Collision Analysis Of Vehicle Following Operations By Two-dimensional Simulation Model: Part II- Vehicle Trajectories With Follow-up Maneuvers

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Collision Analysis of Vehicle Following Operations by Two-Dimensional Simulation Model: Part II – Vehicle Trajectories with Follow-Up Maneuvers

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Collision Analysis of Vehicle Following Operations by Two-Dimensional Simulation Model

II

Vehicle Trajectories with Follow-Up Maneuvers

Project Progress Report
MOU 252

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EXECUTIVE SUMMARY

The work discussed in this report is a continuation of the studies in MOU 252 and the discussions in a preceding report, UCB-ITS-PRR-97-4.

In operations of automated vehicles or Automated Highway Systems (AHS), vehicles may be designed or commanded to travel with a small spacing between them. The automated vehicles should travel safely in normal operating conditions. If collisions occur as a result of failures or malfunctions, it is necessary to minimize the consequences of the collisions. This report presents work conducted to understand the effects of operational variables on the outcome of collision in vehicle-following operations and the feasibility of controlling vehicle motions in collisions.

A two-dimensional simulation model is used in this study. The model allows translational movement on a horizontal plane and the rotational motion (yaw) about the vertical axis of a vehicle. A hard-braking failure scenario is simulated in this study with the leading vehicle decelerating while the following vehicle fails to brake accordingly. By using this model with a variety of initial conditions and vehicle parameters, the effects of offset, vehicle size, spacing and vehicle speed on the outcome of collisions are evaluated.

Several follow-up maneuvers by applying steering or braking inputs on the vehicles to respond to the failure event are also simulated to investigate the feasibility of control actions. Different approaches of follow-up actions are examined to discuss the hazards and benefits of these maneuvers. The work discussed in this paper represent a continuation of safety evaluation for automated vehicles in various operating conditions and an initiation of a comprehensive model of collision analysis for future studies.

INTRODUCTION

In Automated Highway Systems (AHS), vehicles are equipped with automatic control systems to govern the accelerating, steering and braking functions in order to maintain an appropriate speed and spacing from the surrounding vehicles. One concept of AHS suggests the implementation of vehicle platoons with small spacing between vehicles. (1,2) If implemented successfully, the density of vehicles on the roadway is higher and therefore the throughput can be increased. Furthermore, in the events of malfunctions or failures that lead to collisions between a leading vehicle and a following vehicle, the relative speed difference (delta-V) at impact is smaller because the spacing is small.

With vehicles moving closely together in platoons, the hazards of “chain-reaction” collisions become a concern. The benefits of small delta-V need to be weighed against the number of collisions in such feared “chain-collision” scenarios. Hitchcock created a probabilistic model in which he included the statistical distribution of spacing, numbers of vehicle on a highway, vehicle weight, and the roadway friction coefficient to estimate the severity of collision and the probable Abbreviated Injury Scale (AIS) levels of the occupants. (3) His collision model is one-dimensional and plastic thus the vehicle masses are aggregated together once they are involved in collisions.

Tongue and Young examined the consequences and effects of different control schemes in platoon collision dynamics in non-nominal conditions. (4,5,6) Vehicle bumper models were built into a one-dimensional platoon collision model. The effects of selected platoon parameter variations on the platoon response under various control algorithms were investigated. The control algorithms included forward and backward schemes, in which the control of individual vehicle depends on the dynamic information of the vehicles ahead and behind.

This paper discusses the effects of collisions in vehicle-following operations, especially for short-spacing scenarios. In this study, the collision analysis is conducted with a two-dimensional simulation program by which the translational and rotational movements of vehicles can be fully represented. Some earlier work presented by the author has identified certain parameters that are most influential on the post-impact vehicle trajectories. (7,8) For example, a greater delta-V of the initial collisions or a larger lateral offset between the vehicles can cause the greatest deviations from the specified path. Some of the findings will be reviewed in a following section.

Also presented in this paper are simulation scenarios where control actions are taken in post-impact conditions. Vehicle maneuvers in these simulations include steering and braking inputs to perform lane-following and lane changing. The potential implications and the effects of these maneuvers on the vehicle trajectories are investigated. The studies of these post-impact maneuvers offer a perspective on the possible actions for vehicles in automated modes. The current and future work of this study should provide insights for the evaluation of the safety hazards and control strategies in AHS.

SIMULATION MODEL

The analysis of vehicle collisions in this work is conducted with a simulation program developed by Engineering Dynamics Corporation (EDC). The software package, EDSMAC (Engineering Dynamics Corporation Simulation Model of Automobile Collisions), is used for the analysis of a single or two-vehicle accident. It is based on a program called SMAC (9-11) initially developed and validated by Calspan Corporation and subsequently improved by EDC (12-15). EDSMAC uses a set of assumed or estimated initial conditions, including positions and velocities, and predicts the outcome of a collision. Engineers and accident reconstructionists have been using this simulation program to analyze vehicle dynamics and the damage resulting from crashes. Researchers have found that the program yields reasonable results with sound input data (16-21).

In its vehicle model, EDSMAC allows the longitudinal and lateral movements as well as the rotational motion about the vertical axis of vehicles on a horizontal plane. If a contact between vehicles is detected, the collision phase is analyzed. The external forces can be applied either at the tire/road interface or between the vehicles. The vehicle exterior is assumed to have homogeneous stiffness.

In the simulation model, a force proportional to the amount of crush is exerted as the body of a vehicle is crushed. This is accomplished by dividing the vehicle’s perimeter into equally spaced intervals. Each of these intervals forms a pie-shaped wedge having its focus at the center of gravity of the vehicle. By knowing where the vehicles are with respect to each other, EDSMAC locates the wedges which are in contact and equalize the force between them. The resulting summation of forces dictates the motion of each vehicle due to the collision. This process continues for each collision time increment until the vehicles are no longer in contact. Default values of the crush stiffness data according to vehicle class category are used in the simulation.

EDSMAC allows the direct entry of vehicle data by users or the selection of default values. The vehicles are categorized by their wheelbase into several classes. Classes I and II are small passenger cars while Classes III to V are medium to large cars. In this paper, default values provided by EDSMAC are used in the simulation. (15)

Appendix A contains exemplar pages of the program EDSMAC and tables showing the default values of different vehicle classes.

Due to the limitations of the simulation models, the problem is formulated to analyze two-vehicle collisions only. The existing software does not allow a third vehicle or object to be involved in the collision process. The motions of the vehicles are restricted on a horizontal plane. In the discussion of simulation results shown in this paper, the simulation is terminated four seconds after the initial collision.

SIMULATION SCENARIOS, ASSUMPTIONS, AND PARAMETERS

In earlier publications (7, 8), simulation results were discussed for the following scenario:
(1) The two vehicles are proceeding straight and no steering inputs are entered before, during, or after the impact;
(2) The leading vehicle at time zero began braking with a constant 0.7 g deceleration and the following vehicle applied no acceleration or deceleration until collisions occur; Throughout the simulation duration, the braking of the leading vehicle remains applied;
(3) No other objects or vehicles come into contact or collisions with the two vehicles in question.

The simulation scenario was chosen to reflect one of the most critical failure conditions that might occur to cause collisions. Such scenarios might result from malfunctions or failures by:
(1) a miscommunication from the leading vehicle to the following vehicle, and a failure in the range and range rate sensor on the following vehicle, or
(2) a failure in brake actuation on the second vehicle.

The scenario above was simulated with a range of initial spacing, lateral offset between the longitudinal axes, initial speed and vehicle sizes. The outcomes of the simulations were evaluated by examining the vehicle trajectories, such as lateral displacement, angular rotation, and time to depart from a specified path. Other critical variables that may cause complications include the yaw angle and the vehicle speed at time of lane departure, but they are not discussed. Although the outcome of each collision case depended a great deal on the specific conditions, certain parameters proved to be critical.

For example, large delta-V and lateral offset can cause greater deviations of trajectories. Figures 1-3 show the maximum lateral movement of the leading vehicle in a series of simulations with different formations. The three formations are Formation I with two Class III vehicles, Formation II with a small vehicle leading a large vehicle (Class I & IV), and Formation III with a large vehicle leading a small vehicle (Class IV & I). The lateral offset is varied from 0.15 m to 0.75 m for two vehicles of the same size traveling initially at 105 kmph with an initial spacing of 1, 3, 5, or 10 m. In all cases, the lateral movement increase with the lateral offset.

Figures 4 and 5 shows the effects of the initial spacing on the lateral deviation of the leading and following vehicle in three formations of different vehicle. Figure 6 and 7 shows the yaw rotation of the leading vehicle sizes that also reflects the effect of large spacing. The initial spacing is varied from 1 to 10 m for two vehicles initially traveling at 105 kmph with a lateral offset of 0.3 m. In all three formations, the angular motion becomes erratic as the initial spacing increases. Further details and explanations of the simulation results can be found in previous papers by the author. (7,8)

One of the factor that should be mentioned here is the tire-roadway interaction issue. If the tire is skidding due to full braking (and without anti-lock braking capability), the directional stability of vehicle motion control is in jeopardy. When braking is not used (as in the failure vehicle) or only partially used, the steering function can be executed more effectively. Two series with different degrees of brake utilization are simulated to examine the effects of this factor.

In the simulation results shown in Figures 4-7, the tire-roadway friction coefficient is assumed to be 0.7 and the leading vehicle is braking with a deceleration of 0.7 g. Since the vehicle is utilizing the full deceleration capability, the directional stability is lost. As a result, the leading vehicle, upon impact, has a tendency to spin. This can be observed from the large values of yaw angle in Figure 6. A separate series of cases is simulated with an assumed tire-roadway friction coefficient of 0.875 while the leading vehicle is braking at 80% capacity, resulting also a 0.7 g deceleration. Figure 8-11 are counterparts of Figures 4-7 depicting the simulation results in the second series. As illustrated, the yaw angle is somehow smaller in the large spacing cases but the lateral deviation is much greater. This is because the leading vehicle will spin less but move more in the translational mode. Although the "non-locking brake" case shows more lateral deviations in Figure 9, these results represent the cases when no follow-up actions are taken. If control actions taken after the collision involve steering inputs, then the "non-locking brake" becomes significant because it allows directional control, while the "locking" case will not permit meaningful steering input.

POST-COLLISION VEHICLE MANEUVERS

The simulation results from previous studies demonstrated that control actions are necessary to correct or maintain the vehicle motion in its intended path. Without corrective actions, the vehicles can either travel out of its path to collide with other traffic or lose control with excessive translation and rotation. To examine the feasibility of such actions, several types of vehicle maneuvers are simulated to follow up the scenario described in the previous section:
(1) After the initial collision, the following vehicle makes a lane-change maneuver with steering input to avoid further impacts;
(2) After failing to activate braking, the following vehicle initiates a lane-change attempt with steering input to avoid impacts or to minimize the collision magnitude;
(3) After the initial failure, the following vehicle activates an emergency braking actuator with a delay to reduce its speed and to mitigate collision magnitude;
(4) After the initial collision, the following vehicle uses steering input to maintain its own path in the original lane.
All of these scenarios assume that the vehicles are operable after the initial collision to the extent that the required actuation, braking or steering, are still functional. The implications and consequences of these scenarios are explained below.

In the previous section, the simulated scenario assumes two possible types of failure conditions. One involves a failure event in which the following vehicle fails to activate the braking function. If the event represents a total breakdown of the braking system, the following vehicle will continue to lack the braking ability in the following period. Therefore, the first two follow-on actions given above make an attempt to steer away from the decelerating leading vehicle before or after the first collision. Obviously the second maneuver scenario is a better alternative than the first if the collision can be avoided at all. However, both of these actions require a decision making process with the following considerations: 1) The steering function needs to be operable; 2) There is an adjacent lane that is open to accept the lane changing vehicle; and 3) the vehicle has the ability to detect or learn about such availability. Keep in mind that the lane-changing vehicle has a brake failure and will continue to move at a considerable speed even after a successful maneuver. Some further follow-up actions or procedures, such as energy-absorbing soft barriers to stop the vehicle, are required.

The third follow-up maneuver scenario suggests that an "emergency" brake be applied after the initial collision with a time delay. This action represents a condition where the "physical capability of braking" is not lost but the decision making process has failed to activate. It can also imply a system in which a separate "switch" for the braking system is built into the vehicle. This switch is activated by a collision sensor. Again, the basic assumption is that the braking system is still "physically" intact and functional in the collision process.

The fourth follow-up maneuver scenario utilizes the steering input of the following vehicle to perform its "lane keeping" function. Further collisions with the leading vehicle are likely to occur but the magnitude of impact will conitnue to decrease as both vehicles slow down. This action can be explained as an alternative to utilize the stopping capability of the leading vehicle to stop the motions of both vehicles. This action avoids the difficulty of decision making for lane changing but it still requires the ability of both vehicles to perform lane tracking in a collision process involving multiple impacts.

The risks of vehicle damage and occupant injuries in these follow-up actions should be evaluated on a case-by-case basis and require further studies. However, the follow-up actions involve the emergency handling logistics embedded in the design process of automated vehicles and they should be weighed carefully. For example, with Maneuvers One and Two, the attempt is made to move the failure vehicle away from the other vehicle and to bring it to a stop through other methods. On the other hand, Maneuver Four sacrifices the leading vehicle by utilizing its stopping capability to decelerate the failure vehicle. Such "unselfish" approach may be acceptable if the collision magnitude can be determined to be small.

While proposing vehicle maneuvers, we are hoping to resolve answer the following main questions or concerns:
(1) the feasibility of conducting steering functions for lane tracking or lane changing in a collision process;
(2) the type of steering inputs needed to perform such functions;
(3) the effectiveness of delayed emergency braking on the vehicle motions;
(4) the comparison of vehicle trajectories and vehicle status in different follow-up scenarios.

SIMULATION RESULTS

In the simulation of Maneuver One, the steering input to change lanes for the following vehicle is initiated at 1.71 seconds, about 0.5 seconds after the initial impact. In Maneuver Two, the steering action is activated at 0.5 seconds. Both of these scenarios assume that a time period of 0.5 seconds is needed for the decision making process to start the action. The steering angle inputs are selected to complete a 3.6 m (12 ft) lane change. During the lane change, subsequent contacts between vehicles continue to occur, therefore causing the steering inputs to be different from typical lane change maneuvers. In Maneuver Three, a deceleration of 0.7 g on the following vehicle is assumed to be initiated at 0.5 seconds, representing an emergency braking capability activated after the collision. No steering inputs are used in this scenario. In Maneuver Four, steering inputs are applied on both vehicles to maintain both vehicles in the lane but no braking is applied to the following vehicle. In all maneuver scenarios, the braking on the leading vehicle remains at 0.7 g throughout the simulation.

Table 1 and 2 show the vehicle status and positions of the leading and the following vehicles in different maneuvers. Table 1 contains the results from a case of a large vehicle following a small vehicle, and Table 2 from a case of a small vehicle following a large vehicle. It should be noted that although in Maneuver 2 the following vehicle makes a lane-change attempt, a collision still occurs before the lane change is completed. This collision involves a front corner of the following vehicle and a rear corner of the leading vehicle and results in a lowest delta-V impact among all maneuvers. As a result, the following vehicle has the highest speed and travels the longest distance at the termination of the simulation, as indicated in both tables. Maneuver 4, with steering inputs from both vehicles, is most efficient in keeping both vehicles in the original lane. If the braking capability in the following vehicle is lost (as in Maneuvers 1, 2, and 4), Maneuver 4 appears to be a reasonable approach to slow down both vehicles while maintaining vehicles in the original lane. With an emergency braking capability, Maneuver 3 is able to bring the speeds of both vehicles to a much lower level.

