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ABSTRACT

A vehicle may be loaded in varying configurations that affect its mass properties during normal use. These properties include total mass, center-of-gravity (Cg) location, and moments of inertia. The ranges of these parameters, which are determined by the varied load configurations, define the vehicle's mass property envelopes. These envelopes are useful for evaluating the effect of any load configuration relative to vehicle performance/design specifications. Mass property envelopes provide a clear visual representation of a range of key parameters that significantly affect motor vehicle control. Examples are provided in this paper that illustrate the usefulness of the vehicle mass property envelopes.

INTRODUCTION

Vehicle Cg location, mass, and mass moments of inertia are vehicle mass properties. Changes in a vehicle's mass properties, while by no means the only factor, produce first order effects of handling, controllability, and roll stability.[1] Vehicle mass properties are affected by vehicle load. When considering a range of loads, one can determine a range of vehicle properties that describes an envelope of motor vehicle mass properties. This approach provides a means of exploring vehicle properties beyond the usual method of assessing vehicles based on capacity and single point vehicle parametrics.

Mass property envelopes are developed consistent with vehicle "design load weight"[2] and maximum loading recommendations of the vehicle manufacturer as described in the vehicle Owner's Manual. The vehicle loads associated with these assumptions are useful, but overall provide an incomplete description of a vehicle's expected usage. "Design load weight," for example, calls for 68 kilogram occupants, but occupant restraint systems are designed to accommodate a range of occupants weighing significantly less and significantly more.

Consideration of mass or inertial property envelopes when testing or designing motor vehicles or motor vehicle equipment, provides insight into how a specific vehicle can be expected to behave over its range of loading. This may be of particular concern for vehicles that have a large load carrying capacity or special purposes, such as sports utility vehicles, vans, and trucks. Additionally, the outcome from such an analysis can be used in conjunction with a computer model to study vehicle stability.

METHOD

The various mass property envelopes require the acquisition of the vehicle parameters listed in Table 1. Any number of methods could be used to determine these parameters.

The basic vehicle dimensions can be

Table 1: Required Vehicle Parameters for Mass Property Mass

	Vehicle Parameter
1.	Track width and wheelbase
2.	Empty mass
3.	Empty Cg location (3 dimensional)
4.	Cg location with vehicle empty and suspension locked near maximum jounce
5.	Empty yaw mass moment of inertia
6.	Empty roll mass moment of inertia
7.	Front and rear suspension rates (centimeter travel of sprung mass per kilograms force of wheel load)
8.	Cg location, yaw and roll mass moment of inertia of loads to be considered in analysis including occupants, cargo, etc.

measured directly or obtained from a variety of sources. These sources include Motor Vehicle Manufacturers Specifications, Automotive News Market Data Issues, and numerous other vehicle specification documents.[2] Since the published curb weight 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 with the vehicle's optional equipment. SAE Recommended Practice "Motor Vehicle Dimension - J1100" defines curb weight as a vehicle with standard equipment only and full of operating fluids.

Accurate scale systems with the capability of measuring mass at each wheel position simultaneously are available. With proper care, it is possible to accurately measure Cg. A body of literature exists describing the various techniques.[3,4] The accuracy that one may obtain for Cg location may be dependent upon measurement uncertainty and vehicle population variances. Accommodation of these uncertainties may be appropriate when designing mass properties envelopes. Generally, measurement of Cg position within 2% accuracy is possible.[5]

Knowing the Cg location with the vehicle empty and its suspension locked near its maximum compressed deflection allows the calculation of the Cg location movement as a result of suspension deflection during vehicle loading. This can be accomplished by locking the suspension near the maximum compressed suspension deflection and measuring Cg location with the vehicle in its empty configuration. The Cg location of the total vehicle, when empty, moves proportionally to the suspension deflections. An inaccurate Cg location will be calculated if the effect of loading is not accounted for during suspension movement .

Mass moment of inertia is difficult to measure; however, this information exists in the literature for a number of vehicles.[6-8] Included in these references is Cg information.

Front and rear suspension rates are measured by applying loads to each corner of the vehicle at increasing increments and measuring sprung mass (relative to unsprung mass) deflection versus wheel load. This procedure can be performed at all four wheels simultaneously.

