EFFECTS OF PASSENGER AND CARGO LOADING ON A MOTOR VEHICLE'S MASS PROPERTIES

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ABSTRACT

Vehicles may be loaded with passengers and cargo in varying configurations that affect its mass properties during normal use. Mass properties include Cg location, weight, and mass moments of inertia. The objective of this paper is to develop an approach identifying possible passenger and cargo load configurations and accurately calculate and display their effect on a motor vehicle's mass properties. An approach is presented and discussed. The calculation method accounts for suspension compliance due to passenger and cargo loading. Overall, ie approach provides more accurate and useful estimates of a motor vehicle's Cg location and other mass properties. The approach may be of use to vehicle designers, operators, and regulators, providing enhanced access to vehicle parameters which are relevant to motor vehicle safety.

INTRODUCTION

While by no means the only factor, a motor vehicle's mass properties are ingredients in a motor vehicle's safety performance. Mass properties are important in that they affect motor vehicle handling, including control and braking, and drive train/suspension durability. The objective of this paper is to describe an approach of identifying possible passenger and cargo load configurations and accurately calculating and displaying their effect on a motor vehicle's mass properties. The approach encourages the development of passenger and cargo load configurations based upon the possible use of a motor vehicle. The calculation method takes into account suspension compliances due to passenger and cargo loading.

A vehicle is certified at a gross vehicle weight and gross front and rear axle weights pursuant to U.S. lational Traffic and Motor Vehicle Safety Act of 1966 Act, 1966). A label listing these weight ratings is required on every vehicle sold in the U.S. Beyond government regulation, a vehicle's mass properties, in conjunction with other vehicle properties, can be related to the responsiveness of a vehicle to driver input or the ease of vehicle control in steady-state maneuvers (Gillespie, 1992).

STATEMENT OF PROBLEM

This work addresses two fundamental questions in the approach presented. First, how can one anticipate possible passenger and cargo loading and calculate and display a vehicle's mass properties? Secondly, if the vehicle passenger and cargo space are loaded consistent with their possible use, do the resulting mass properties exceed vehicle specifications?

METHOD

The approach for identifying possible passenger and cargo loads and calculating and displaying mass properties of motor vehicles involves three separate and distinct operations. First, the approach requires defining passenger and cargo load configurations which are possible for the vehicle of interest. Secondly, data is generated and calculation made to determine the mass properties. The calculation accounts for changes in vehicle mass properties due to suspension deflection. Lastly, the mass properties which are calculated are displayed so that they can be effectively utilized to benefit a vehicle's safety.

When establishing the possible loadings of any particular motor vehicle, it is useful to consider its passenger and cargo space, the occupant/driver population, the vehicle's utility, and the vehicle usage environment. Overall, numerous possible vehicle loadings should be developed representing a range of possible mass properties. Although important, especially when comparing results, establishing specific weight and cargo ratings should be secondary to how one might anticipate the possible use of a vehicle's space.

Defining possible vehicle loading based upon space may require judgment and analysis. For example, rear seats in small passenger cars designed for two seating positions may be wide enough to accommodate three people; and, roof cargo racks, though often specified for 100 lbs. of cargo, may be large enough to accept greater cargo weight. At this stage of analysis, one should not be trying to judge how people should be using a vehicle, rather how they possibly will use the vehicle. Cargo can be considered for determining its mass properties as homogeneous solids located in available vehicle cargo space. Passengers in adjustable seats may be considered over the range of seat adjustment consistent with possible occupant's size.

The size and weight of possible vehicle occupants can obviously vary greatly. Since all designated seating positions in a motor vehicle must have seat belt restraints that accommodate up to 95th percentile male occupants (CFR, 1986a), consideration of occupants to at least this size and weight seems appropriate. Occupant mass properties are available from several sources, with the weight reported for a 95th percentile U.S. male being 98 kilograms (CFR, 1986a), 102 kilograms (NHTSA, 1983a), and 103 kilograms (NHTSA, 1983b).

An additional consideration for defining loading of a vehicle is its utility and environment. Again, judgment and analysis may be required to develop these effects fully. For example, multipurpose vehicles, by virtue of their designed utility, have large potential for significantly different load configurations due to their size (space) and interior changeability. Vehicles which are intended to carry a lot of cargo and/or people (for example vans) may have loadings consistent with that intent. Similarly, vehicles which appeal to market groups interested in camping or sporting activities (for example sport utility vehicles) may have loadings consistent with that intent. A vehicle operator's potential for risk taking and mechanical acumen may also be important considerations.