Table 1 Class I v. Class IV, v1= v2= 105 kmph, a1= -0.7 g, f = 0.875
Leading Vehicle

	Lateral Position Range (m)	Yaw Angle Range (deg)	Final Total Speed (kmph)	Final Yaw Angle (deg)	Final Position (m)
No Action	-8.55, 0.06	-192.29, 0.00	15.372	-192.29	98.91, -8.55
Maneuver 1	-4.12, 0.06	-142.99, 0.00	0.08	-142.78	87.42, -4.12
Maneuver 2	-0.00, 0.47	0.00, 0.88	0.00	0.27	64.70, 0.46
Maneuver 3	-5.29, 0.06	-8.47, 0.00	*3.89*	-8.47	*87.80, -5.29*
Maneuver 4	*-0.74, 0.06*	-6.04, 3.20	*59.71*	-0.58	114.33, -0.02

Following Vehicle with an intial offset of 0.30 m

	Lateral Position Range (m)	Yaw Angle Range (deg)	Final Total Speed (m/sec)	Final Yaw Angle (deg)	Final Position (m)
No Action	-6.75, 0.25	-9.39, 2.92	76.30	-7.92	114.91, -6.75
Maneuver 1	-0.32, 3.76	-1.69, 7.97	85.23	0.32	120.57, 3.60
Maneuver 2	-4.19, -0.31	-10.89, 3.39	101.01	-0.23	136.70, -3.72
Maneuver 3	-0.32, 2.09	0.00, 3.33	*5.16*	3.33	*84.57, 2.09*
Maneuver 4	*-0.32, 0.40*	-6.20, 5.41	*60.00*	0.42	110.21, 0.40

Table 2 Class IV v. Class I, v1= v2= 105 kmph, a1= -0.7 g, f = 0.875
Leading Vehicle

	Lateral Position Range (m)	Yaw Angle Range (deg)	Final Total Speed (kmph)	Final Yaw Angle (deg)	Final Position (m)
No Action	0.00, 0.88	0.00, 1.48	0.00	1.21	75.46, 0.88
Maneuver 1	0.00, 0.95	0.00, 1.60	0.00	1.60	74.64, 0.94
Maneuver 2	-0.63, 0.02	-1.75, 0.00	0.00	-1.75	62.54, -0.63
Maneuver 3	0.00, 0.91	0.00, 1.47	*3.68*	1.47	*74.50, 0.91*
Maneuver 4	*0.00, 0.98*	-5.01, 4.48	*19.40*	4.48	87.20, 0.82

Following Vehicle with an intial offset of 0.30 m

	Lateral Position Range (m)	Yaw Angle Range (deg)	Final Total Speed (m/sec)	Final Yaw Angle (deg)	Final Position (m)
No Action	-5.64, -0.31	-4.41, 0.01	74.26	-4.41	107.77, -5.64
Maneuver 1	-3.57, -0.31	-8.39, 0.01	75.90	-0.04	109.86, -3.57
Maneuver 2	-3.81, -0.31	-9.92, 0.76	100.95	0.13	136.35, -3.66
Maneuver 3	-1.39, -0.31	-6.10, 0.01	*0.00*	-6.10	*63.63, -1.39*
Maneuver 4	*-0.98, 0.41*	-3.32, 11.14	*19.53*	1.29	82.97, -0.15

Figure 12 and 13 depicts several variables representing the motion of the leading and following vehicles in a simulation with no follow-up actions in Table 1. Figures 14-21 are the corresponding plots for maneuvers 1-4. In these figures, the lateral position and speed, yaw angle and yaw rate, lateral acceleration and steering angle at the front wheel are plotted. In these cases, a leading small vehicle and a following large vehicle are both traveling at 105 kmph with an initial spacing of 5 m and a lateral offset of 0.3 m. At time 0, the leading vehicle begins braking at a deceleration of 0.7 g and at 1.21 seconds the first collision occurs. In Maneuver 1, roughly 0.5 seconds after the first impact, steering actions are taken on the following vehicle in an attempt to change lanes. In Maneuver 2, at time = 0.5 seconds (0.5 seconds after the initial failure), steering actions are taken on the following vehicle in an attempt to change lanes. In Maneuver 3, at time = 0.5 seconds (0.5 seconds after the initial failure), emergency braking is applied on the following vehicle, but no steering actions are taken on both vehicles. In Maneuver 4, roughly 0.5 seconds after the first impact, steering actions are taken on both vehicles to maintain both vehicles in the original lane.

Figure 22 compares the velocity profiles of both vehicles in the four different maneuvers and the original simulation where no actions are taken In Table 1. It can be seen that Maneuver 3 brings the final speeds down to the lowest levels because the braking of the following vehicle is activated after the first impact. Maneuver 2 yields the highest speed of the following vehicle because the lane change maneuver is initiated before the first collision occurs. It is noteworthy that delta-V in subsequent collisions in Maneuver 4 gradually decreases. This is significant because the strategy deployed in Maneuver 4 is only sensible when the subsequent collisions cause less severe damage to vehicles and injuries to occupants in subsequent impacts.

Using the initial and final speeds of both vehicles for calculation, the “equivalent” stopping deceleration are 0.25g and 0.46g respectively for Maneuver 4 in Tables 1 and 2. This “equivalent” deceleration represents the effective braking capability of both vehicles without braking power in the following vehicle. The difference in the deceleration in both cases is caused by the vehicle weight differential. In the simulation program, a Class I vehicle has a default weight of 1000 kgs (2202 lbs) and Class IV a weight of 1928 kgs (4247 lbs).

The magnitude of steering angle and the timing of steering and braking inputs in these maneuvers are determined after a few iterations of simulation by an ad hoc approach. Since the maneuver objectives are well defined, the selection of steering inputs is accomplished in a few iterations. The values selected in these simulations are reasonable but they will ultimately depend on the design specifications of automated vehicles and control algorithms.

One issue that is not discussed in this paper is the effects of operational variables and vehicle maneuvers on vehicle damage. It should be noted that vehicle damage or structural deformation is not linear or additive in multiple collisions. For example, two collisions of 10 kmph delta-V on the same region of a vehicle are not likely to generate the same degree of damage when compared to a single 20 kmph collision. Sophisticated modeling and reliable crush measurement data are needed for accurate estimates of vehicle damage in multiple collisions. A thorough investigation into this problem may lead to certain guidelines of structural requirements and the effects of collisions on the integrity of control systems and vehicle operability.

SUMMARY

This report reviews the effects of certain operational parameters on the post-impact vehicle trajectories. Simulations of vehicle-following collisions show that large lateral offset and large initial spacing can result in significant path deviations or vehicle rotation and cause quick departure from the original traveling lane. The speed-differential or delta-V in collision appears to be a significant factor of the collision outcome in typical highway operations, as reflected in the large initial-spacing cases. The results also indicate that without control actions, the vehicles involved in a collision can be out of their lanes within 1 to 3 seconds.

Several maneuvers are proposed to examine the feasibility of controlling vehicle motions during or after collisions. These maneuvers involve the use of steering and/or braking inputs on one or both vehicles. The results demonstrate lane-change or lane-keeping functions can be accomplished in the representative scenarios. An emergency braking function, if implemented, will be desirable to reduce the vehicle speed and their traveling distance.

The understanding of vehicle motions in collisions is an important element in evaluating the safety hazards and benefits of automated vehicles. The use of two-dimensional crash models allows the examination of lateral and rotational movement. These simulations enable the assessment of operational parameters as well as the control inputs in crash conditions. A continuation of this work should include the implementation of a closed-loop control model with the crash and dynamic models. Efforts in developing a model with similar features for multiple vehicle collisions are also considered.

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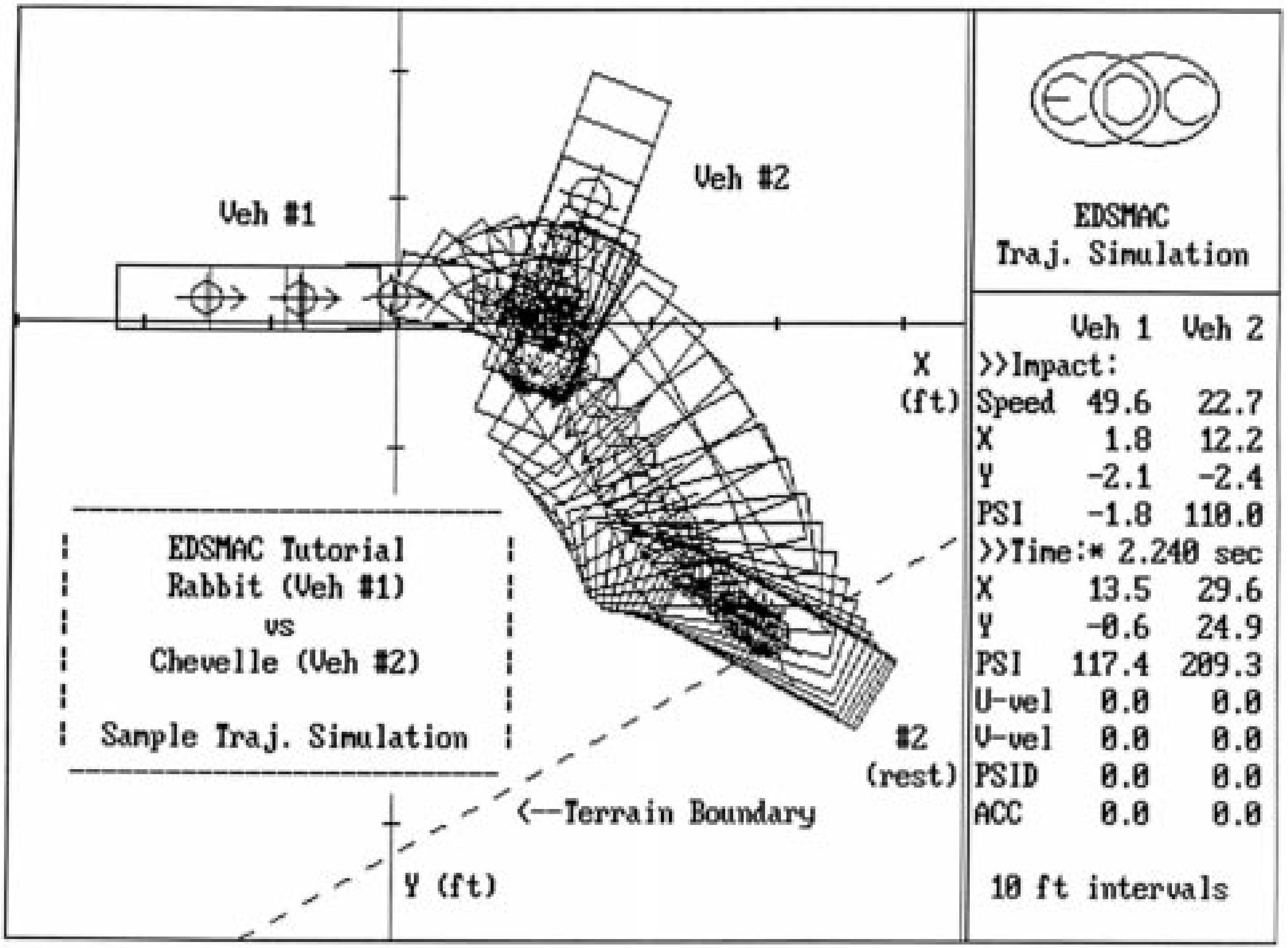
APPENDIX A

The following figures are pages from the user’s manual of EDSMAC. (13)

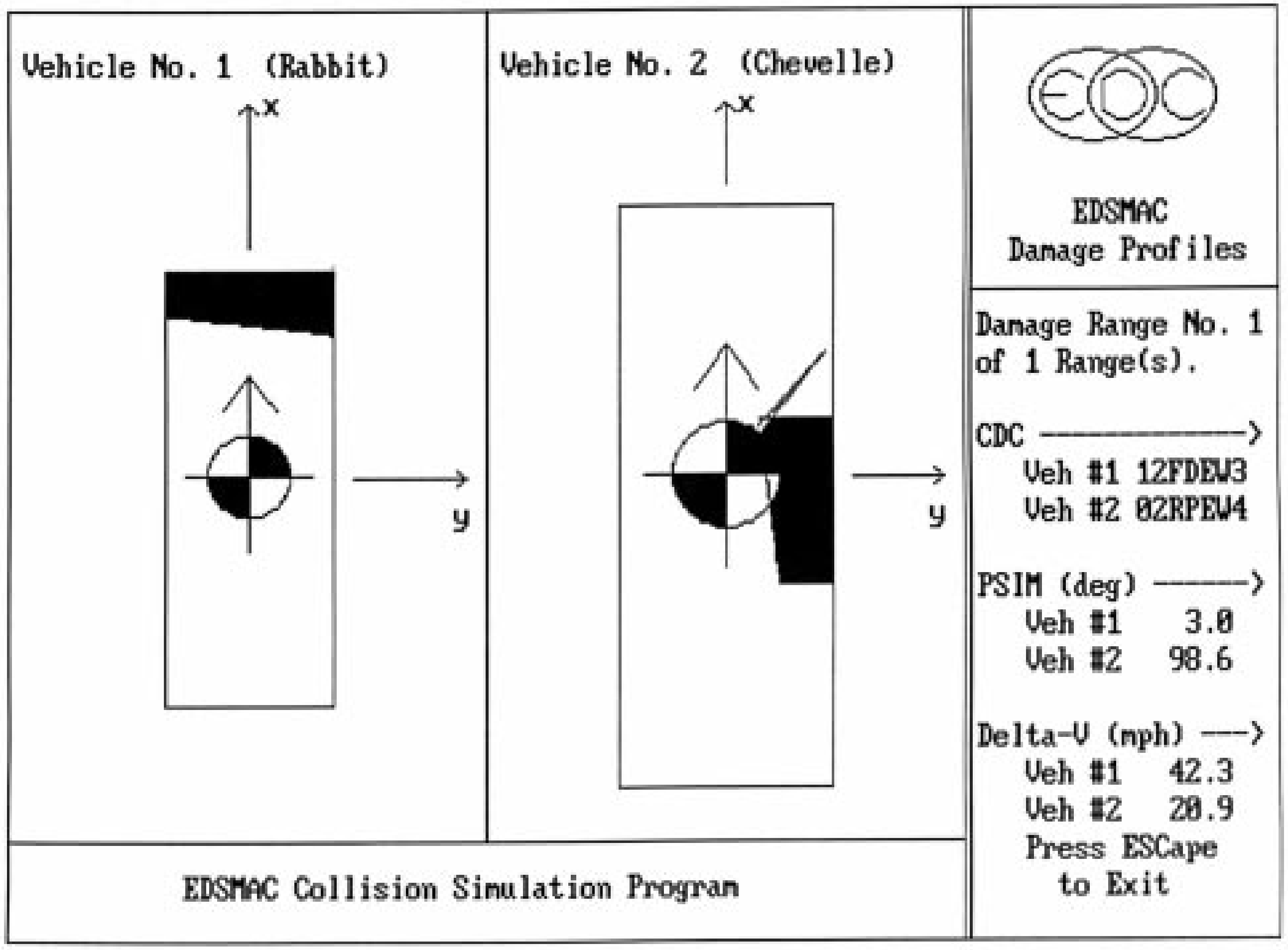
No.	*Title of Figures*
1.	A typical screen display of an EDSMAC simulation.
2.	A post-simulation display of vehicle damage.
3.	A graphic illustration of selected variables of an EDSMAC simulation.
4.	The classification of vehicle sizes by their wheel base and the default values of vehicle parameters.
5.	Different classes of vehicle stiffness and exemplar vehicles.

Trajectory Simulation



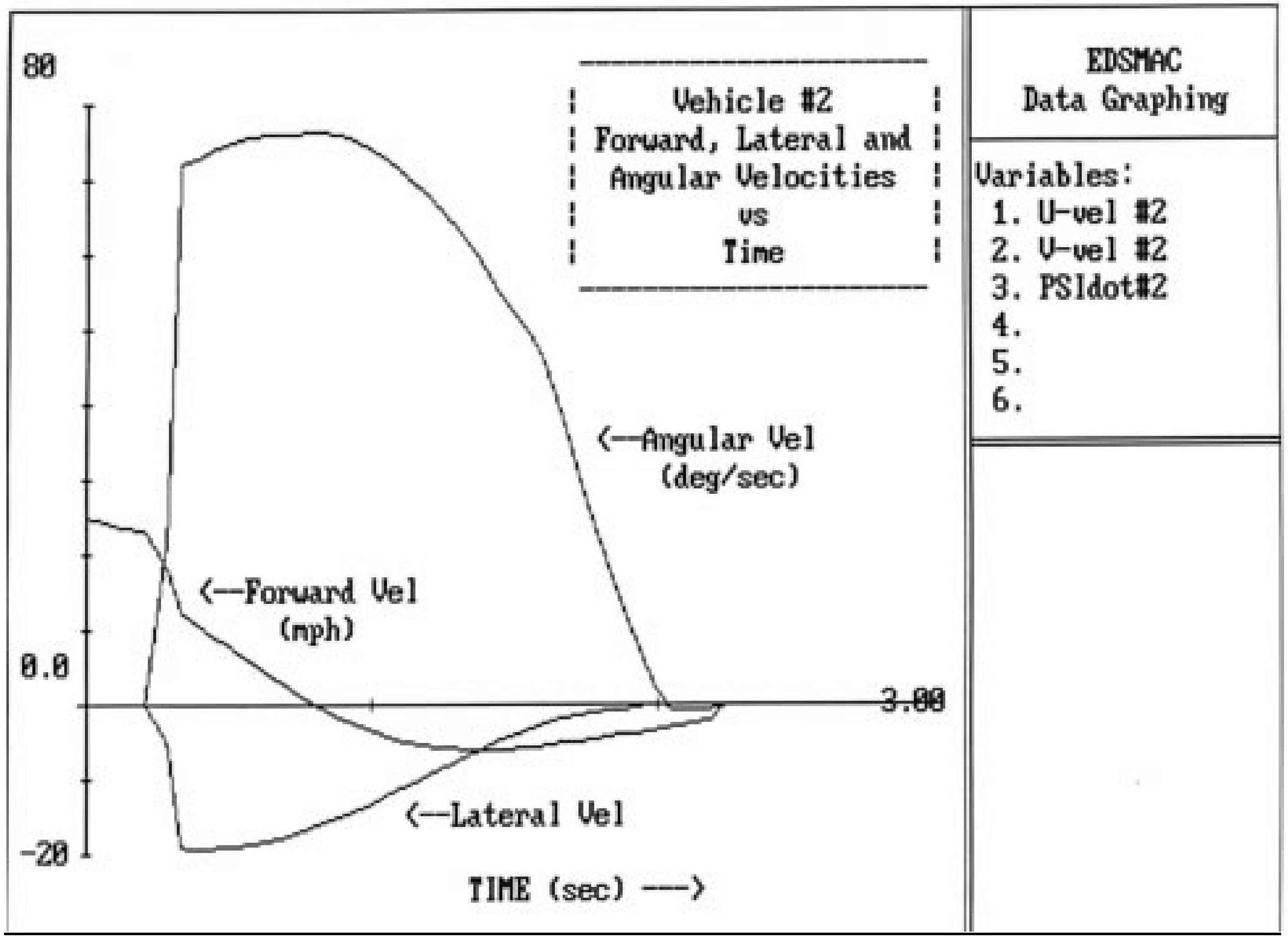
```
         Veh 1   Veh 2
>>Impact:
Speed    49.6    22.7
X         1.8    12.2
Y        -2.1    -2.4
PSI      -1.8   110.0
>>Time:* 2.240 sec
X        13.5    29.6
Y        -0.6    24.9
PSI     117.4   209.3
U-vel     0.0     0.0
V-vel     0.0     0.0
PSID      0.0     0.0
ACC       0.0     0.0

 10 ft intervals
```

