

Estimation of Secondary Mass Changes in Vehicle Design

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ABSTRACT

It is well known that an unplanned component mass increase during vehicle design creates a ripple effect of changes throughout the vehicle subsystems, which require resizing for the additional mass. This in turn, increases overall vehicle mass. And the opposite is true in vehicle mass reduction where subsystem resizing is necessary to account for an initial mass reduction enabled, for example, by a new technology. These secondary mass changes can be significant and must be considered in the mass budgeting process due to their importance to fuel consumption and greenhouse gas emission assessments. Secondary mass reduction may be modeled using subsystem *mass influence coefficients*-the incremental change in subsystem mass for a unit change in gross vehicle mass. This paper focuses on means to estimate influence coefficients using two methods: Analytical and Regression.

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1. INTRODUCTION

Vehicle design engineers intuitively know that an unplanned mass increase in a component during vehicle design has a ripple effect throughout the vehicle; subsystems need to be resized to function with this additional mass. This further increases vehicle mass even more than the initial mass increase. The phrase '*mass begets mass*' describes this phenomenon. A more encouraging view of this behavior is considering a reduction in the mass of a component enabled by a new technology, which then results in a greater mass savings due to the resizing of other subsystems because of the initial mass reduction. These secondary mass changes can be significant, and it is important to consider them during the mass budgeting process. This is because important vehicle metrics, such as fuel consumption and greenhouse gas assessments, depend upon vehicle mass.

Secondary mass reduction may be modeled using subsystem *mass influence coefficients*-the incremental change in subsystem mass for a unit change in gross vehicle mass. This paper focuses on means to estimate influence coefficients using two methods, Analytical and Regression, with the following objectives:

1. Provide and compare estimates for mass influence coefficients using two methods: Analytical and Regression.
2. Review prior work on secondary mass estimation.
3. Suggest uniform terminology for secondary mass change analysis.

2. SECONDARY MASS REDUCTION POTENTIAL: STATE-OF-THE-ART

Generally within a detailed literature research, several values for the relationship between secondary and the primary mass change potential are identified and as many as 1300 different sources are screened. However, only 48 publications deal with the topic "secondary mass changes".

Eighteen sources estimate empirical values in a wide range from 0.16 to 1.0 for the secondary mass reduction potential. Further, these sources did not conduct scientific analyzes to confirm these values. Only five publications comprise detailed information about the calculation approach and use equations for the determination of the secondary mass reduction potential. [Figure 1](#) gives an overview of the different values identified within the literature research. The first five sources are those using a scientific approach. No

discussion appeared as to whether estimated secondary mass change was simple (one resizing iteration), or compounded (repeated resizing iterations). The reader is referred to reference 31 for a detailed discussion of these papers.

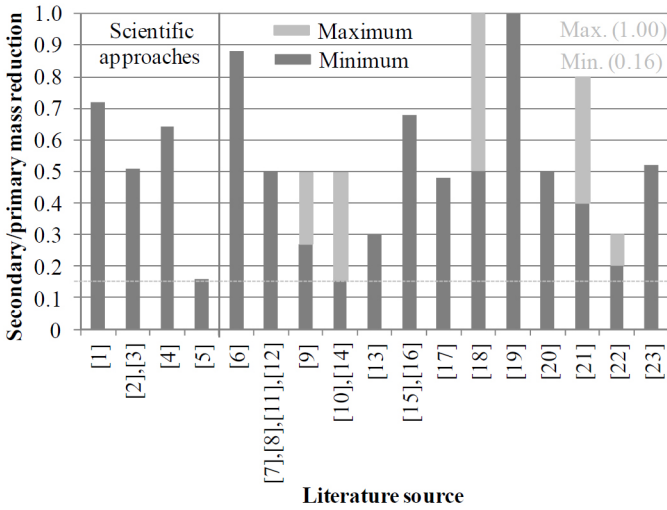


Figure 1. Secondary to primary mass reduction potential

3. SECONDARY MASS CHANGE MODELING

To model secondary mass change, we begin having a balanced vehicle design—that is all mass dependent subsystems are sized to the gross vehicle mass, M_0 , for the particular vehicle. We further assume that the vehicle is yet in the design stage, and we are free to redesign the subsystems. These assumptions define the *initial* vehicle and subsystems.