Load mass properties and location can be determined by measurement, analysis, or referenced sources. Descriptions of properties for occupants are available in references.[9-11] Rectangular solids with homogeneous density approximate loads in a vehicle's cargo volume. Measuring the occupant H-point(s) and cargo positions directly in the vehicle is the simplest method to define load position.

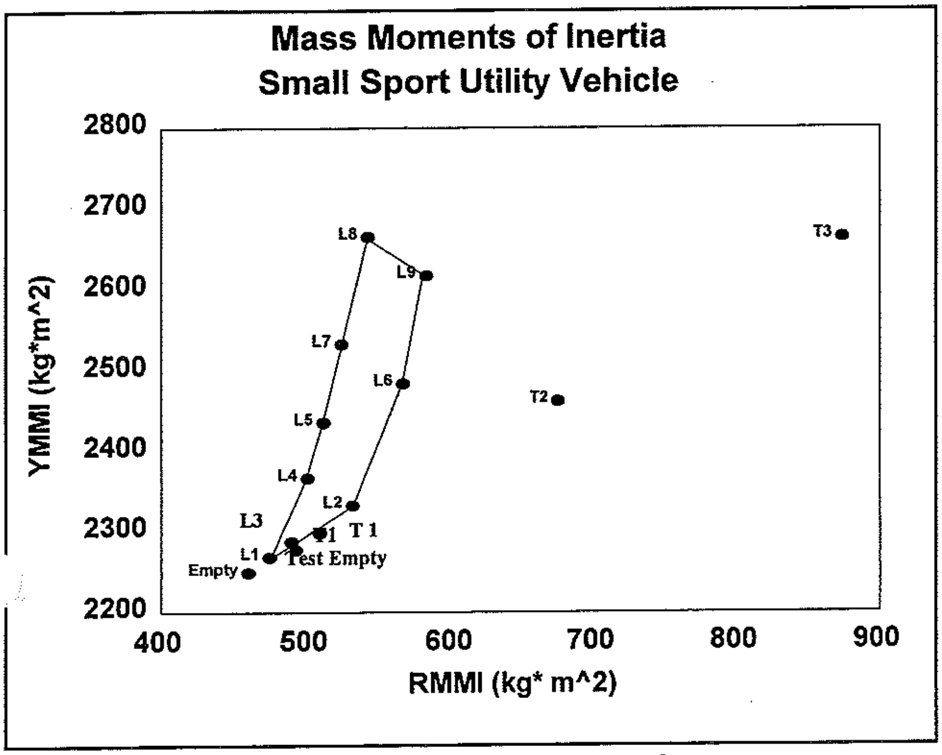

Figure 1 : Inertial Envelope for a Small Sport Utility Vehicle

Once the necessary measurements have been made and the desired load configurations defined, the mass properties for each configuration can be derived. The loaded Cg location and mass properties, along with roll and yaw mass moment of inertias, are then calculated for the loading configuration of interest.

One can plot these properties that form the envelopes when the vehicle mass properties for all the load configurations of interest are determined. These envelopes can be in formats such as vertical Cg location versus longitudinal Cg location, yaw moment of inertia versus roll moment of inertia, and front axle weights versus rear axle weights, among other envelopes.

APPLICATION

The development of a method for determining a vehicle mass properties envelope was precipitated by requirements to test a small sport utility vehicle in limit maneuvers with appropriate safety equipment and instrumentation (roll bar, outriggers, and 16-channel data acquisition). One requirement for the testing was maintaining the vehicle Cg location and mass properties as similar to driver-only condition as possible. Analysis of other tests of vehicles conducting limit maneuvers suggested that on-board vehicle instrumentation and safety equipment produced vehicle inertial properties well in excess of those expected in a vehicle's maximum conceivable load, much less a driver-only condition. In any test, the equipment necessary to conduct the test should have minimal effects on the test results. The usefulness of test results in motor vehicle handling and stability testing for evaluating non-test vehicles may be suspect if necessary on-board equipment causes properties to be outside the mass properties envelopes intended by the vehicle design or expected use.

Mass properties envelopes of a small sport utility vehicle were calculated using "design load weight" (design load weight is defined by SAE J1100) and loading recommendations consistent with the vehicle manufacturer. The mass properties envelopes also were calculated for the small sport utility vehicle in three test configurations. The different test configurations are described as light, medium, and heavy, which broadly represent a range of outrigger designs.[12] The envelopes associated with these parameters are shown in Figures 1 and 2 with the load configurations listed in Table 2.