Damage Profiles



```
EDSMAC
Damage Profiles

Damage Range No. 1
of 1 Range(s).

CDC -------------->
    Veh #1 12FDEW3
    Veh #2 02RPEW4

PSIM (deg) ------>
    Veh #1     3.0
    Veh #2    98.6

Delta-V (mph) --->
    Veh #1    42.3
    Veh #2    20.9
    Press ESCape
      to Exit

EDSMAC Collision Simulation Program
```

Data Graph

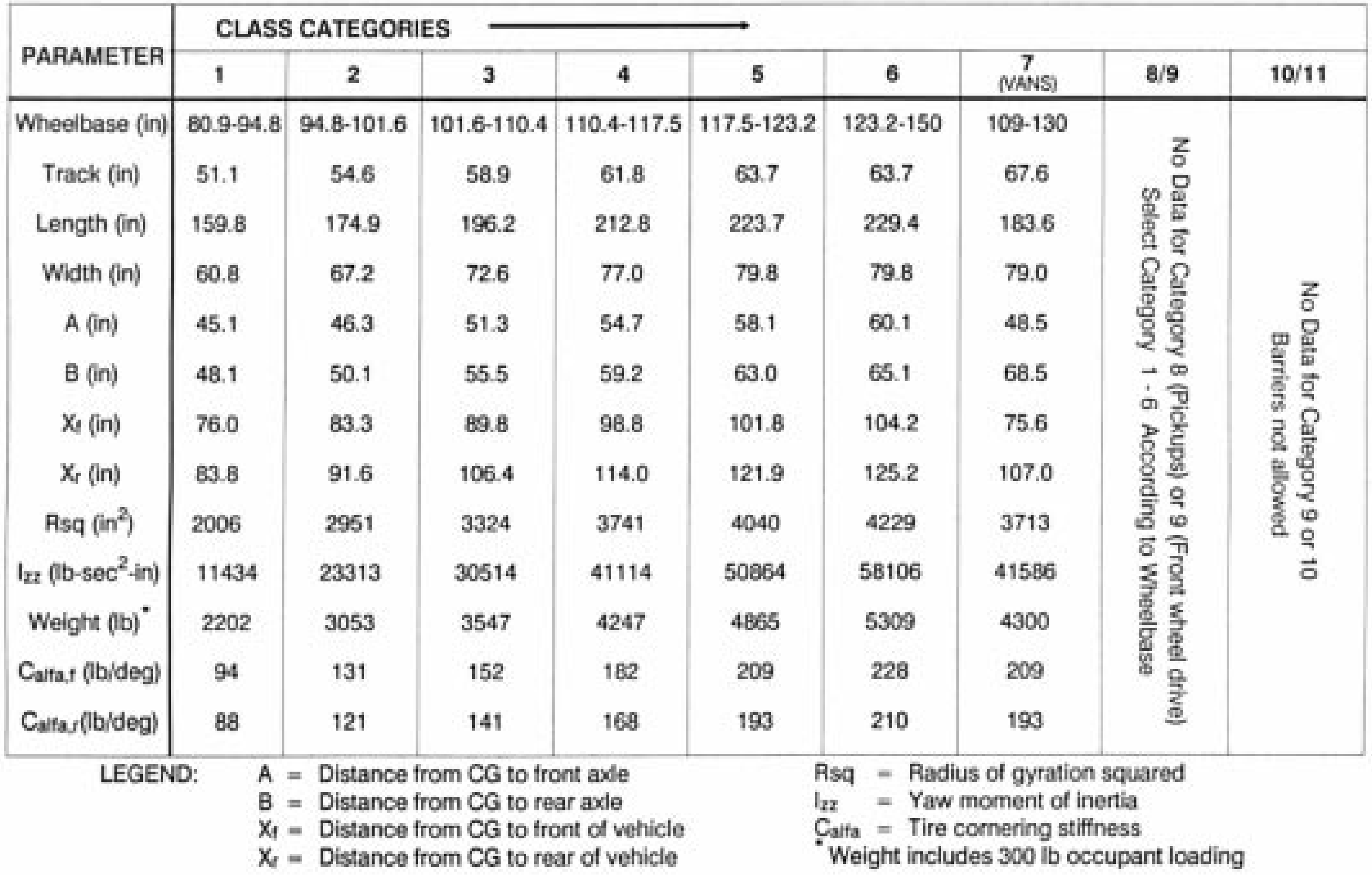


EDSMAC
Data Graphing

Variables:
1. U-vel #2
2. V-vel #2
3. PSIdot#2
4.
5.
6.

CALIFORNIA PATH

Vehicle Class Categories



PARAMETER	CLASS CATEGORIES → 1	2	3	4	5	6	7 (VANS)	8/9	10/11
Wheelbase (in)	80.9-94.8	94.8-101.6	101.6-110.4	110.4-117.5	117.5-123.2	123.2-150	109-130	No Data for Category 8 (Pickups) or 9 (Front wheel drive) Select Category 1 - 6 According to Wheelbase	No Data for Category 9 or 10 Barriers not allowed
Track (in)	51.1	54.6	58.9	61.8	63.7	63.7	67.6		
Length (in)	159.8	174.9	196.2	212.8	223.7	229.4	183.6		
Width (in)	60.8	67.2	72.6	77.0	79.8	79.8	79.0		
A (in)	45.1	46.3	51.3	54.7	58.1	60.1	48.5		
B (in)	48.1	50.1	55.5	59.2	63.0	65.1	68.5		
X_f (in)	76.0	83.3	89.8	98.8	101.8	104.2	75.6		
X_r (in)	83.8	91.6	106.4	114.0	121.9	125.2	107.0		
Rsq (in^2)	2006	2951	3324	3741	4040	4229	3713		
I_{zz} (lb-sec^2-in)	11434	23313	30514	41114	50864	58106	41586		
Weight (lb)*	2202	3053	3547	4247	4865	5309	4300		
$C_{alfa,f}$ (lb/deg)	94	131	152	182	209	228	209		
$C_{alfa,r}$ (lb/deg)	88	121	141	168	193	210	193		

LEGEND:

A = Distance from CG to front axle

B = Distance from CG to rear axle

X_f = Distance from CG to front of vehicle

X_r = Distance from CG to rear of vehicle

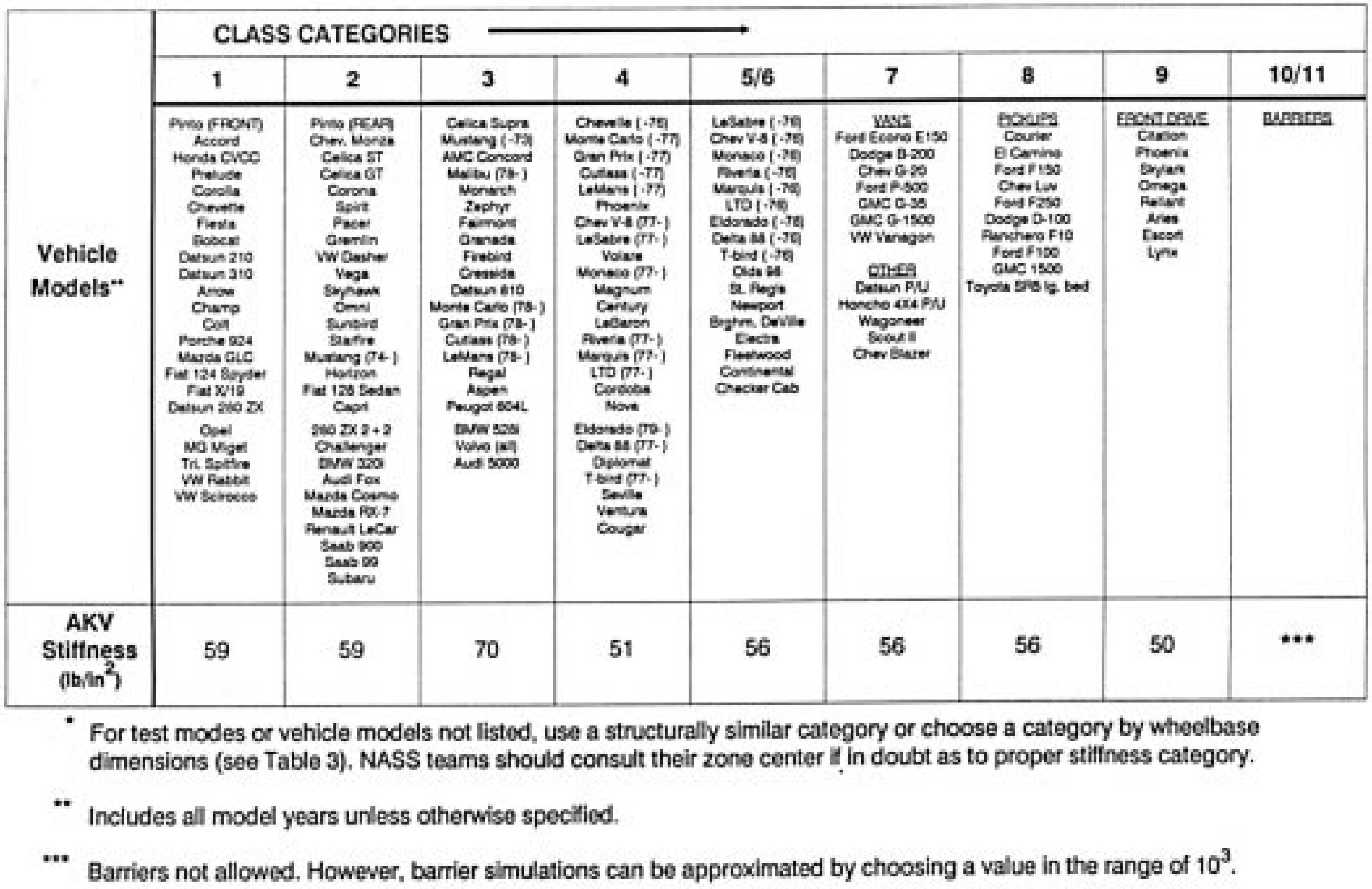
Rsq = Radius of gyration squared

I_{zz} = Yaw moment of inertia

C_{alfa} = Tire cornering stiffness

* Weight includes 300 lb occupant loading

Vehicle Crush Stiffness Categories



	CLASS CATEGORIES →								
	1	2	3	4	5/6	7	8	9	10/11
Vehicle Models**	Pinto (FRONT) Accord Honda CVCC Prelude Corolla Chevette Fiesta Bobcat Datsun 210 Datsun 310 Arrow Champ Colt Porche 924 Mazda GLC Fiat 124 Spyder Fiat X/19 Datsun 280 ZX Opel MG Miget Tri. Spitfire VW Rabbit VW Scirocco	Pinto (REAR) Chev. Monza Celica ST Celica GT Corona Spirit Pacer Gremlin VW Dasher Vega Skyhawk Omni Sunbird Starfire Mustang (74-) Horizon Fiat 128 Sedan Capri 280 ZX 2 + 2 Challenger BMW 320i Audi Fox Mazda Cosmo Mazda RX-7 Renault LeCar Saab 900 Saab 99 Subaru	Celica Supra Mustang (-73) AMC Concord Malibu (78-) Monarch Zephyr Fairmont Granada Firebird Cressida Datsun 810 Monte Carlo (78-) Gran Prix (78-) Cutlass (78-) LeMans (78-) Regal Aspen Peugot 604L BMW 528i Volvo (all) Audi 5000	Chevelle (-76) Monte Carlo (-77) Gran Prix (-77) Cutlass (-77) LeMans (-77) Phoenix Chev V-8 (77-) LeSabre (77-) Volare Monaco (77-) Magnum Century LeBaron Riveria (77-) Marquis (77-) LTD (77-) Cordoba Nova Eldorado (79-) Delta 88 (77-) Diplomat T-bird (77-) Seville Ventura Cougar	LeSabre (-76) Chev V-8 (-76) Monaco (-76) Riveria (-76) Marquis (-76) LTD (-76) Eldorado (-76) Delta 88 (-76) T-bird (-76) Olds 98 St. Regis Newport Brghm. DeVille Electra Fleetwood Continental Checker Cab	VANS Ford Econo E150 Dodge B-200 Chev G-20 Ford P-500 GMC G-35 GMC G-1500 VW Vanagon OTHER Datsun P/U Honcho 4X4 P/U Wagoneer Scout II Chev Blazer	PICKUPS Courier El Camino Ford F150 Chev Luv Ford F250 Dodge D-100 Ranchero F10 Ford F100 GMC 1500 Toyota SR8 lg. bed	FRONT DRIVE Citation Phoenix Skylark Omega Reliant Aries Escort Lynx	BARRIERS
AKV Stiffness (lb/in^2)	59	59	70	51	56	56	56	50	***

* For test modes or vehicle models not listed, use a structurally similar category or choose a category by wheelbase dimensions (see Table 3). NASS teams should consult their zone center if in doubt as to proper stiffness category.

** Includes all model years unless otherwise specified.

*** Barriers not allowed. However, barrier simulations can be approximated by choosing a value in the range of 10^3.

LIST OF FIGURES

No. *Title of Figures*

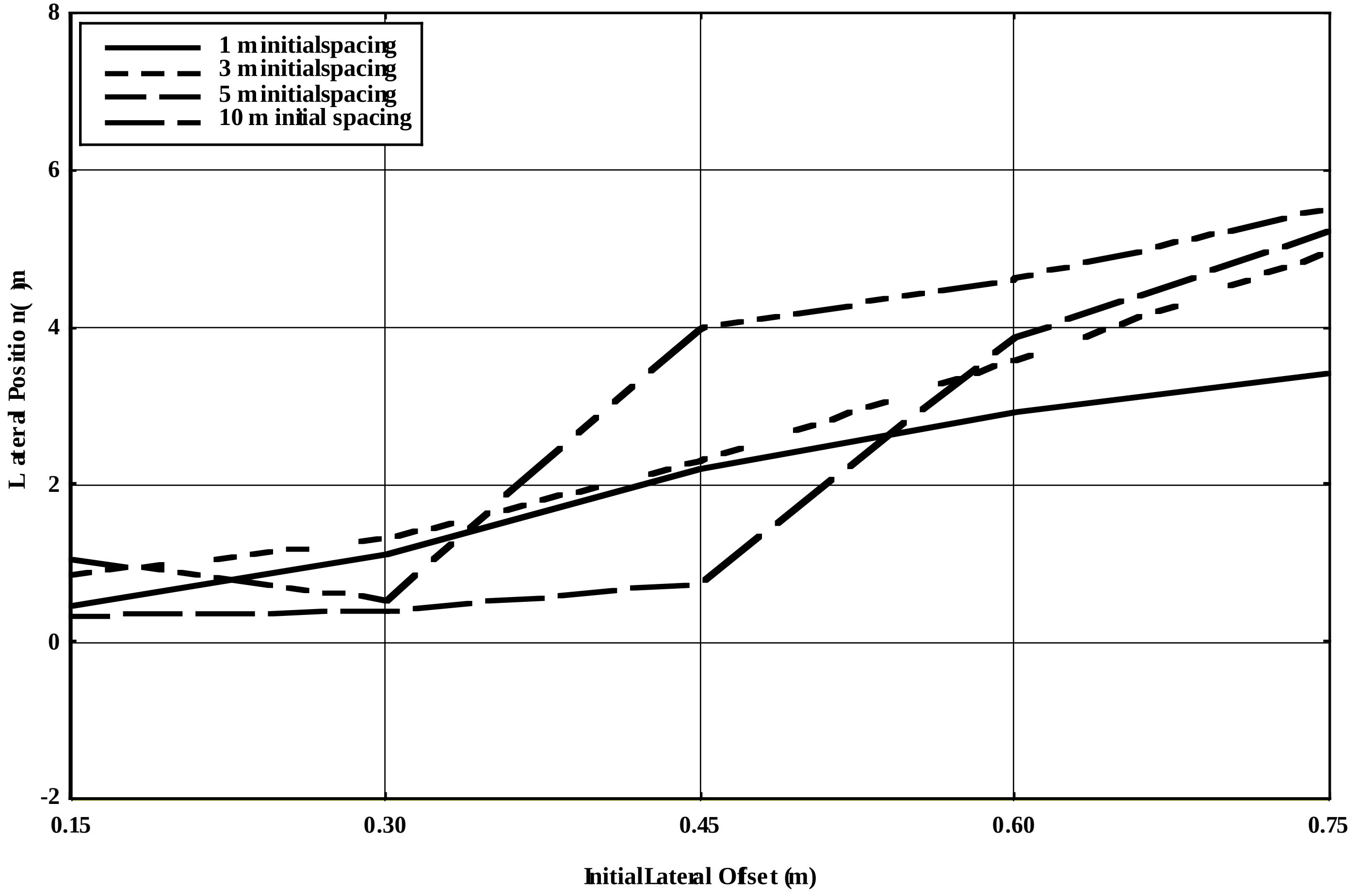


Figure 1. Maximum Lateral Position of Leading Vehicle with Class III Leading and Class III Following for Various Spacing and Lateral Offset