DATA AND CALCULATION

To calculate a motor vehicle's loaded mass properties, the data listed in Table 1 are required. A listing of formulas and a description of the calculations is contained in Appendix A.

Basic vehicle dimensions can be measured or obtained from a vehicle's manufacturer. Since published vehicle curb weights may be difficult to replicate in any particular vehicle, the "empty" configuration weight is measured. The "empty" configuration weight shall be defined as curb weight plus the vehicle's optional equipment. SAE Recommended Practice "Motor Vehicle Dimensions - J1100" defines curb weight as a vehicle with standard equipment and full of operating fluids (SAE, 1984).

Accurate scale weighing systems with the capability of measuring weight at each vehicle wheel simultaneously are available. With proper care, it is possible to accurately measure center gravity location. A body of literature exists describing various techniques for measuring Cg location (SAE, 1985; Winkler, 1991). The values one may obtain for Cg location may be dependent upon measurement uncertainty and vehicle population variances. Accommodation of these uncertainties may be appropriate when considering calculated loaded vehicle mass properties. Generally, measurement of Cg position within two percent accuracy is possible (Shapiro, 1995).

Required Vehicle Parameters	
Vehicle Parameters	
1.	Track width and wheelbase
2.	Empty mass
3.	Empty Cg location
4.	Empty Cg location suspension locked near maximum jounce
5.	Empty yaw and roll moment of inertia
6.	Front and rear suspension rates
7.	Mass properties and Cg position of passenger cargo loads

Table 1: Required vehicle parameters

To accurately account for the effect of suspension deflection due to vehicle loading, a second Cg location measurement must be taken with the vehicle suspension locked near its maximum deflection with the vehicle in its "empty" configuration. The Cg location of the total vehicle, when empty, moves proportionally to the suspension deflection. An inaccurate Cg location will be calculated if the effect of suspension deflection due to loading is not taken into account.

Mass moment of inertia can be measured, or this information can be obtained from literature for a number of vehicles (Garrott, 1988). Front and rear suspension rates are measured by applying loads to each corner of the vehicle at increasing increments and measuring sprung mass deflection versus wheel load.

Possible passenger and cargo load mass properties and location can be determined by measurement, analysis, or reference sources. Descriptions of mass properties for occupants are available in a publication by NHTSA (1986b). Measuring occupant H-point and cargo position directly from a vehicle is the simplest and most reliable method to define load positions.

DISPLAY OF RESULTS

It is possible to develop a range of calculated mass properties representing numerous possible passenger and cargo loadings of a motor vehicle. Calculated data by itself is interesting; however, the task of analyzing is most effectively utilized when presented or compared in a format that can be clearly and easily interpreted. There are numerous mathematical expressions related to steady-state vehicle handling and limit roll stability which utilize