In a second example, the effects of an after-market roof-top carrier on a vehicle's mass, Cg, and inertial properties are evaluated. Mass properties envelopes were developed similar to that of the small sport utility vehicle in the above example using the vehicle "design load weight" and loading recommendations of the vehicle manufacturer. The vehicle Owner's Manual recommends a roof-top luggage rack with a weight limit of 44 kg. However, the after-market car-top carrier provides an empty weight of 44 kg and a rated load capacity of 91 kg,

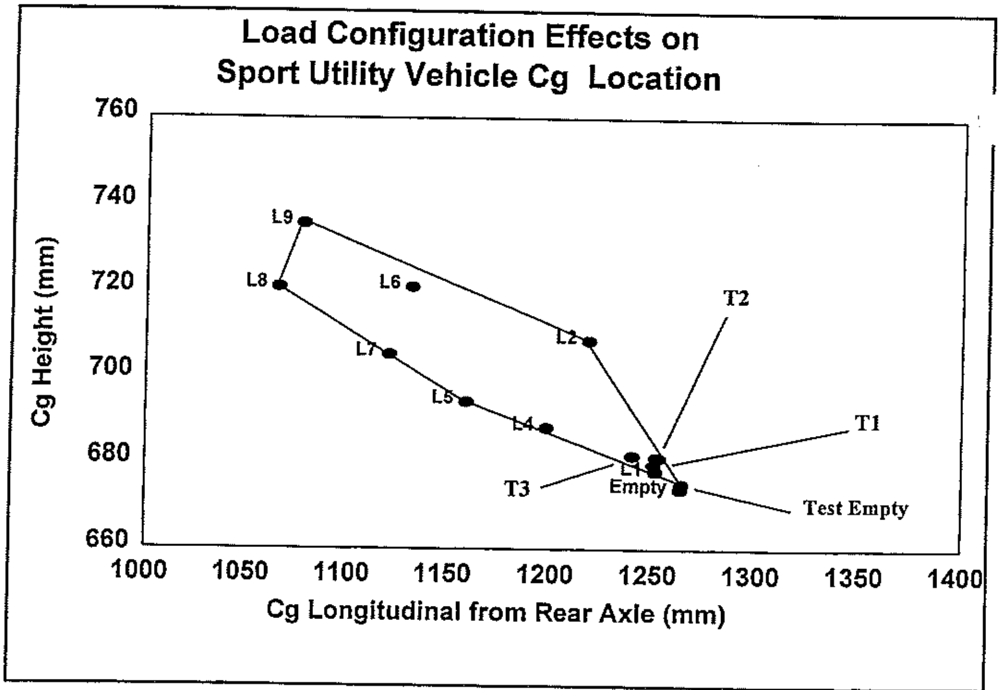

Figure 2: Cg Envelope for a Small Sport Utility Vehicle

Table 2: Small Sport Utility Vehicle Load Configuration

Load Configuration Description	
Config.	Description
Empty	Full fluids, no occupants, no cargo
L 1	Empty + driver @ 68 kg
L 2	Empty + driver @ 68 kg, 45 kg cargo on roof
L 3	Empty + driver, & RF passenger @ 68 kg ea.
L 4	Empty + driver, RF & LR passenger @ 68 kg ea.
L 5	Empty + driver, RF, LR & RR passenger @ 68 kg ea.
L 6	Empty + driver, RF, LR & RR passenger @ 68 kg ea., 45 kg cargo on roof
L 7	Empty + driver, RF, LR & RR passenger @ 68 kg ea., 45 kg cargo behind rear seat
L 8	Empty + driver, RF, LR & RR passenger @ 68 kg ea., 90 kg cargo behind rear seat
L 9	Empty + driver, RF, LR & RR passenger @ 68 kg ea., 68 kg cargo behind rear seat, 45 kg cargo on roof
Test Empty	Test vehicle @ empty w/ lightweight outriggers
T 1	Test vehicle @ empty + driver @ 76 kg w/ lightweight outriggers
T 2	Test vehicle @ empty + driver @ 76 kg w/ medium weight outriggers
T 3	Test vehicle @ empty + driver @ 76 kg w/ medium weight outriggers