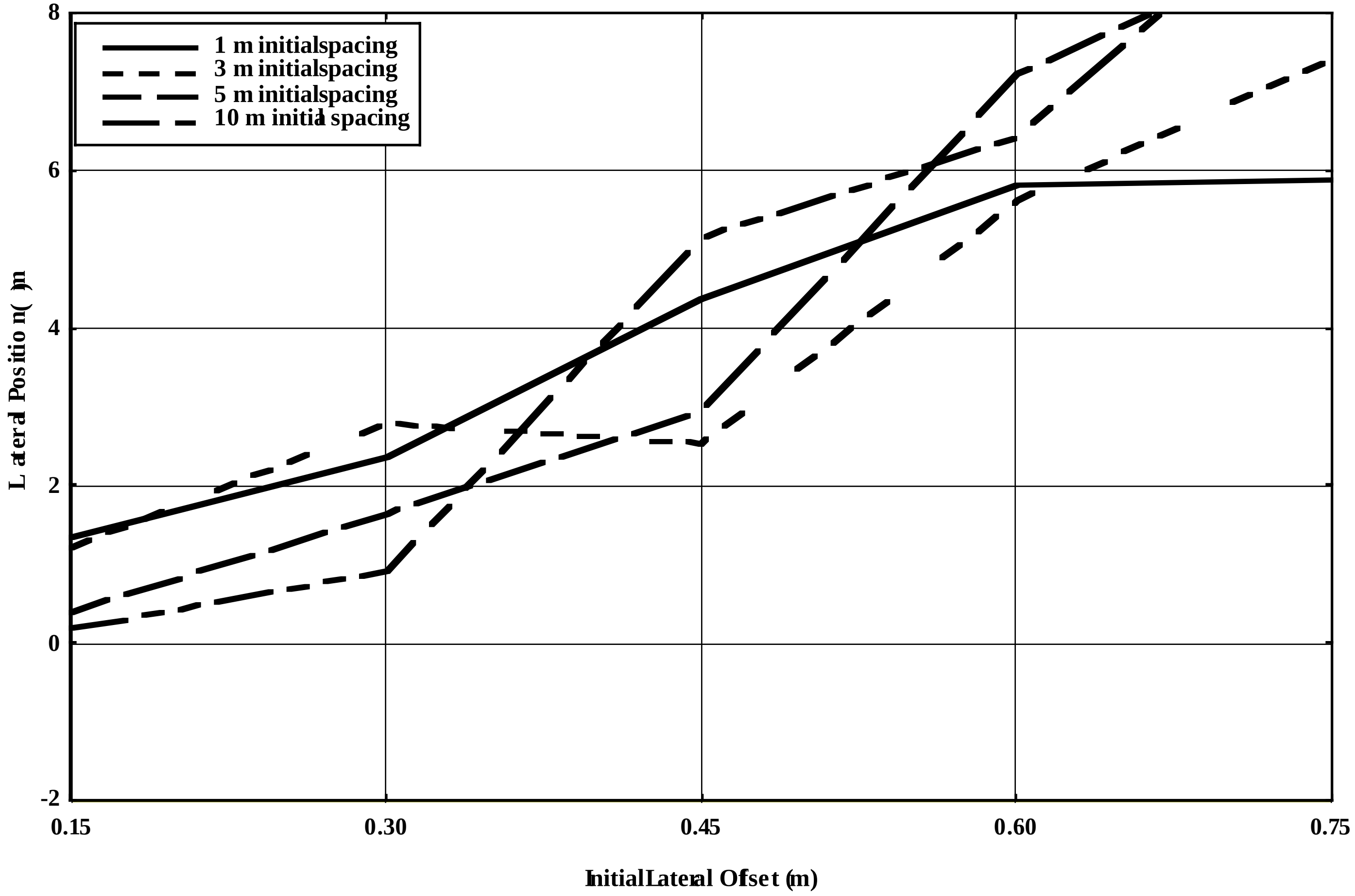


Figure 2. Maximum Lateral Position of Leading Vehicle with Class I Leading and Class IV Following for Various Spacing and Lateral Offset

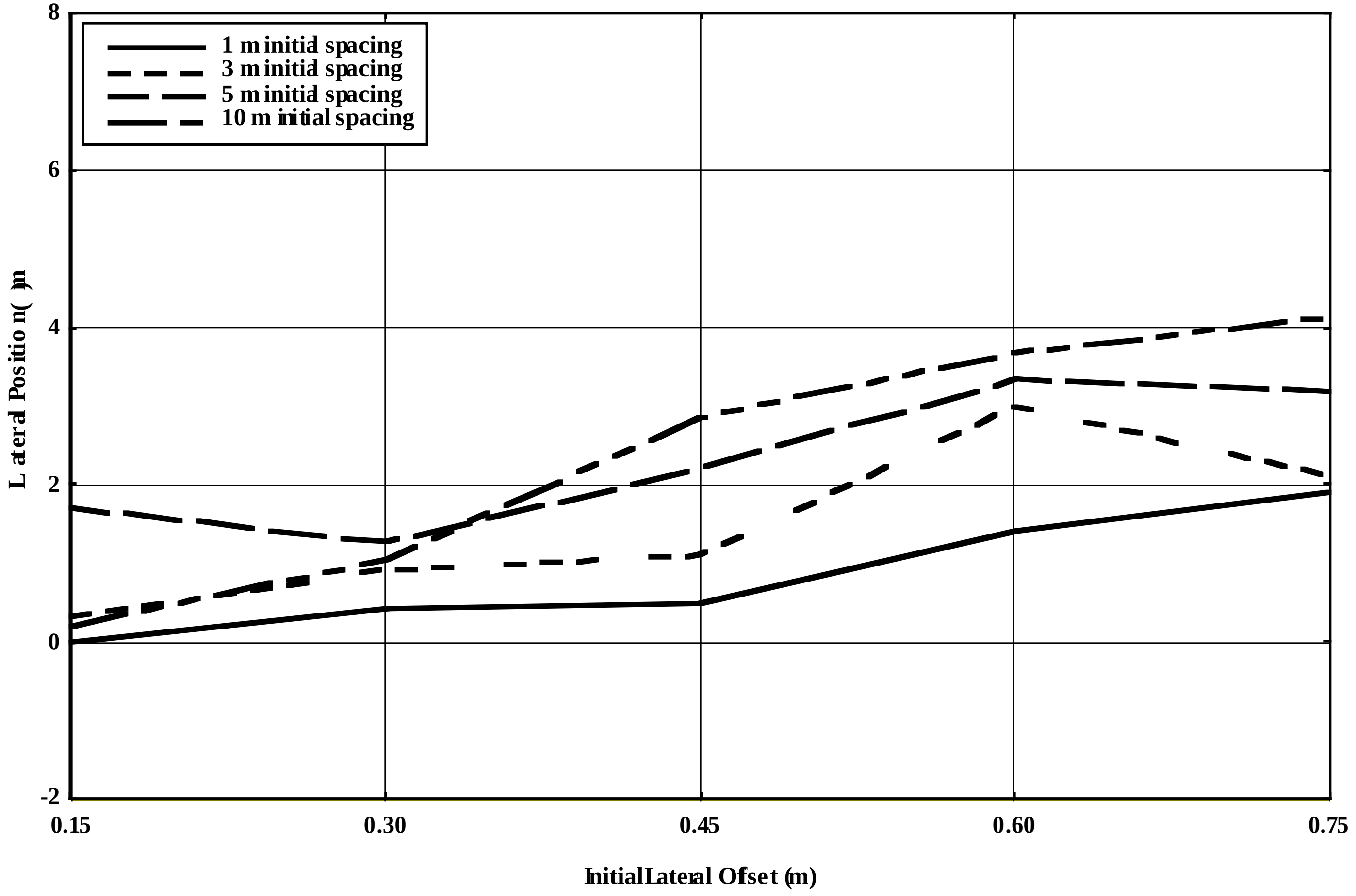


Figure 3. Maximum Lateral Position of Leading Vehicle with Class IV Leading and Class I Following for Various Spacing and Lateral Offset

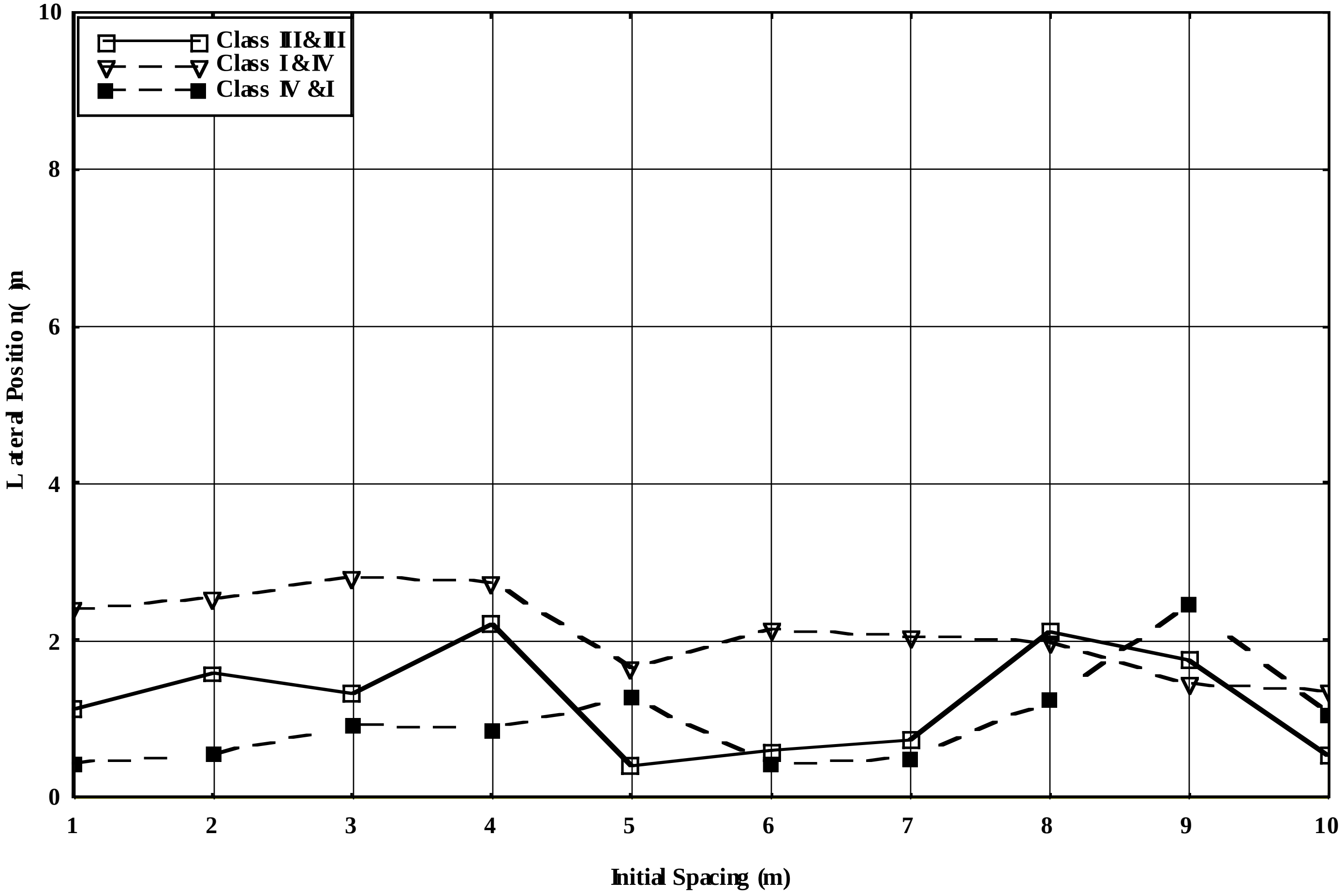


Figure 4. Maximum Abs(Lateral Position) of Leading Vehicle with 105 kmph Initial Speed and 0.3 m Lateral Offset for Various Formations and Initial Spacing, Friction Coeff. = 0.7, Deceleration of Leading Vehicle = 0.7g

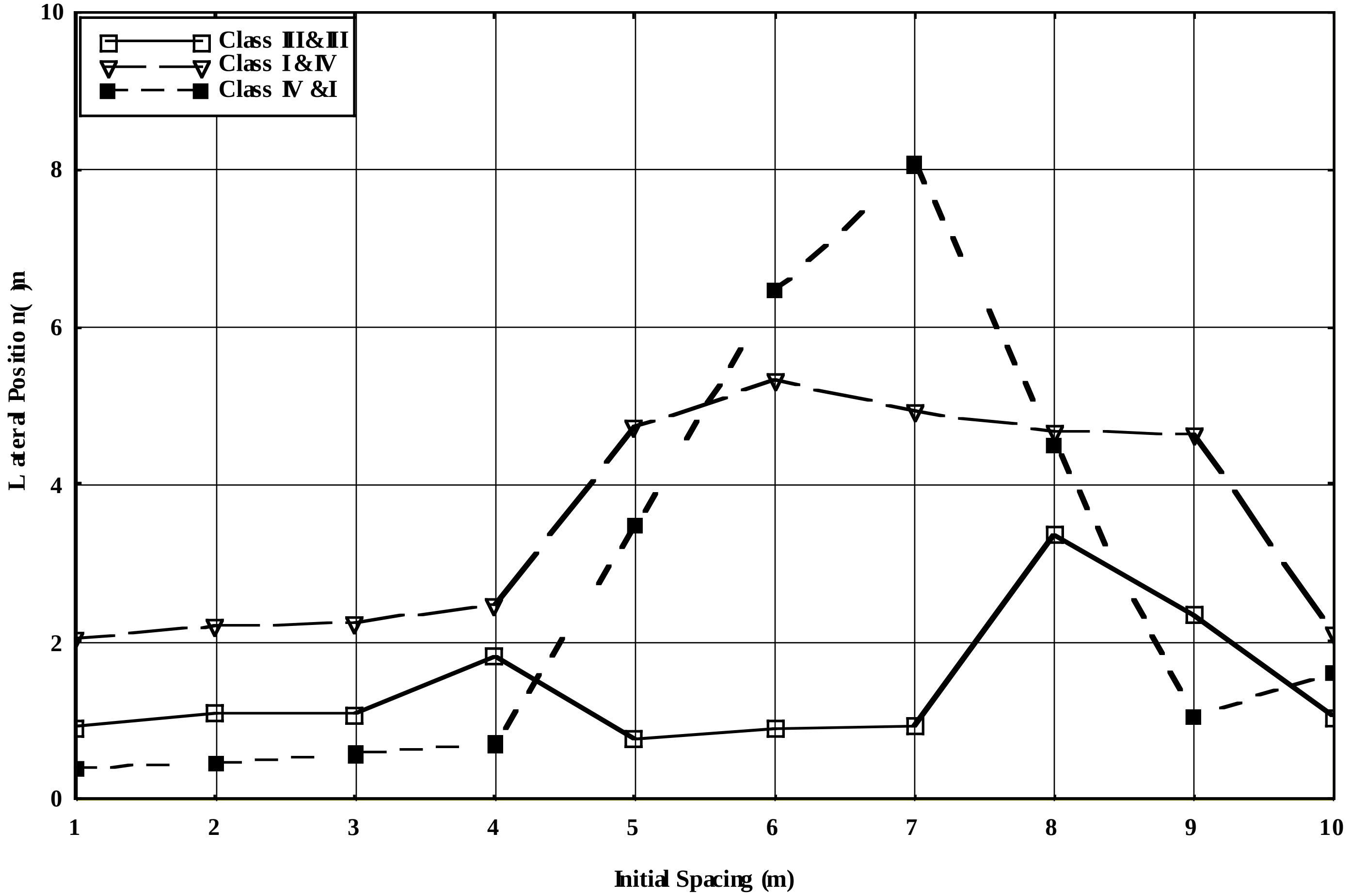


Figure 5. Maximum Abs(Lateral Position) of Following Vehicle with 105 kmph Initial Speed and 0.3 m Lateral Offset for Various Formations and Initial Spacing, Friction Coeff. = 0.7, Deceleration of Leading Vehicle = 0.7g