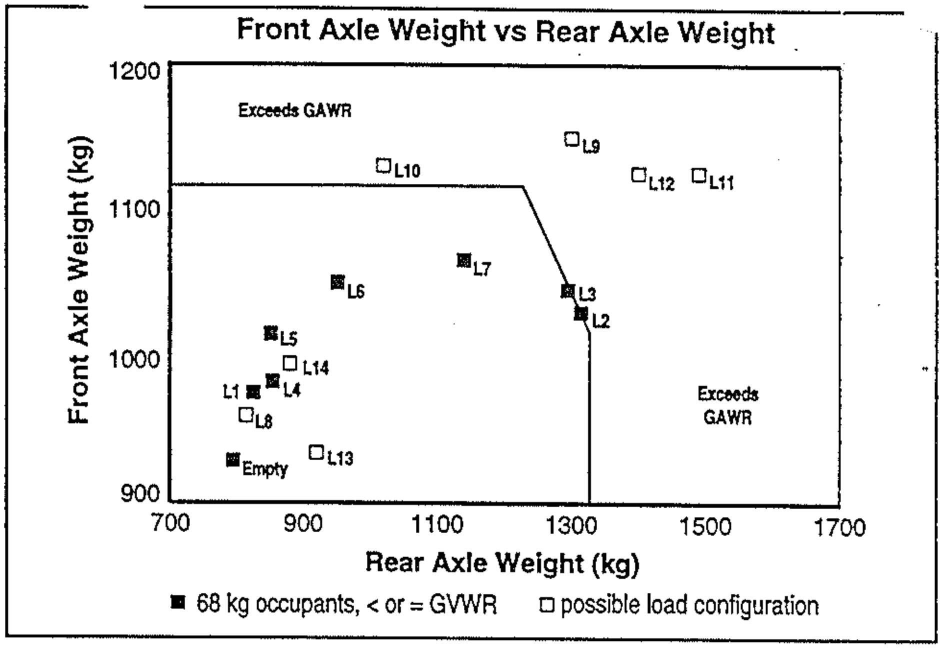

Figure 1: Front axle weight versus rear axle weight

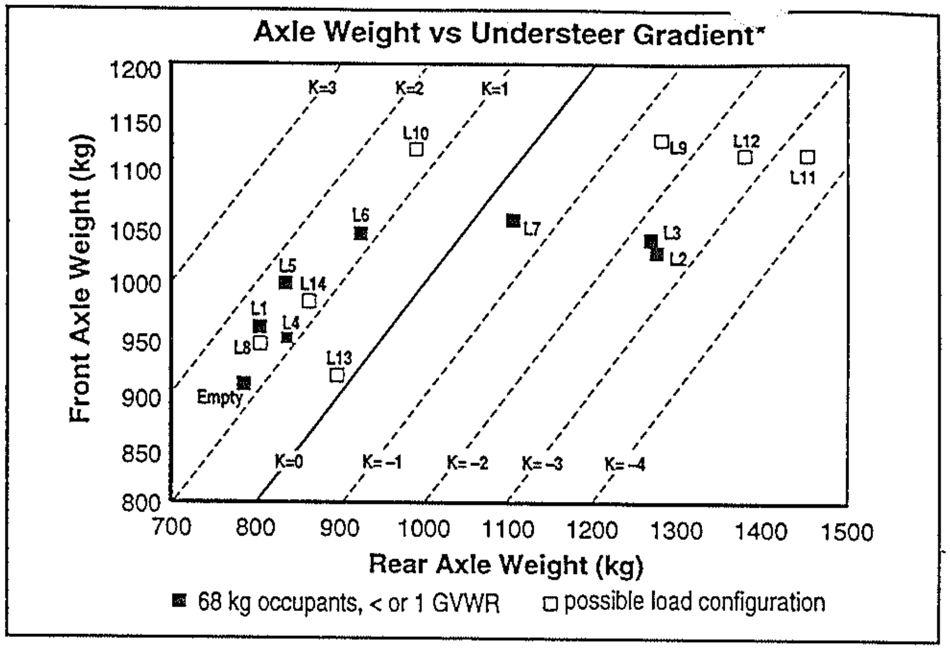

Figure 2: Axle weight versus understeer gradient

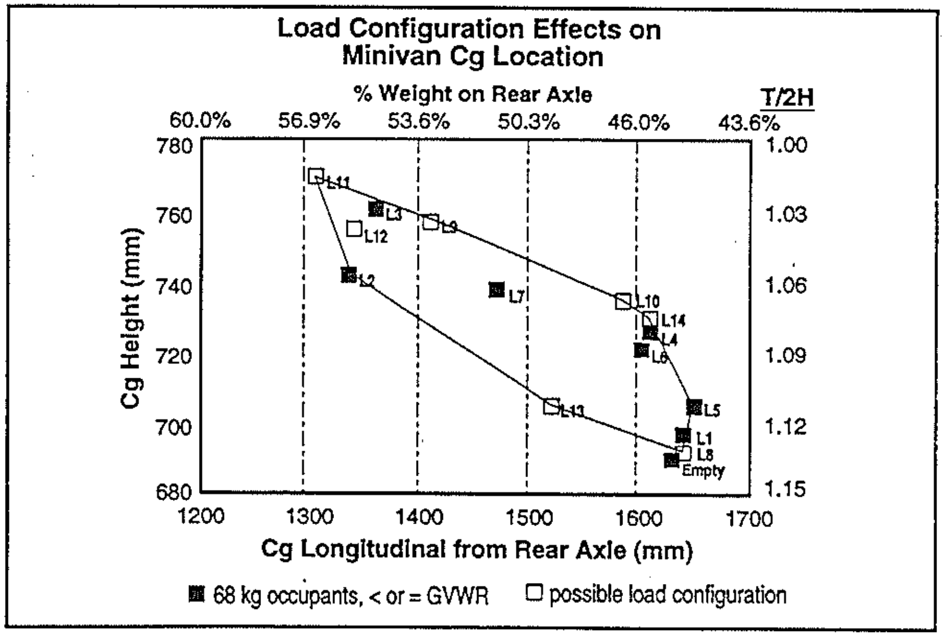

Figure 3: Load configuration effects on minivan Cg location

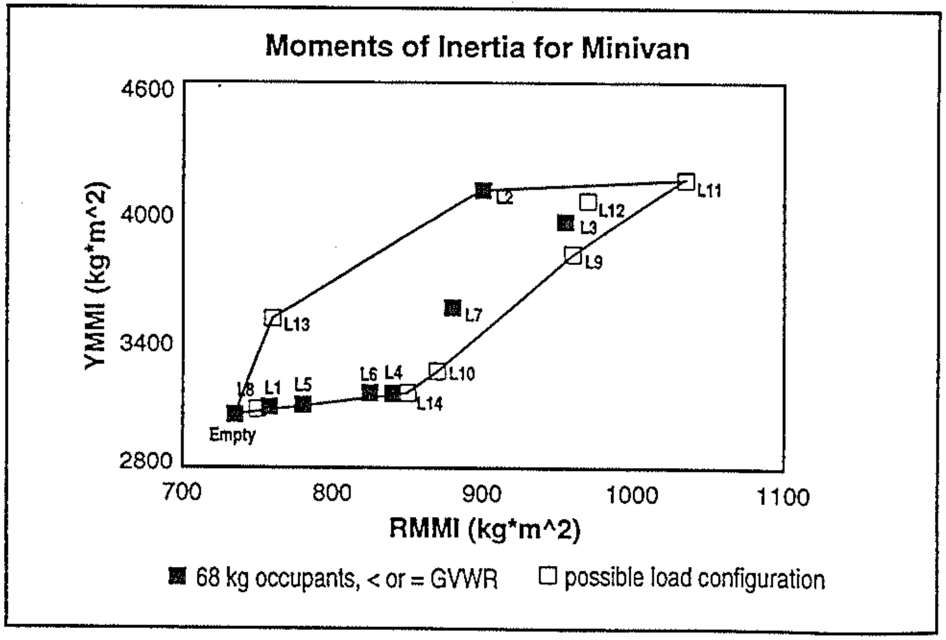

Figure 4: Moments of inertia for minivan

tions for larger or smaller occupants in H-point position due to seat cushion deflection or occupant anthropometry. Finally, larger or smaller occupants may position a seat more rearward or forward than illustrated in the examples provided. A refinement of occupant mass properties seated in the minivan might be expected to produce slightly different vehicle mass property values.

A series of figures—Figures 1 through 4—displays plots of front versus rear axle weight, axle weight versus understeer gradients, Cg location, and yaw versus roll moment of inertia, respectively. Data points representing adherence to the manufacturer's gross weight ratings and utilizing 68-kg occupants are included in Figures 1 through 4. The use of 68-kg occupants is a practice which is consistent with federal regulation of weight rating determination (CFR, 1986b) and SAE recommended practices (SAE, 1984); further, the 68-kg occupant is discussed in the owner's manual as part of a suggested practice for assuring adherence to front axle weight specifications (Ford, 1992). Table 2 lists the load configurations displayed in Figures 1 through 4 for the studied minivan.

While the authors do not presume to know or imply Ford's design intent or designed assumptions relative to its 1991 Aerostar minivan's passenger and cargo loading, it is interesting to illustrate the approach discussed in the previous section by comparing possible vehicle loadings to vehicle loadings which are within the vehicle's gross vehicle weight rating and gross axle weight rating and assume 68-kg occupants. The comparison provides the opportunity to observe the effect of various load configurations on a vehicle's weight, Cg location, handling, controllability, and roll stability factors.

RELEVANCE TO SAFETY

Figure 1 shows front versus rear axle weight for the studied load configurations. Several of the possible passenger and cargo load configurations produce weights in excess of gross vehicle weight ratings. Operating the vehicle at weights in excess of its weight ratings may cause vehicle damage and affect the dependable life of vehicle components. Further, brakes become less effective with increasing vehicle weight. U.S. FMVSS 105 requires brake tests at a maximum vehicle weight equal to its certified gross weight (CFR, 1986c).