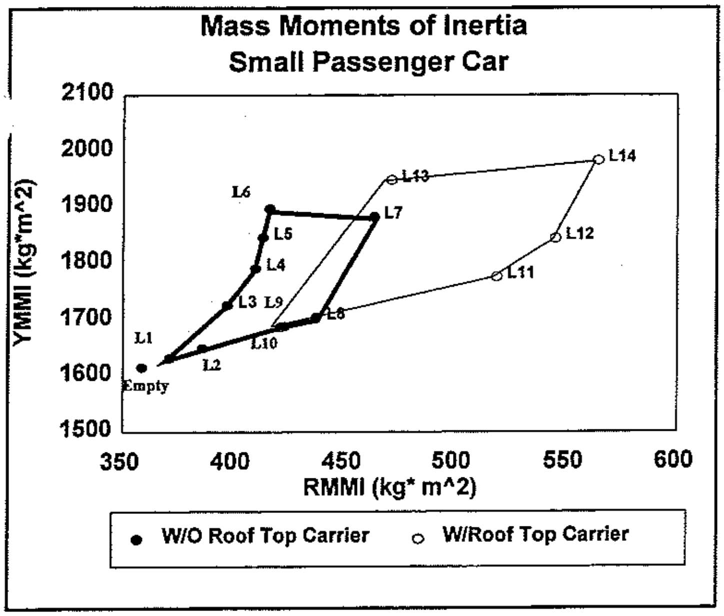

Figure 3: Inertial Envelope for a Small Passenger Car

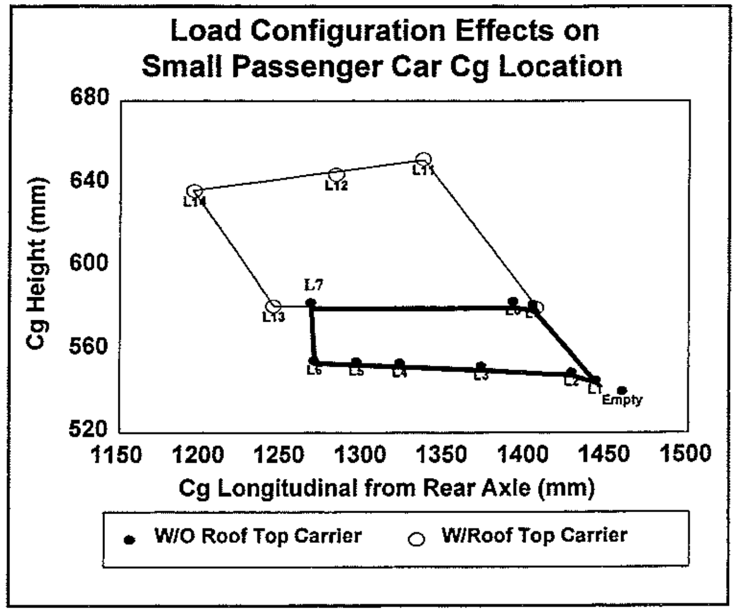

Figure 4: Cg Envelope for a Small Passenger Car

or a gross weight of 135 kg. Figures 3 and 4 show the Cg and inertial property envelopes for a small passenger car, and points of inertial properties associated with the addition of the after-market car-top carrier. Table 3 describes the load configurations that make up Figures 3, 4 and 5. This car-top carrier, by virtue of its utility and size, practically

Table 3: Small Passenger Car Load Configuration

Load Configuration Description	
Config.	**Description**
Empty	full of fluids, no occupants, no cargo
L 1	Empty + driver @ 68 kg
L 2	Empty + driver, & RF passenger @ 68 kg ea.
L 3	Empty + driver, RF & LR passenger @ 68 kg ea.
L 4	Empty + driver, RF, LR & RR passenger @ 68 kg ea.
L 5	Empty + driver, RF, LR & RR passenger @ 68 kg ea., 23 kg cargo behind rear seat
L 6	Empty + driver, RF, LR & RR passenger @ 68 kg ea., 45 kg cargo behind rear seat
L 7	Empty + driver, RF, LR & RR passenger @ 68 kg ea., 23 kg cargo behind rear seat, 45 kg cargo on roof
L 8	Empty + driver & RF passenger @ 68 kg ea., 45 kg cargo on roof
L 9	Empty + driver @ 68 kg , 45 kg cargo on roof
L 10	Empty + driver @ 68 kg , car top carrier on roof
L 11	Empty + driver @ 68 kg , 90 kg cargo in car top carrier on roof
L 12	Empty + driver, RF, LR & RR passenger @ 68 kg ea., 90 kg cargo in car top carrier on roof
L 13	Empty + driver, RF, LR & RR passenger @ 68 kg ea., 45 kg behind rear seat, car top carrier on roof
L14	Empty + driver, RF, LR & RR passenger @ 68 kg ea., 45 kg behind rear seat, 90 kg cargo in car top carrier on roof

guarantees vehicle operations outside of the calculated vehicle "design load weight," Cg and inertial property envelopes.