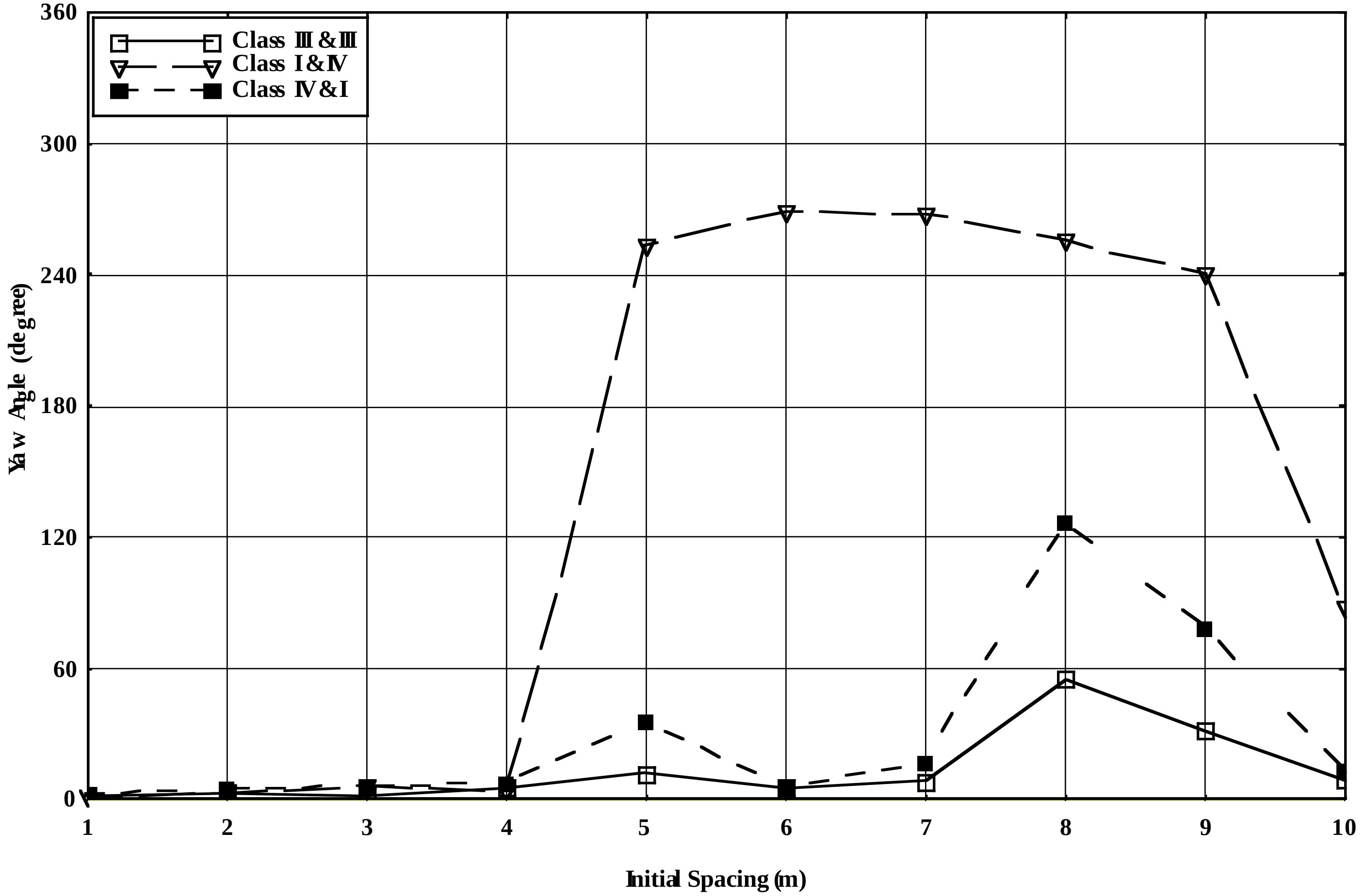


Figure 6. Maximum Abs(Yaw Angle) of Leading Vehicle with 105 kmph Initial Speed and 0.3 m Lateral Offset for Various Formations and Initial Spacing, Friction Coeff. = 0.7, Deceleration of Leading Vehicle = 0.7g

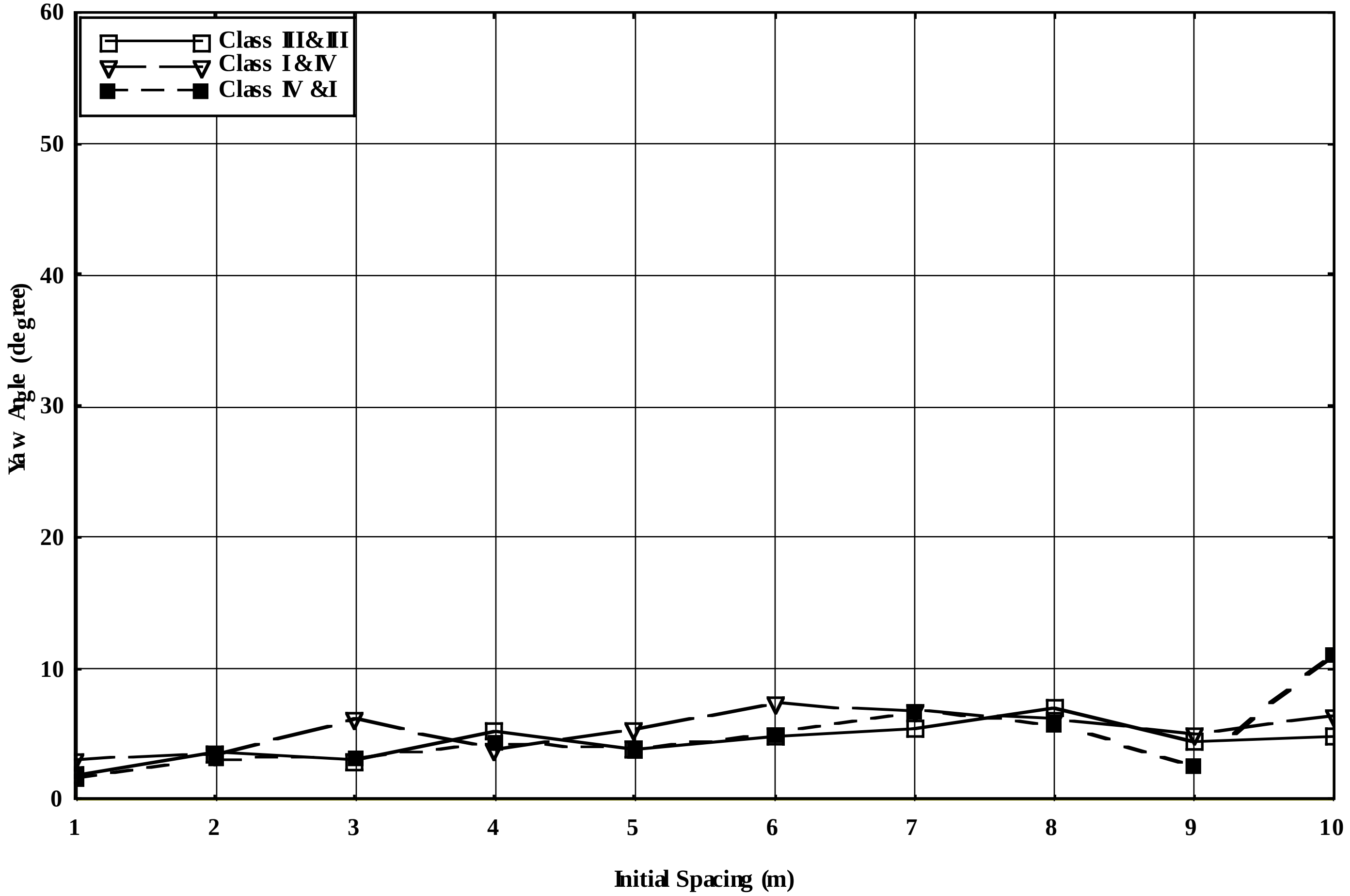


Figure 7. Maximum Abs(Yaw Angle) of Following Vehicle with 105 kmph Initial Speed and 0.3 m Lateral Offset for Various Formations and Initial Spacing, Friction Coeff. = 0.7, Deceleration of Leading Vehicle = 0.7g

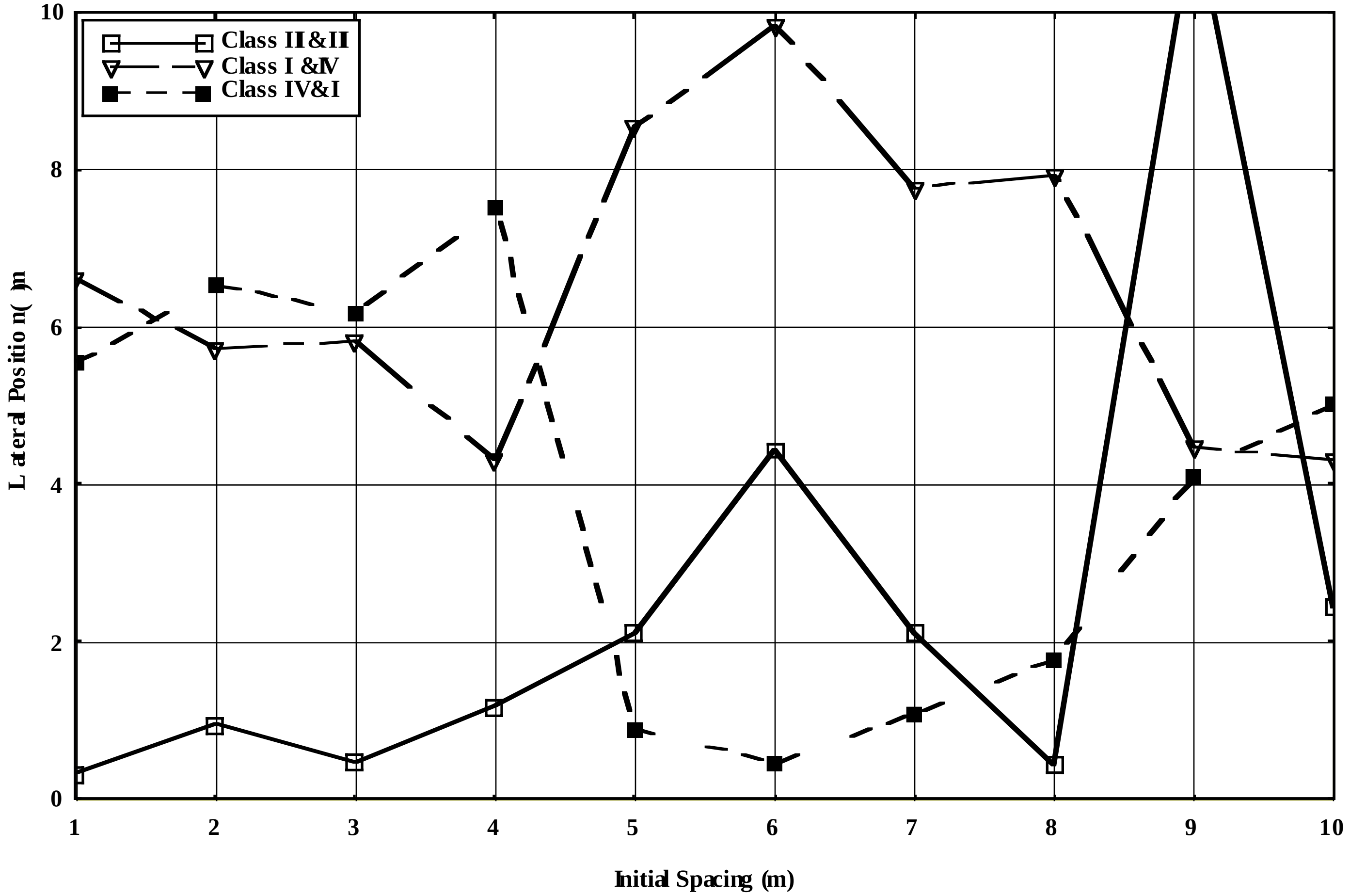


Figure 8. Maximum Abs(Lateral Position) of Leading Vehicle with 105 kmph Initial Speed and 0.3 m Lateral Offset for Various Formations and Initial Spacing, Friction Coeff. = 0.875, Deceleration of Leading Vehicle = 0.7g

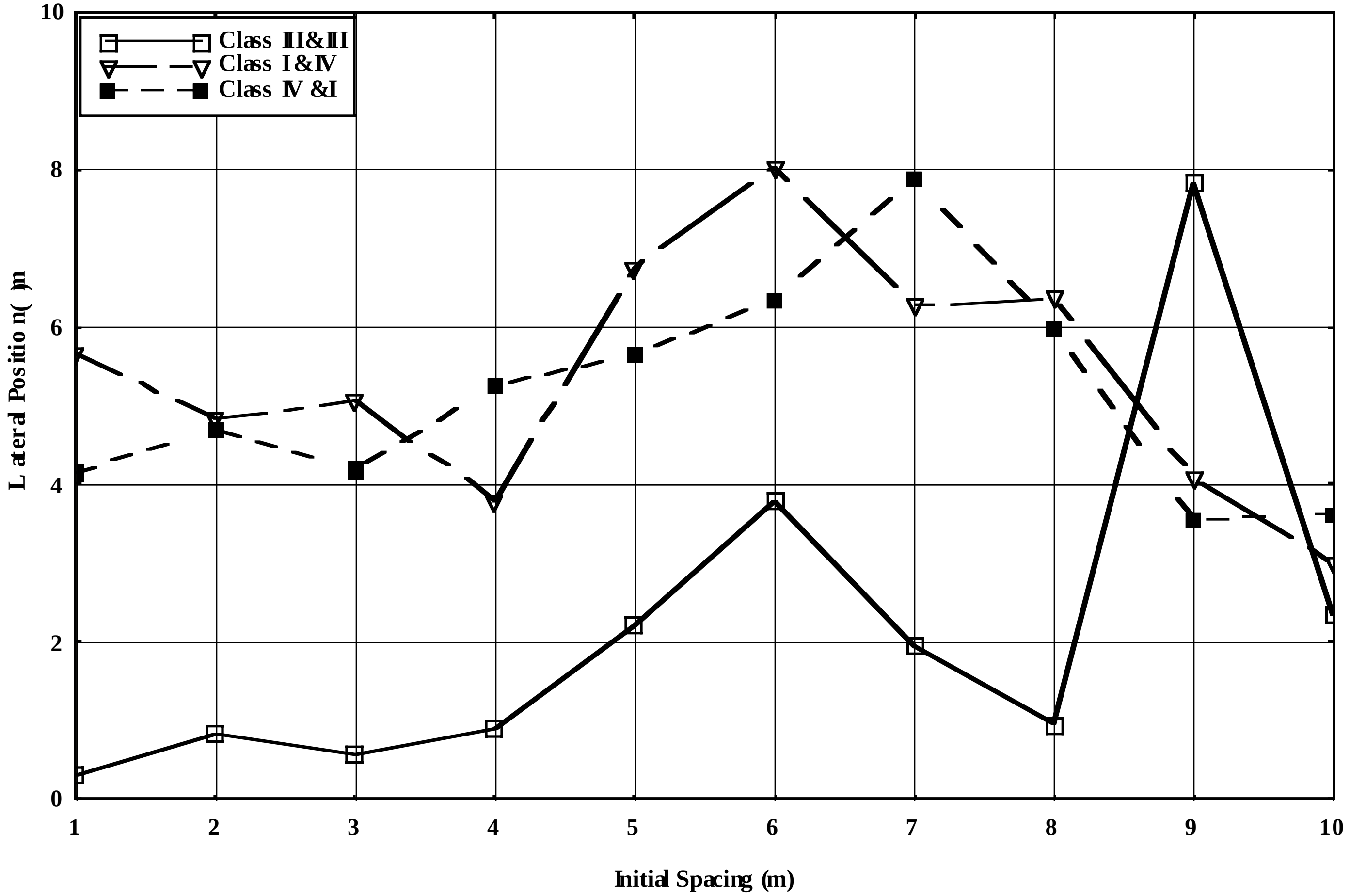


Figure 9. Maximum Abs(Lateral Position) of Following Vehicle with 105 kmph Initial Speed and 0.3 m Lateral Offset for Various Formations and Initial Spacing, Friction Coeff. = 0. 875, Deceleration of Leading Vehicle = 0.7g