Front-to-rear weight bias is also related to an element of the formulation of a vehicle's steady-state understeer gradient. Figure 2 displays the relationship using an objective formula shown by Gillespie (1992) and assuming equal front and rear tire corning stiffness. The vehicle, as shown in Figure 2, demonstrates a front weight bias for passenger loads which are small and positioned forward; however, a transition to rear weight bias occurs for heavy passenger and cargo loads or loads positioned more rearward. Wong, in his book, Theory of Ground Vehicles, describes front-to-rear weight bias as a prime factor controlling a vehicle's steady-state handling characteristics (1978). There are many elements to the formulation of a vehicle's steady-state handling. Insight can be gained into the magnitude and relative importance of various elements of a vehicle's steady-state understeer behavior (handling) by having access to a range of understeer gradient due to possible front-to-rear weight bias.

The minivan also exhibits a large range of possible longitudinal Cg locations, as illustrated in Figure 3. Further, the vertical Cg location changes with increasing passenger load because of the relatively high passenger seating. Adding loads to the roof top cargo rack increases Cg height further. Figure 3 represents a possible envelope of the vehicle's longitudinal and vertical Cg locations. Similar envelopes could be developed with lateral Cg location. Finally, Figure 4 is a graph showing the roll versus yaw moment of inertia for the various passenger and cargo load configurations.

Cg location is a particularly important mass property in that it relates, in conjunction with other vehicle parameters, to several elements of a vehicle's handling and limit roll stability. Vertical Cg location affects vehicle weight transfers during braking and cornering.

Interpretation of the displayed data of Figures 1 through 4 provides opportunities for analysis and, if appropriate, action which may affect a vehicle's safety. In cases where possible load configurations produce mass properties which exceed a specification or design assumption, the opportunity to mitigate dangerous circumstances is provided.

In particular, by developing a list of possible passenger and cargo load configurations, one could determine corresponding mass properties which may aid in the design of testing and computer modeling for safety assurance. Efficient simulation or testing may be conducted at the limits of a vehicle's possible mass properties. This testing and computer modeling might be particularly valuable in the analysis of after-market equipment.

SUMMARY/CONCLUSION

An approach for identifying possible passenger and cargo loads and calculating and displaying associated motor vehicle mass properties has been described and illustrated.

1. Occupant and cargo space may be primary determinants of possible loading configurations.
2. Suspension deflection must be considered to accurately calculate a vehicle's mass properties due to possible cargo and passenger loading.
3. Gross weight ratings can be easily exceeded when considering the possible passenger and cargo loadings of many vehicles.
4. Considering all the possible loadings of a motor vehicle provides access to potential loading problems and their solutions. The effective utilization of a vehicle's mass properties data requires its presentation in a display which is tailored to its users. Data displayed in a manner that is easily understood and interpreted will

APPENDIX A
MASS PROPERTIES CALCULATIONS

The center of gravity (CG) location of a system of objects can be calculated if the locations of the CGs of the constituent objects are known. The system CG location is calculated using Equation A1:

$$x_{CG} = \frac{\Sigma m_i \bullet x_i}{\Sigma m_i}$$

$$y_{CG} = \frac{\Sigma m_i \bullet y_i}{\Sigma m_i} \qquad \text{(A1)}$$

$$z_{CG} = \frac{\Sigma m_i \bullet z_i}{\Sigma m_i}$$

where:

x_{CG}, y_{CG}, z_{CG} are the coordinates of the system CG,
x_i, y_i, z_i are the coordinates of the component CGs,
m_i are the component masses.

This formula may be used to calculate the CG position of vehicles in various load conditions. The coordinate system used in this work is illustrated in Figure A1. The load conditions analyzed include occupants, as well as cargo stored in the vehicle or on the roof (Figure A2).

The moment of inertia of the system about an axis can be calculated with Equation A2 if the moments of inertia of its components about parallel centroidal axes are known:

$$I_{Axis} = \Sigma \left(I_i + m_1 \bullet d_i \right) \qquad \text{(A2)}$$

where:

I_{Axis} is the mass moment of inertia of the system about the desired axis,
I_i is the mass moment of inertia of each component about its centroidal axis parallel to the desired axis,
d_i is the distance between the desired axis and the parallel centroidal axis.

The CG position and moments of inertia of a loaded vehicle can be calculated using the above equations. However, the location of the component CGs must be adjusted to account for suspension deflection due to the load. The following procedure describes how this is accomplished.