Now an unplanned mass change, Δ , occurs in a component: a positive change for a mass increase, negative for a mass reduction. This change upsets the balanced design, and the subsystems are no longer sized for the current vehicle mass ($M_0 + \Delta$). We now assume that the subsystems are redesigned to resize them for this new vehicle mass. This subsystem resizing will cause additional-secondary-changes in the subsystem mass. These changes may be added to result in the vehicle's secondary mass change.

This resizing may be done as a series of design iterations. If one iteration is completed, the secondary mass change is referred to as *simple secondary mass change*. However, note that after the first redesign, the vehicle subsystems are sized for a vehicle of mass ($M_0 + \Delta$). Yet the mass of the vehicle is now ($M_0 + \Delta + \text{simple secondary mass change}$). Thus the vehicle subsystems are not yet in balance and may be redesigned again. We can imagine that this iterative redesigning occurs theoretically over an infinite number of cycles. The mass changes eventually converges to a larger secondary mass change—the *compounded secondary mass change* (an example of this iterative resizing is provided later).

This behavior is captured in the following equations. The overall vehicle mass after resizing, M_{RS} , is

$$M_{RS} = M_0 + \Delta + \Delta\Gamma \quad (1)$$

where

M_0 =Initial vehicle mass for which the subsystems are sized

Δ =Initial total mass change (*primary* mass change)

M_{RS} =Vehicle mass after resizing subsystems

$\Delta\Gamma$ =Additional (*secondary*) mass change due to resizing subsystems

Γ =Secondary mass coefficient which depends on the treatment of resizing iterations: *Simple* for one resizing. *Compounded* for an infinite series of resizings

The secondary mass coefficient, Γ , depends on subsystem mass influence coefficients, γ_i —the change in mass of subsystem i when the gross vehicle mass increases by 1 kg.

The simple secondary mass coefficient assuming one resizing iteration is

$$\Gamma = \gamma_V \quad (2)$$

Assuming that the subsystem mass influence coefficients are constant, and that the sum is less than one, $0 < \gamma_V < 1$, then after an infinite number of resizing iterations we have the secondary mass coefficient for compounded secondary mass change

$$\Gamma = \frac{\gamma_V}{1 - \gamma_V} \quad (3)$$

The mass influence coefficient for the vehicle, γ_V , is given by

$$\gamma_V = \sum \gamma_i \quad (4)$$

The resulting mass for subsystem i due to an initial vehicle mass increase of Δ is

$$mi_{RS} = mi_0 + \Delta_i + \Delta\tau \quad (5)$$

for simple secondary mass change

$$\tau = \gamma_i \quad (6)$$

for compounded secondary mass change

$$\tau = \frac{\gamma_i}{1 - \gamma_V} \quad (7)$$

where

m_{i0} =Initial subsystem i mass

Δ_i =Initial mass change in subsystem i

m_{iRS} =Resized subsystem i mass

$\Delta\tau$ =Additional (secondary) mass change for subsystem i

To illustrate the use of these equations, consider a vehicle with the subsystem influence coefficients shown in Figure 2, second column from left (using influence coefficients from the analytical approach described in Section 5 [26]). A primary mass reduction of $\Delta = -100$ kg occurs. In the first design iteration, each subsystem mass is reduced by the product of the primary mass reduction and the subsystem influence coefficient. These mass reductions are shown in the column labeled *Resizing iteration number 1*. The sum of these mass reductions is the *simple secondary mass change* for the vehicle: -34.15 kg. However, the vehicle subsystems are not yet balanced as this -34.15 kg change has not yet been taken into account. Thus in iteration 2, subsystem mass may be further reduced as shown. This process may be repeated. Each iteration will result in a smaller secondary mass reduction. Four iterations are shown in Figure 2 to illustrate this compounding behavior.

