamic understeer/oversteer is desirable. Further exploration of the limit handling regime is necessary at higher speeds.

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