The CG position of the empty vehicle is measured. Then, the vehicle's suspension is tied down to simulate the suspension compression when the vehicle is loaded to its gross axle ratings. The vehicle's CG position is measured in this configuration. The CG shift due to suspension deflection is then calculated from Equation A3:

$$\delta_x = \frac{x_V - x'_V}{\overline{s}}$$

$$\delta_z = \frac{z_V - z'_V}{\overline{s}} \qquad \text{(A3)}$$

where:

δ_x, δ_z are the changes of the x and z coordinates of the vehicle CG due to suspension compression,
z_V, z_V are the x and z coordinates of the unloaded vehicle CG,
z'_V, z'_V are the x and z coordinates of the unloaded vehicle CG with compressed suspension,
$\overline{s}$ is the average suspension deflection.

The lateral (y) location of the vehicle's CG is not significantly affected by the suspension deflections, so this component is ignored in this analysis.

The wheel weights of the loaded vehicles are calculated:

$$W'_{LF} = m_T \bullet g \bullet \frac{X_{Rear} - X_{CG}}{X_{Rear} - X_{Front}} \bullet \frac{Y_{Right} - Y_{CG}}{Y_{Right} - Y_{Left}}$$

$$W'_{RF} = m_T \bullet g \bullet \frac{X_{Rear} - X_{CG}}{X_{Rear} - X_{Front}} \bullet \frac{Y_{CG} - Y_{Left}}{Y_{Right} - Y_{Left}}$$

$$W'_{LR} = m_T \bullet g \bullet \frac{X_{CG} - X_{Front}}{X_{Rear} - X_{Front}} \bullet \frac{Y_{Right} - Y_{CG}}{Y_{Right} - Y_{Left}}$$

$$W'_{RR} = m_T \bullet g \bullet \frac{X_{CG} - X_{Front}}{X_{Rear} - X_{Front}} \bullet \frac{Y_{CG} - Y_{Left}}{Y_{Right} - Y_{Left}} \qquad \text{(A4)}$$

where:

W'_{LF}, W'_{RF}, W'_{LR}, W'_{RR}, are the weights on each wheel,
X_{CG}, Y_{CG} are the coordinates of the system CG (Equation A1),
X_{Front}, X_{Rear} are the x coordinates of the front and rear spin axes,
Y_{Left}, Y_{Right} are the y coordinates of the left and right tire contact patches,
m_T is the total mass of the loaded vehicle,
g is acceleration due to gravity.

The suspension deflections are then calculated from Equation A5:

$$S_F = \frac{(W'_{LF} - W_{LF}) \quad + \quad (W'_{RF} - W_{RF})}{2 \bullet K_R}$$

$$S_R = \frac{(W'_{LR} - W_{LR}) \quad + \quad (W'_{RR} - W_{RR})}{2 \bullet K_R}$$

$$S_{AVG} = \frac{S_F + S_R}{2} \qquad \text{(A5)}$$

where:

S_F , S_R, are the front and rear suspension deflections of the loaded vehicle,

S_{AVG} is the average suspension deflection of the loaded vehicle,

W_{LF}, W_{RF}, W_{LR}, W_{RR} are the wheel weights of the unloaded vehicle (measured),

K_F, K_R are front and rear suspension spring constants (measured),

The change in the CG position of the vehicle component of the system due to suspension compression is calculated with Equation A6:

$$\Delta X_S = S_{AVG} \bullet \delta_X$$

$$\Delta Z_S = S_{AVG} \bullet \delta_Z \qquad \text{(A6)}$$

where

ΔX_S, ΔZ_S are the shifts of the x and z coordinates of the vehicle component of the system, ajdusted for the suspension compression.

Thus, the CG position of the vehicle component of the system, adjusted for the suspension compression is calculated with Equation A7:

$$X'_V = X_V + \Delta X_s$$

$$Z'_V = Z_V + \Delta Z_s \qquad \text{(A7)}$$

where

X_V, Z_V are the x and z coordinates of the unloaded vehicle (measured),

X'_V, Z'_V are the x and z coordinates of the vehicle component of the system, adjusted for the suspension compression.