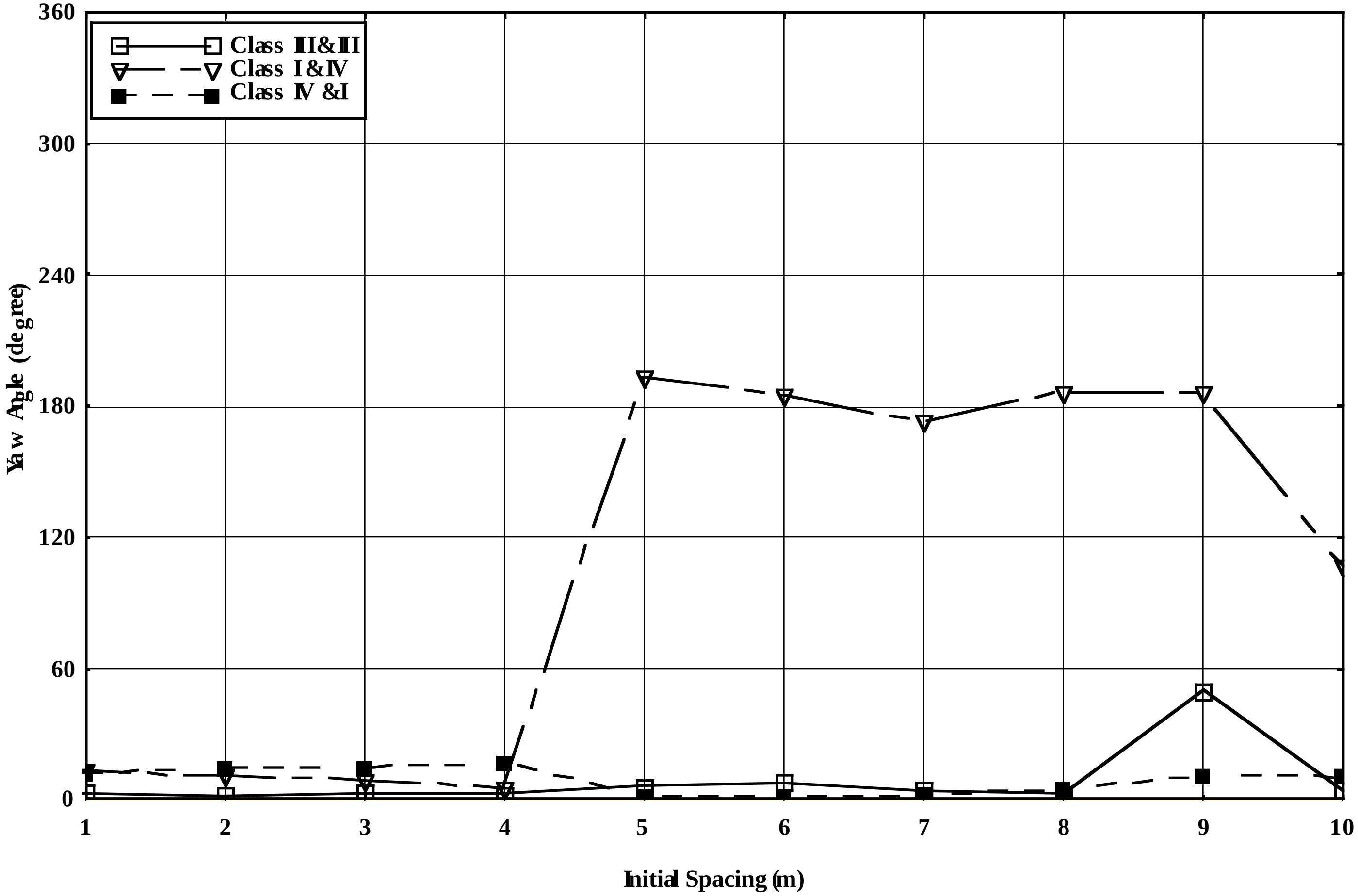


Figure 10. Maximum Abs(Yaw Angle) of Leading Vehicle with 105 kmph Initial Speed and 0.3 m Lateral Offset for Various Formations and Initial Spacing, Friction Coeff. = 0. 875, Deceleration of Leading Vehicle = 0.7g

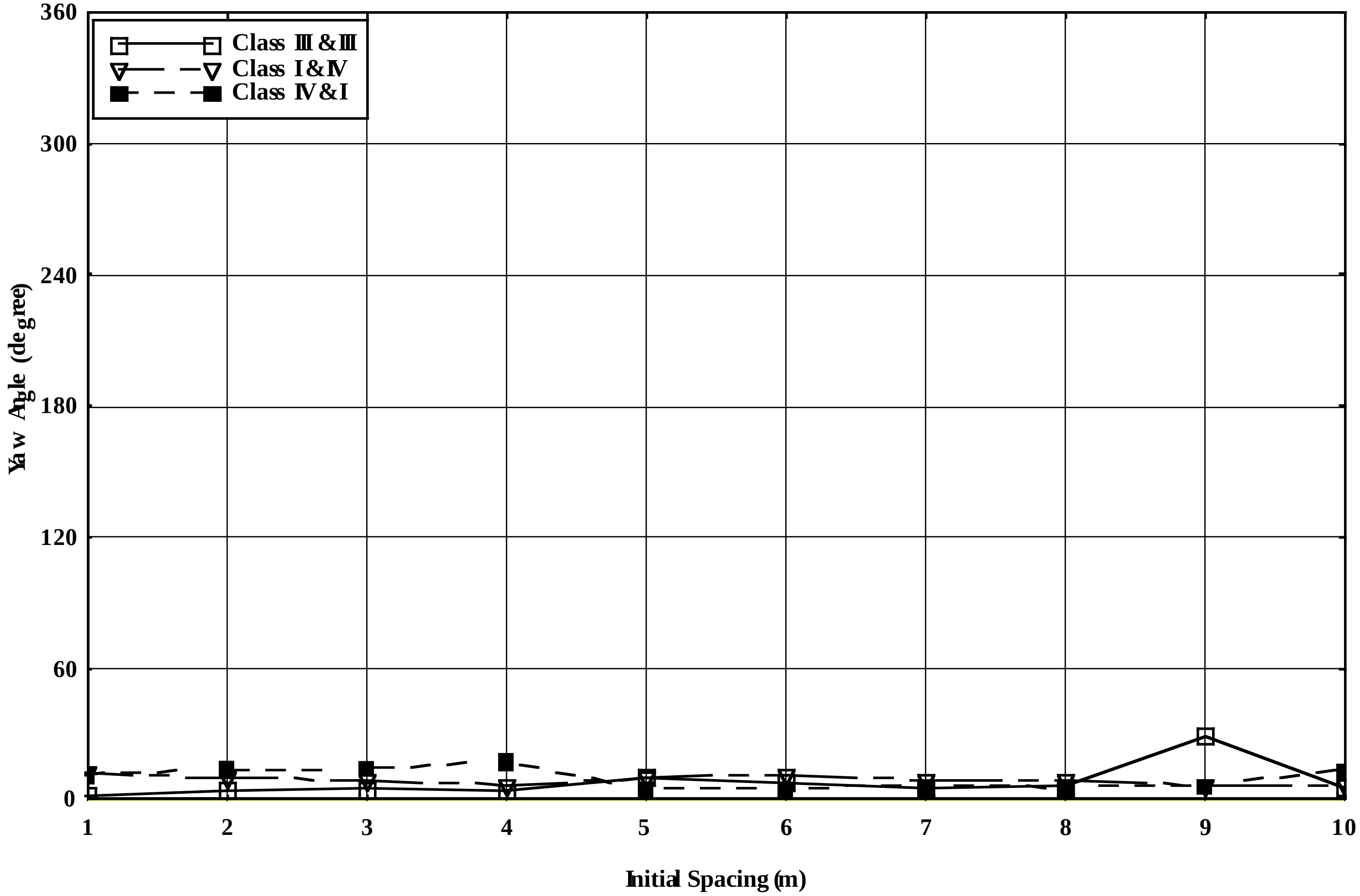


Figure 11. Maximum Abs(Yaw Angle) of Following Vehicle with 105 kmph Initial Speed and 0.3 m Lateral Offset for Various Formations and Initial Spacing, Friction Coeff. = 0. 875, Deceleration of Leading Vehicle = 0.7g

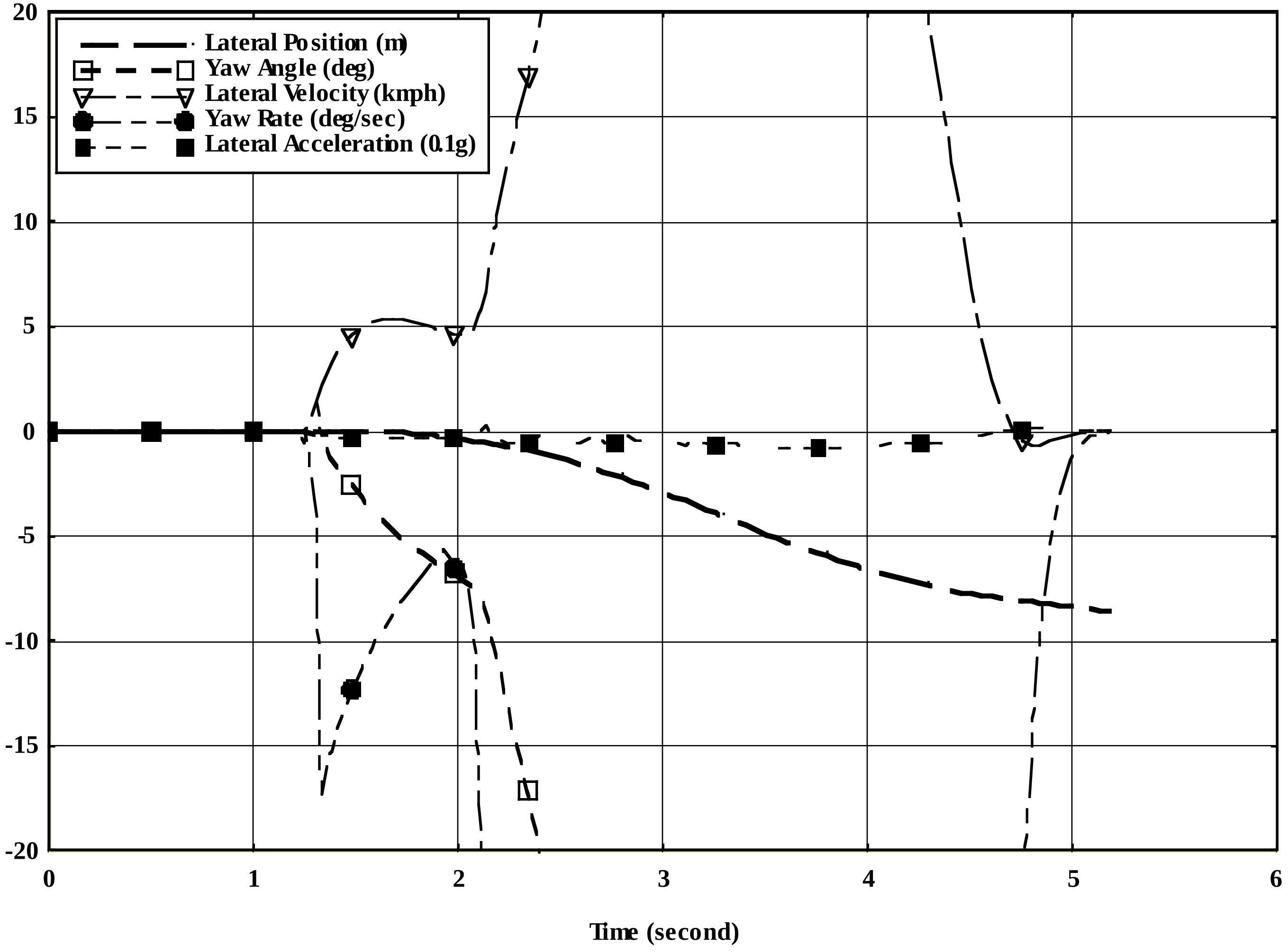


Figure 12. Motion Variables of Leading Vehcile with 105 kmph Initial Speed, 5 m Initial Spacing, 0.3 m Lateral Offset and No Follow-Up Maneuvers, Class IV Following Class I

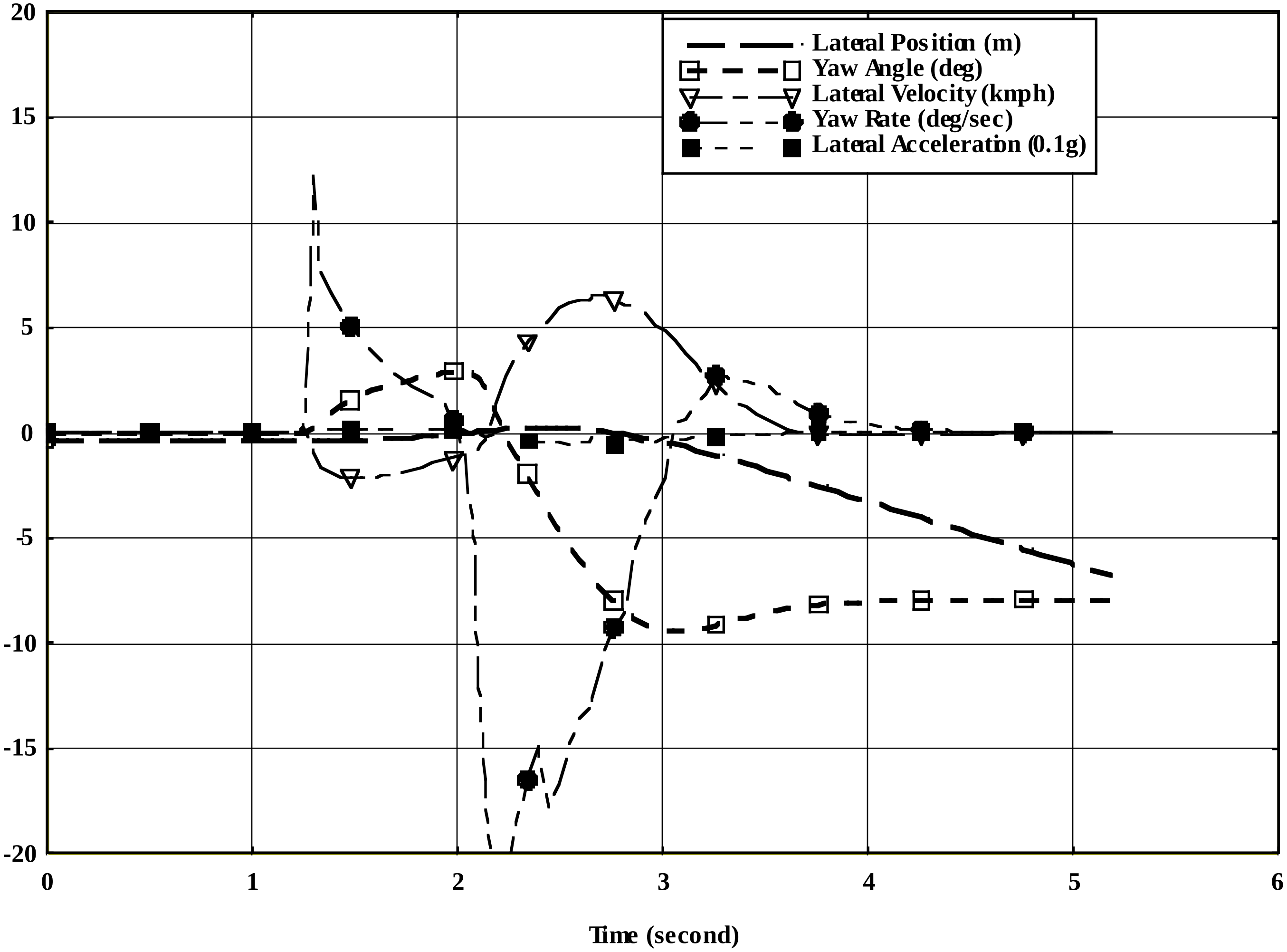


Figure 13. Motion Variables of Following Vehcile with 105 kmph Initial Speed, 5 m Initial Spacing, 0.3 m Lateral Offset and No Follow-Up Maneuvers, Class IV Following Class I