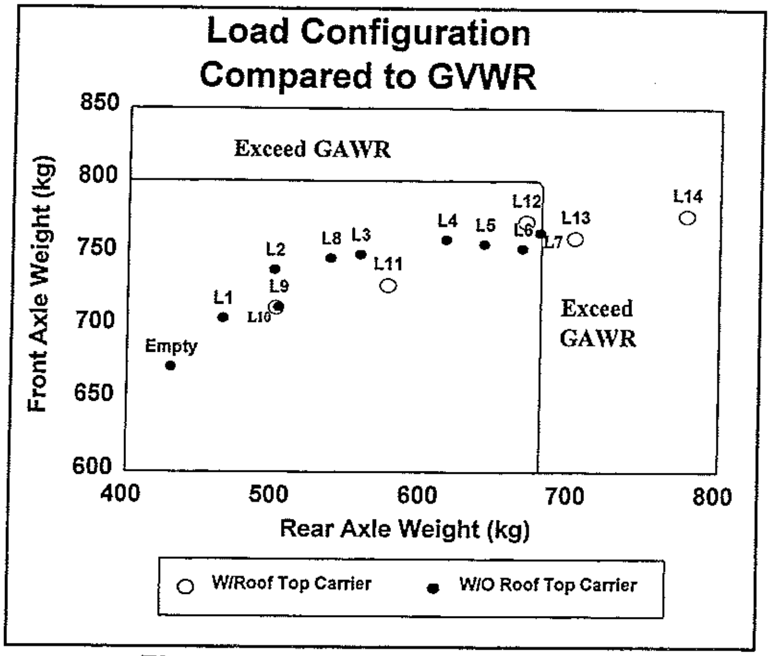

Figure 5: Axle Weights of Small Passenger Car Based on Expected Usage

Typically, roof-top carriers are used when other space inside a vehicle is not available or items too bulky for in-vehicle storage need to be transported (bicycles, canoes, etc.). Besides producing load configurations outside the calculated mass properties envelope, the roof-top carrier produces changes in the front and rear axle weights that, under expected usage of the vehicle, will exceed the specified weight capacities of the vehicle, as shown in Figure 5.

The practice of drawing straight lines between points for a given envelope represents an approximation of the true mass properties envelope. One could better define the shape of the envelope by calculating the intermediate points depending upon the specific interest.

Vehicle loads and associated vehicle mass properties were selected to represent obvious points defining an envelope. These points represent vehicle loads of 68 kg occupants and cargo consistent with manufacturer's recommendations and not in excess of vehicle weight ratings. These loads, while consistent with "design load weight," are obviously inconsistent with the wide range of possible occupant sizes and cargo positions.

The example of the roof-top carrier provides a context for a final discussion of mass property envelopes and expected usage. Prior examples of mass property envelopes were developed consistent with a vehicle's design load weight and loading recommendations of the vehicle's manufacturer. A vehicle's expected mass property envelopes can be developed, given load configurations consistent with the vehicle's expected use, including after-market equipment. For example, a vehicle's design load weight assumes a 68 kg occupant in each seating position; however, it is expected that occupants weighing in excess of 68 kg may sit in one or more seating positions. Similarly, a seat designated for two occupant positions may be wide enough for three or two occupants with cargo.

SUMMARY

Examples have been provided in this paper that illustrate the presentation and utility of vehicle mass property envelopes. These envelopes are useful for evaluating the effect of any load configurations relative to vehicle performance/design specifications as well as for minimizing effects of vehicle modifications for testing. The mass property envelopes can provide automotive designers and after-market designers a method for evaluating the effects of various load configurations on the fundamental properties of the vehicle for appropriate vehicle design, usage, instruction and warning.

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