The CG locations, adjusted for suspension compression, of the components comprising the load are then calculated with Equation A8:

$$X'_i = X_i + \Delta X_S$$

$$Z'_i = Z_i - \left[S_F + (S_R - S_F) \bullet \frac{X_i - X_F}{X_R - X_F} \right] \qquad \text{(A8)}$$

where

X'_i, Z'_i are the x and z coordinates of the load components' CGs, adjusted for suspension compression.

The loaded vehicle's CG position is calculated using Equation A1. This is shown in Equation A9:

$$x_{CG} = \frac{m_V \bullet X'_V + \sum m_i \bullet X'_i}{m_V + \sum m_i}$$

$$y_{CG} = \frac{m_V \bullet y'_V + \sum m_i \bullet y'_i}{m_V + \sum m_i}$$

$$z_{CG} = \frac{m_V \bullet z'_V + \sum m_i \bullet z'_i}{m_V + \sum m_i} \qquad \text{(A9)}$$

where:

m_V is the mass of the unloaded vehicle.

These equations are solved iteratively to converge on the solution for the system CG. The moments of inertia are calculated using equation A2.

APPENDIX B
VEHICLE PARAMETERS

1991 Ford Aerostar minivan, extended van, #1FMDA31UMZB09082
Track width = 1544.0 mm; Wheelbase = 3016.25mm
Empty Mass (kg)(1): LF = 472, RF = 457, LR = 394, RR = 398
Empty Cg location (mm)(1): X = 1630.17, Y = 2.54, Z = 689.61
Empty with suspension compressed Cg location (mm)(1): X = 1629.28,Y = 2.54, Z = 647.39
Empty mass properties: mass(1) = 1722kg, RMMO(1) = 734 kg · m2, YMMOI(2) = 3077kg · m2
Suspension rates (per wheel, kg/mm)(1) : Front = 3.23, Rear = 4.44
Cg shift per average suspension shift (mm/mm)(1) X = -0.02, Y = 0.00, Z = -1.00
Gross weight ratings (kg)(3) : Vehicle = 2353, F axle = 1115, R axle = 1335

PASSENGER AND CARGO LOAD MASS PROPERTIES
(CG POSITION IN UNLOAD VEHICLE)

Description	Cg Position (mm)			Weight	I_X	I_Z
	X	Y	Z	(kg)	(kg·m^2)	(kg·m^2)
Driver @ 46 kg(4)	1868.68	-406.40	955.87	46.00	2.98	2.67
Driver @ 68 kg(4)	1872.49	-406.40	991.87	68.00	5.29	5.40
RF passenger @ 68 kg(4)	1826.26	406.40	1001.52	68.00	5.29	5.40
LC passenger @ 68 kg	997.71	-355.60	1093.47	68.00	5.29	5.40
RC passenger @ 68 kg	997.71	152.4	1093.47	68.00	5.29	5.40
LR passenger @ 68 kg	156.21	-406.40	1071.37	68.00	5.29	5.40
RR passenger @ 68 kg	156.21	406.40	1071.03	68.00	5.29	5.40
CR passenger @ 68 kg	156.21	0.00	1071.03	68.00	5.29	5.40
Driver @ 103 kg(4)	1872.68	-406.40	955.87	103.00	8.95	9.75
RF passenger @ 103(4)	1828.80	406.40	1012.19	103.00	8.95	9.75
LC passenger @ 103	997.97	-355.60	1104.14	103.00	8.95	9.75
RC passenger @ 103	997.97	152.40	1104.14	103.00	8.95	9.75
LR passenger @ 103	156.46	-406.40	1082.04	103.00	8.95	9.75
RR passenger @ 103	156.46	406.40	1082.04	103.00	8.95	9.75
CR passenger @ 103	156.46	0.00	1082.04	103.00	8.95	9.75
Cargo behind rear seat(5)	-560.32	0.00	971.55	90.00	7.59	8.13
Cargo behind rear seat(5)	-560.32	0.00	971.55	111.00	9.79	10.74
Cargo behind rear seat(5)	-560.32	0.00	971.55	156.00	14.50	16.33
Cargo on the roof(6)	254.00	0.00	2006.6	45.00	2.88	2.54

[1] Measured by Arndt & Associates, Ltd. Test Lab.
[2] As listed by Garrott (1988)
[3] From vehicle certification placard
[4] Adjustable seat in middle position, H-point equal to 50th percentile male
[5] Cargo centered in rear space, 343 mm above load floor
[6] Cargo centered in roof cargo rack 152 mm above roof