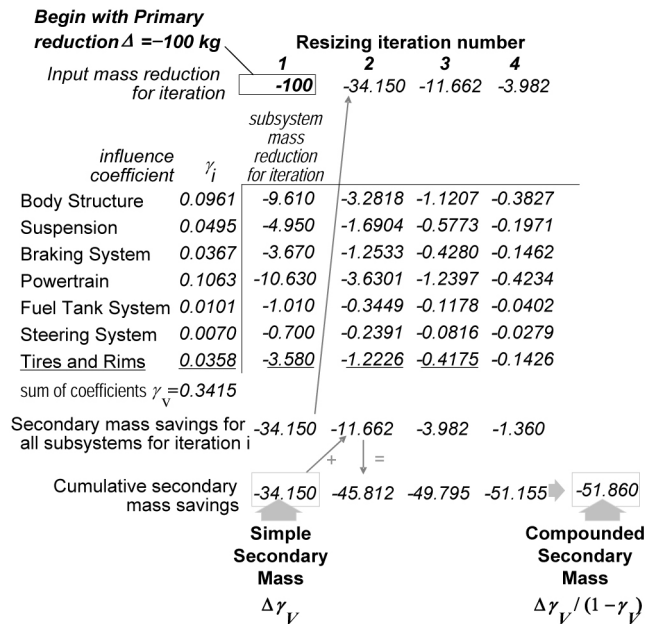


Figure 2. Illustration of secondary mass change calculation (Using influence coefficient data from [26])

For a large number of iterations, the cumulative mass change for the vehicle, $\Delta\Gamma$, converges to a value given by Eq. (3). Whether *simple* or *compounded* secondary mass change is most appropriate will depend on the particular design context. If the design activity is at the product planning stage, then the full advantage of compounded secondary mass change may be gained. If the design activity is at the detail design stage, simple secondary mass change would be a more appropriate reflection of the constraints on the ability to redesign subsystems.

4. MEANS TO ESTIMATE INFLUENCE COEFFICIENTS

It is clear from Eqs. (1),(2),(3),(4),(5),(6),(7) that estimations of secondary mass change depend on the subsystem influence coefficients, γ_i , for the vehicle mass dependent subsystems. Three methods to estimate mass influence coefficients for these subsystems are Ratio, Regression, and Analytic, Figure 3

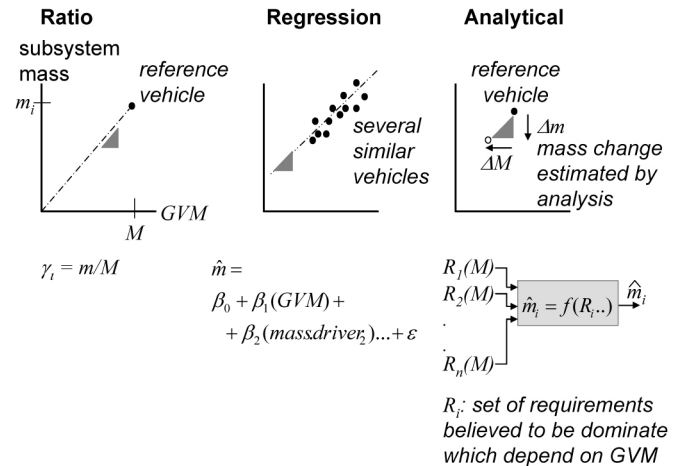


Figure 3. Methods to estimate secondary mass influence coefficients

In the Ratio method, a linear relationship is assumed between subsystem mass and gross vehicle mass-GVM. A representative reference vehicle is selected and the ratio between subsystem mass and gross vehicle mass is determined for each mass dependent subsystem and becomes the influence coefficient. The appeal of the ratio method is its modest data requirements (mass data from only one vehicle is sufficient for estimation). However, its assumption of linearity and the assumed sole dependence of subsystem mass on gross vehicle mass results in a consistent bias on the high side. Therefore the ratio method is typically used only for a quick check on estimates from other methods.

For more accurate estimates of mass influence coefficients, both the Analytical method and Regression method are used in practice today to a limited degree. It is the intent of this paper to extend and improve both secondary mass change data and methodology. In the following sections, recent work is described in determining mass influence coefficients estimates for sedans and hatchbacks having integral body structure, front wheel drive, and internal combustion engine.

5. ANALYTICAL METHOD

The analytical method contains the development of a classification system for the analytical determination of the simple and compounded secondary mass reduction in vehicles. Based on defined selection criteria, all components the vehicle body, powertrain, chassis (consisting of the