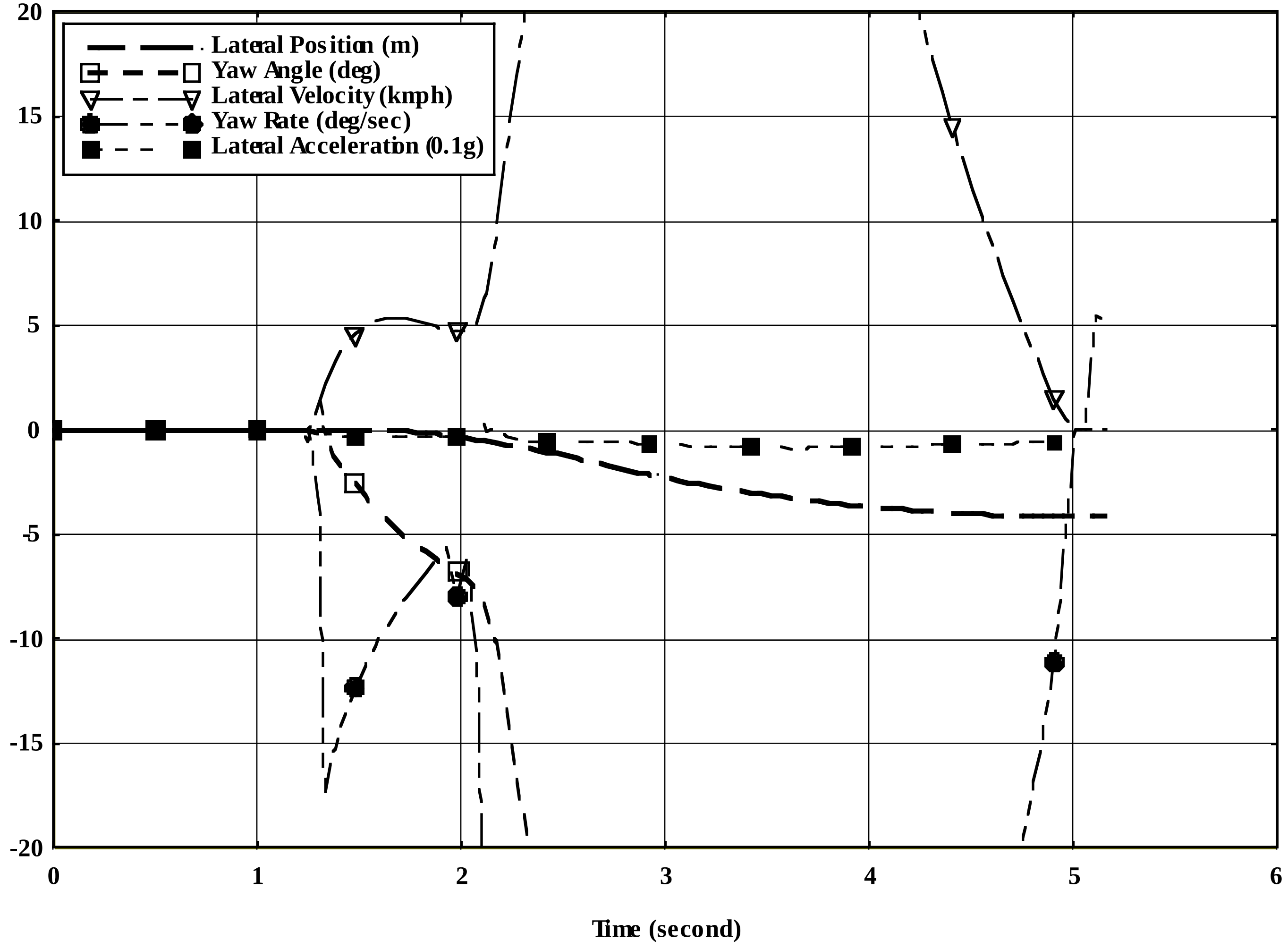


Figure 14. Motion Variables of Leading Vehcile with 105 kmph Initial Speed, 5 m Initial Spacing, 0.3 m Lateral Offset and Follow-Up Maneuver I, Class IV Following Class I

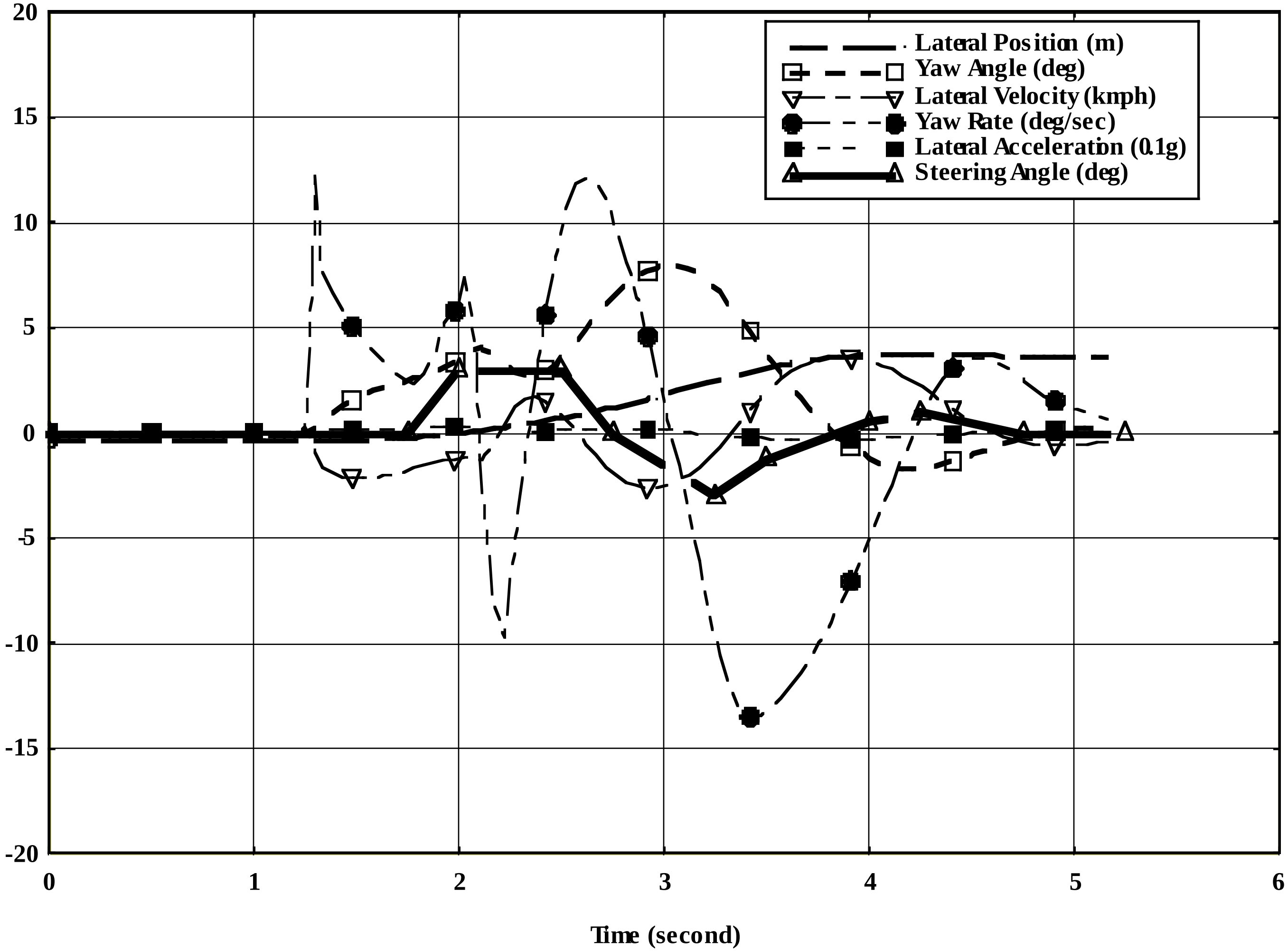


Figure 15. Motion Variables of Following Vehcile with 105 kmph Initial Speed, 5 m Initial Spacing, 0.3 m Lateral Offset and Follow-Up Maneuver I, Class IV Following Class I

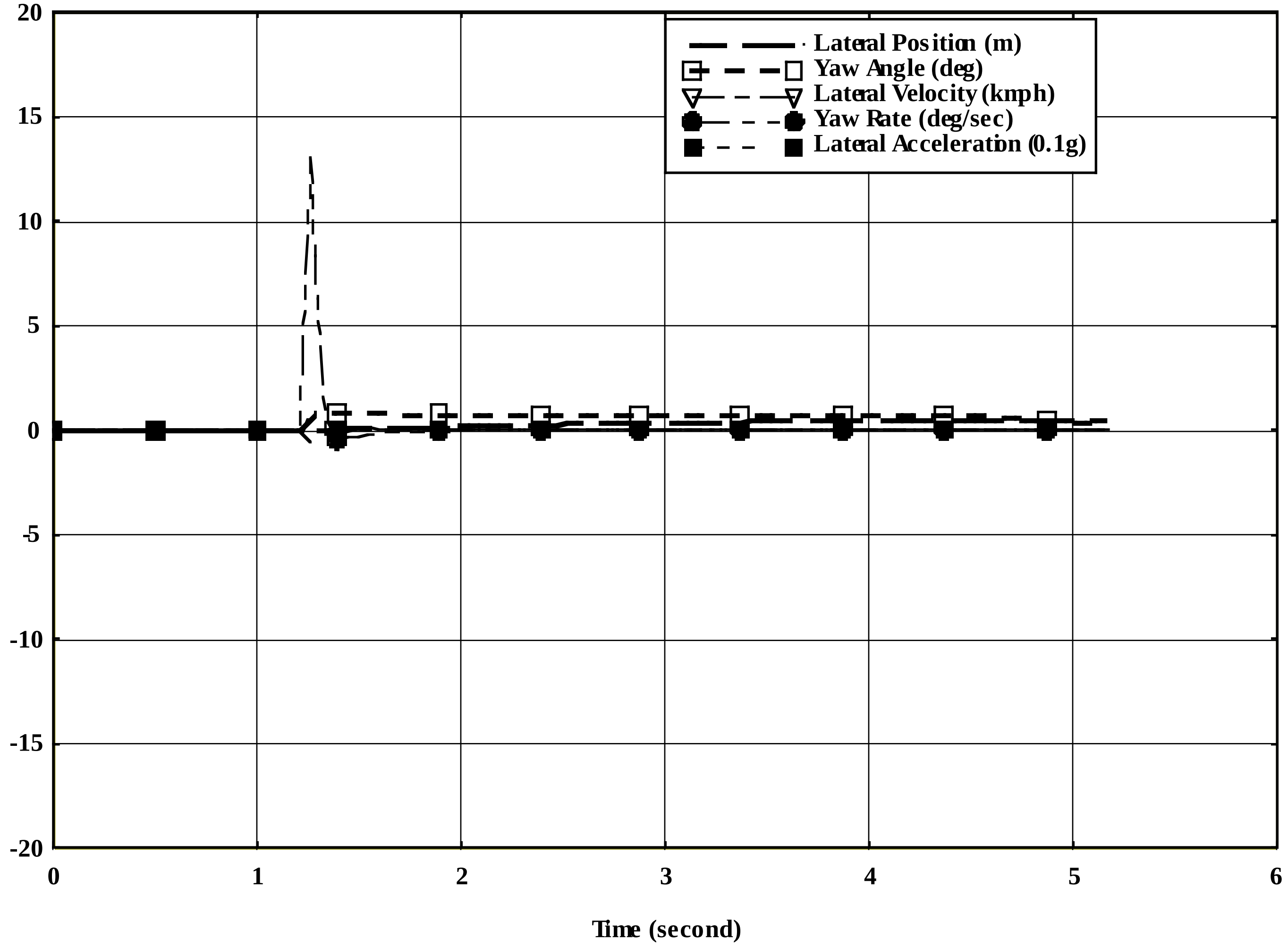


Figure 16. Motion Variables of Leading Vehcile with 105 kmph Initial Speed, 5 m Initial Spacing, 0.3 m Lateral Offset and Follow-Up Maneuver II, Class IV Following Class I

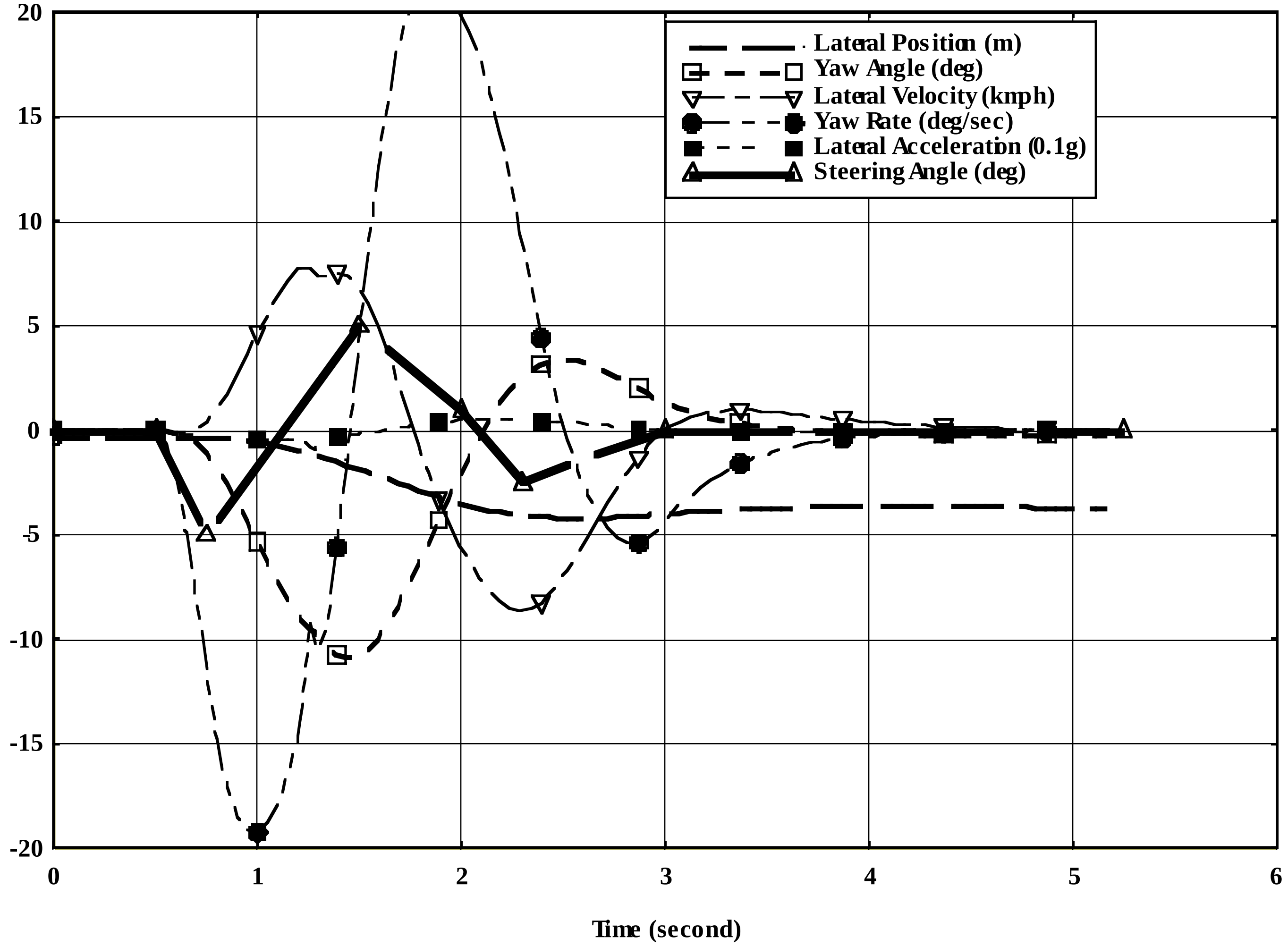


Figure 17. Motion Variables of Following Vehcile with 105 kmph Initial Speed, 5 m Initial Spacing, 0.3 m Lateral Offset and Follow-Up Maneuver II, Class IV Following Class I

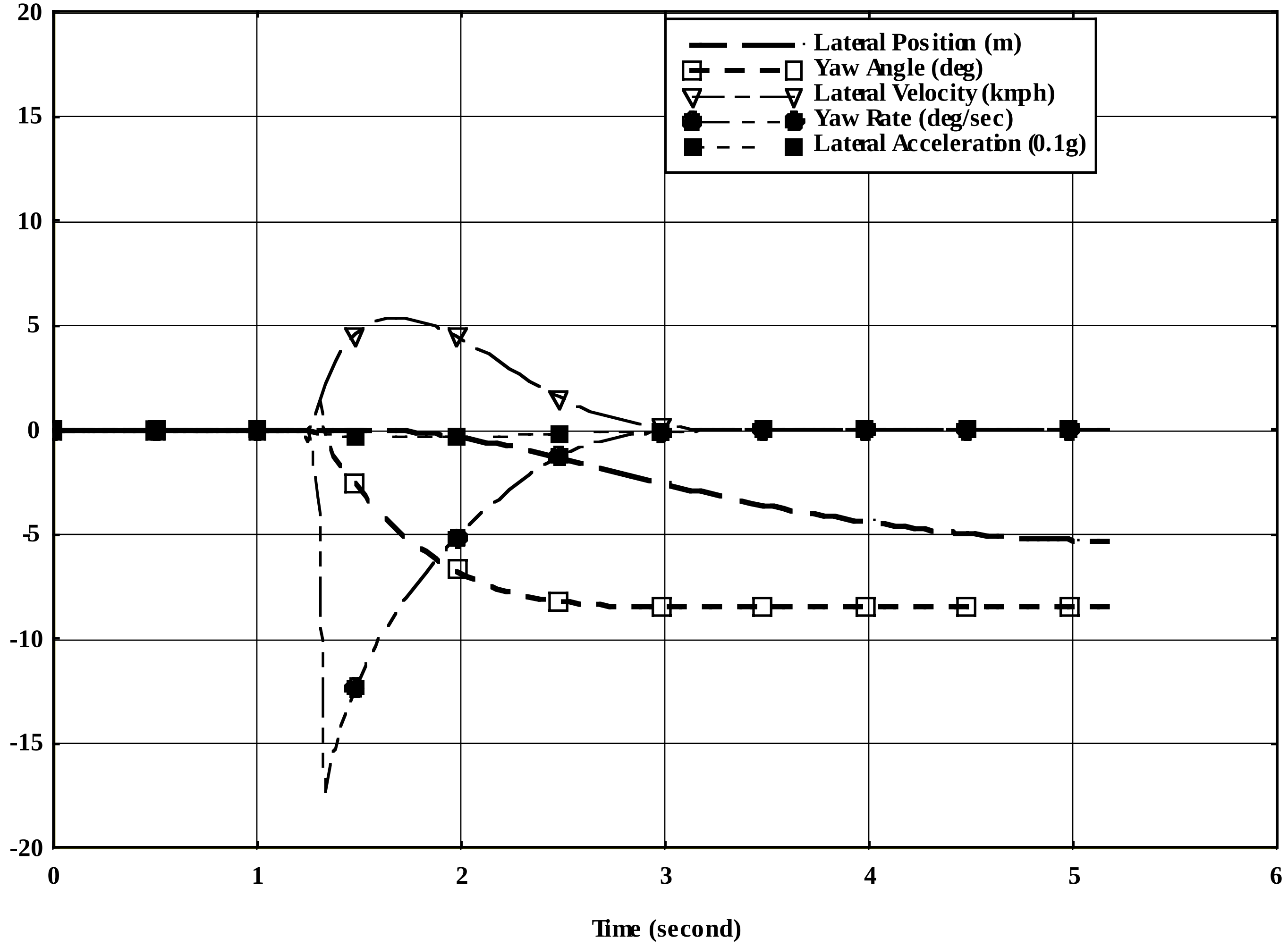


Figure 18. Motion Variables of Leading Vehcile with 105 kmph Initial Speed, 5 m Initial Spacing, 0.3 m Lateral Offset and Follow-Up Maneuver III, Class IV Following Class I

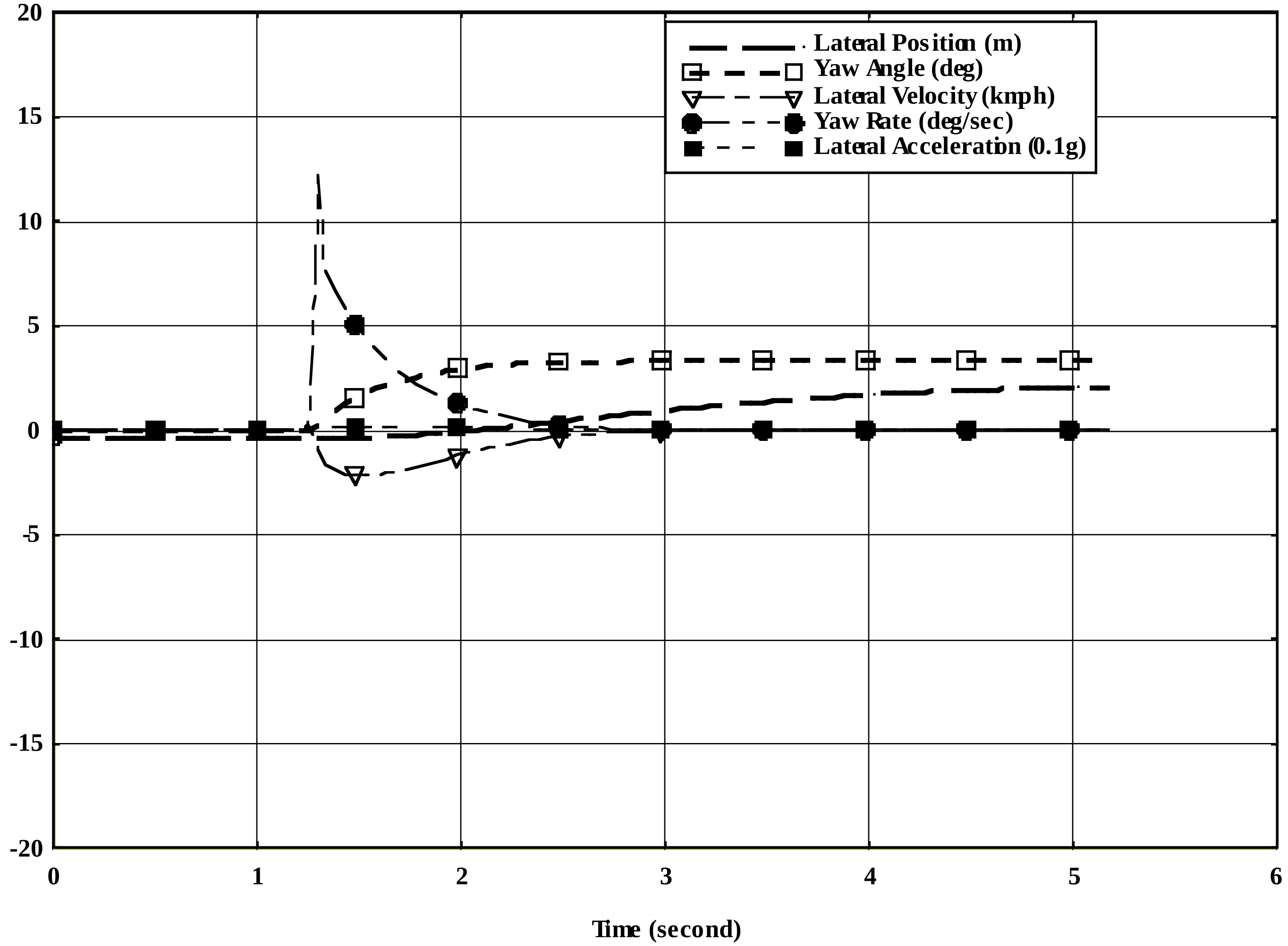


Figure 19. Motion Variables of Following Vehcile with 105 kmph Initial Speed, 5 m Initial Spacing, 0.3 m Lateral Offset and Follow-Up Maneuver III, Class IV Following Class I

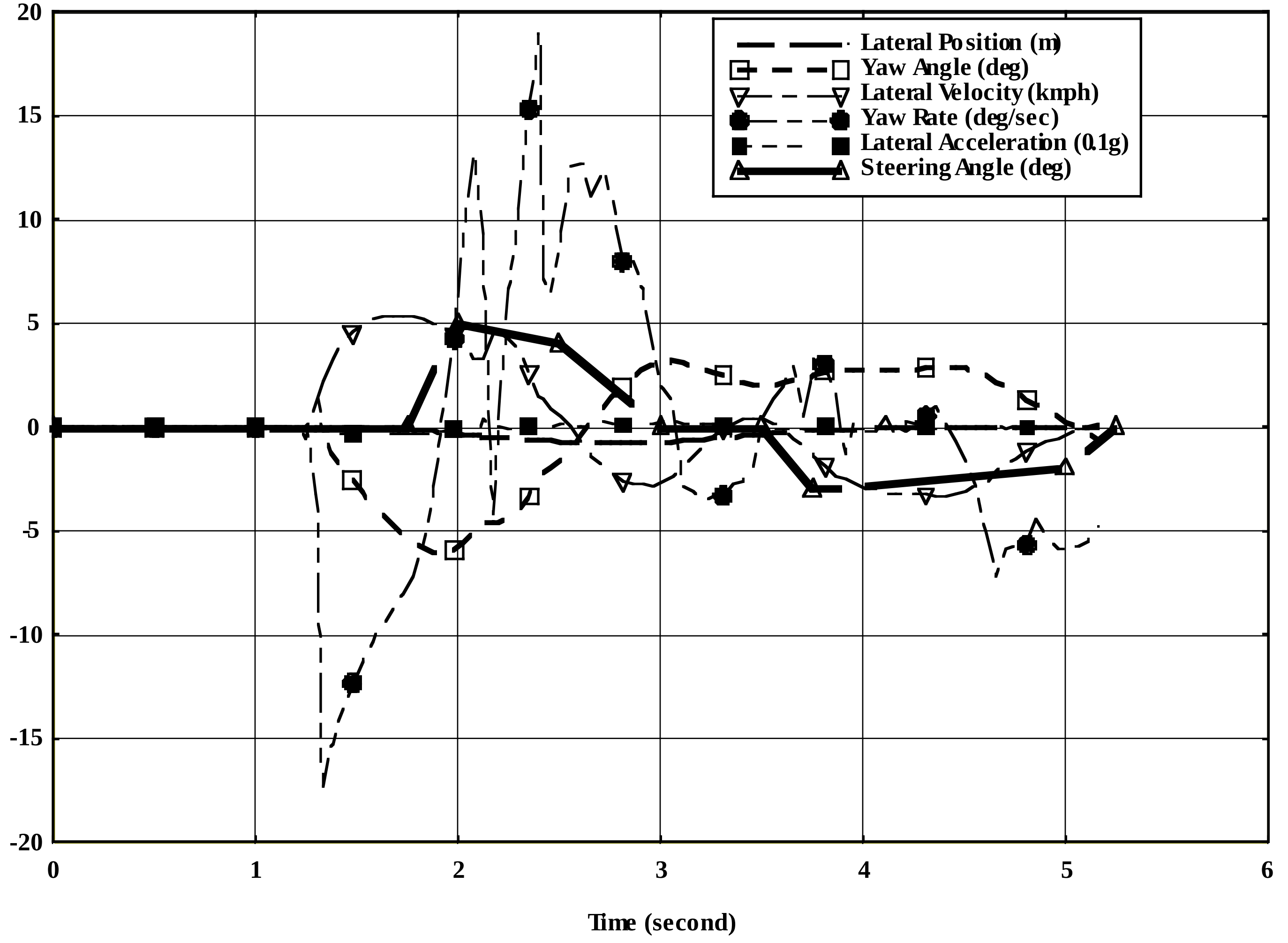


Figure 20. Motion Variables of Leading Vehcile with 105 kmph Initial Speed, 5 m Initial Spacing, 0.3 m Lateral Offset and Follow-Up Maneuver IV, Class IV Following Class I

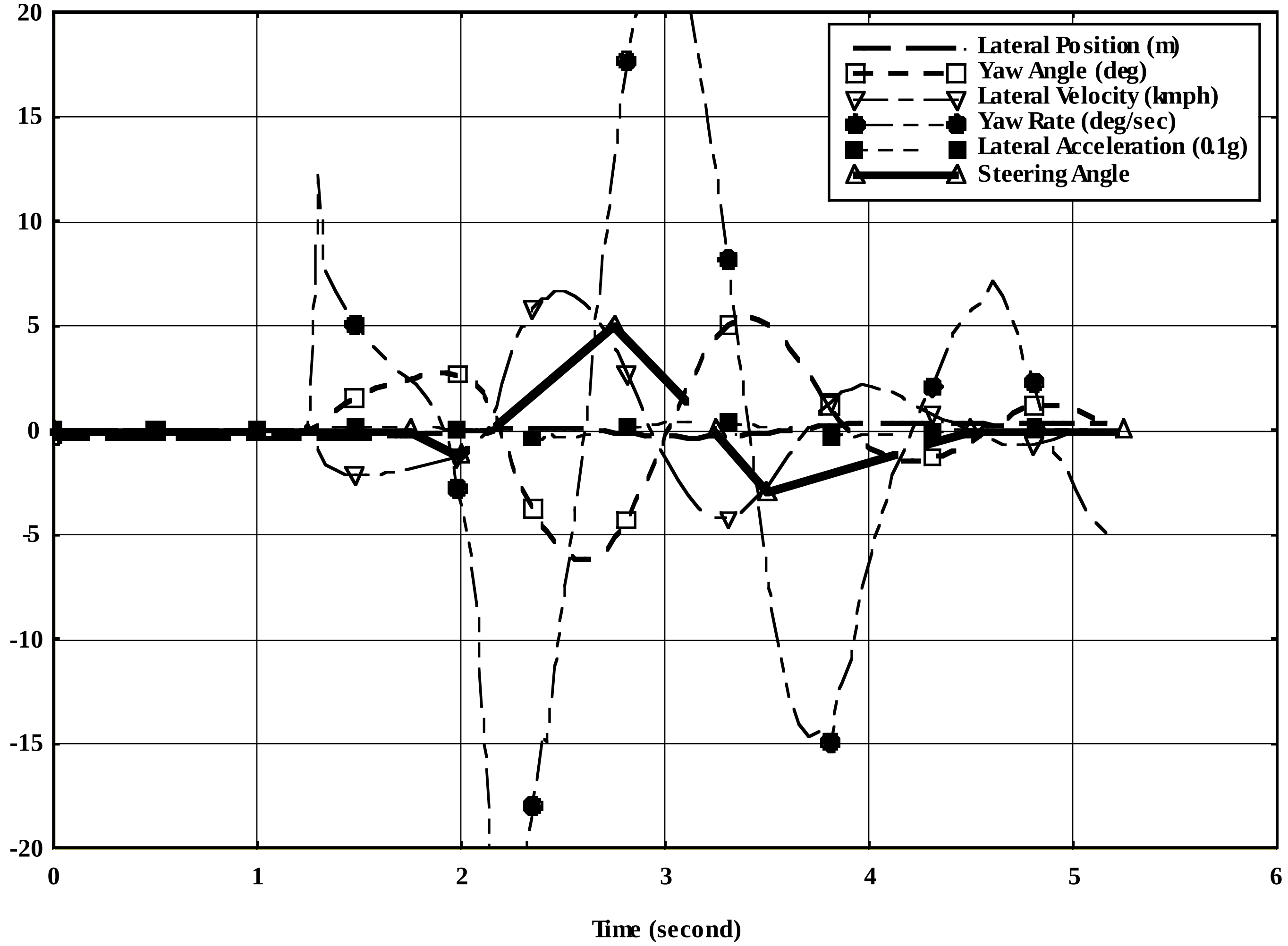


Figure 21. Motion Variables of Following Vehcile with 105 kmph Initial Speed, 5 m Initial Spacing, 0.3 m Lateral Offset and Follow-Up Maneuver IV, Class IV Following Class I

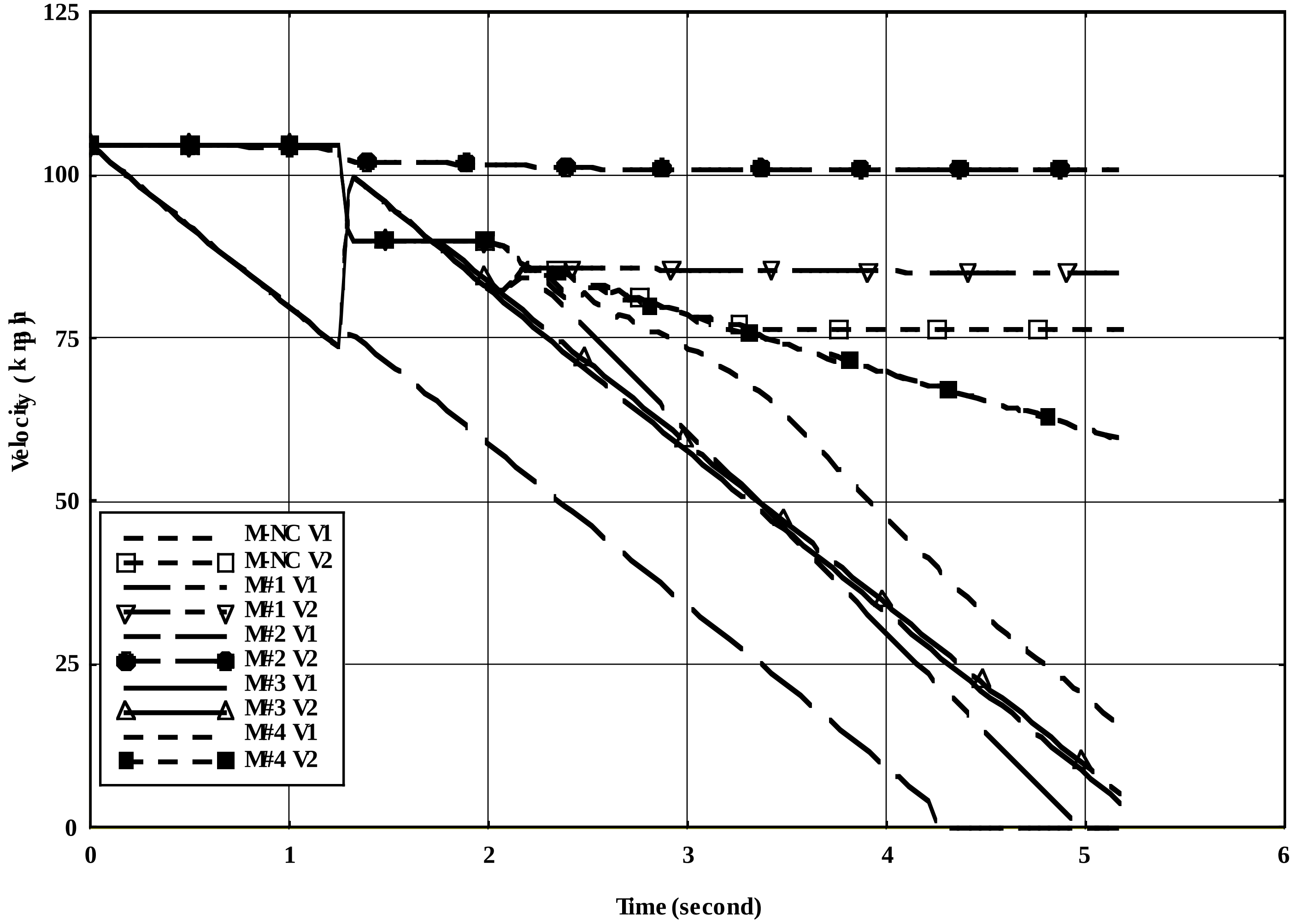


Figure 22. Comparison of Vlocity Profiles with Various Maneuvers Shown in Figures 12-21