# Preliminary Vehicle Mass Estimation Using Empirical Subsystem Influence Coefficients

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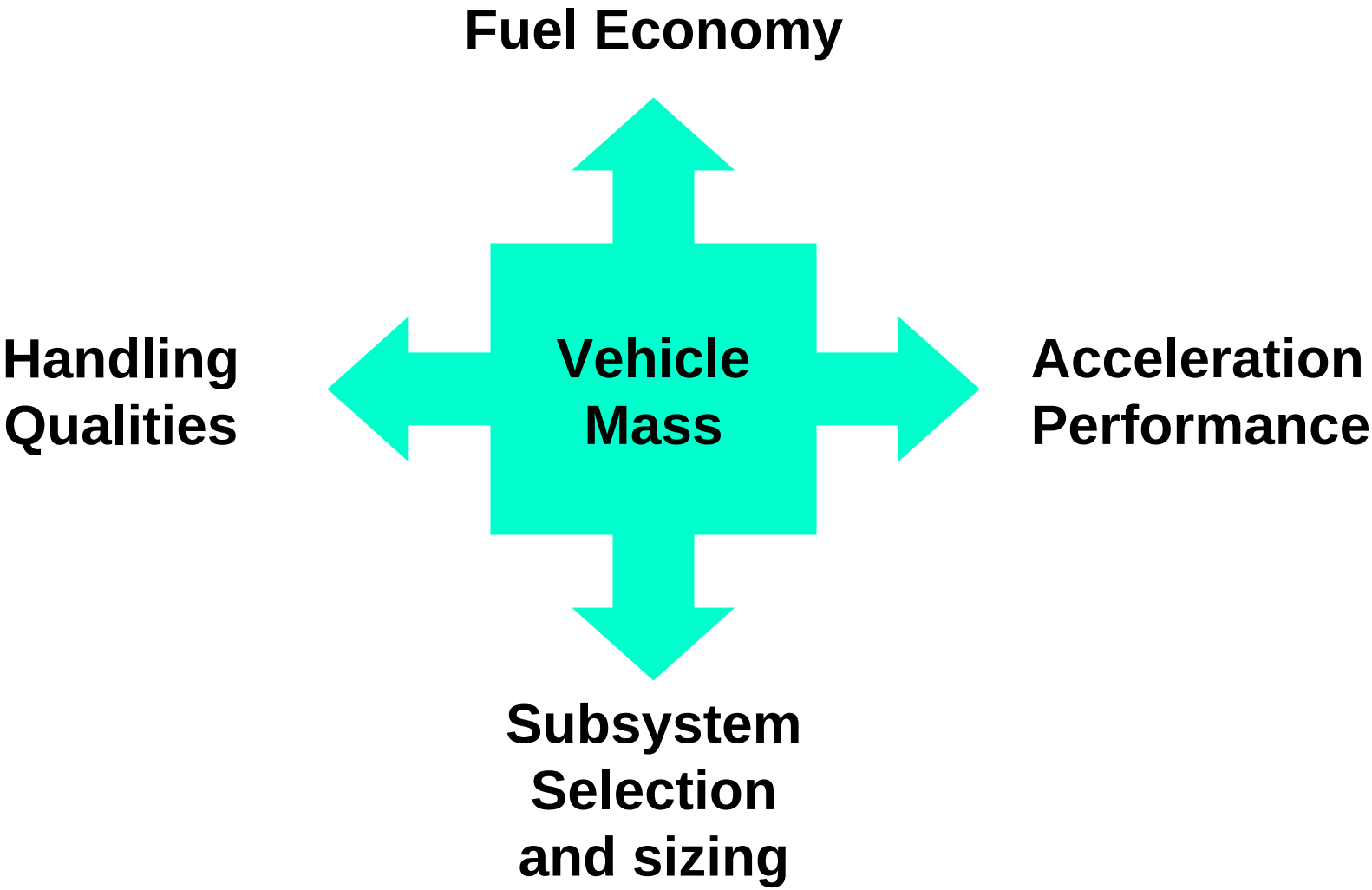
University of Michigan

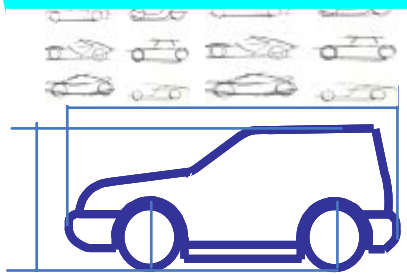
A project supported by the
**Auto/Steel Partnership**

# Mass Estimation in Vehicle Design



# Vehicle Development Stage

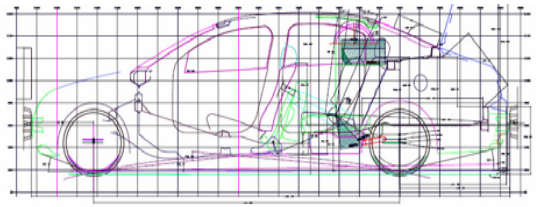
## PreConfiguration
*Product Planning*



***Decide if vehicle concept is consistent with mission***

***What is mass if designed as a typical vehicle for this size and class?***

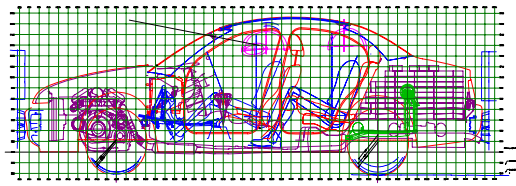
## Configuration
*Advance Vehicle Development*



***Decide which configuration is best in meeting vehicle goals***

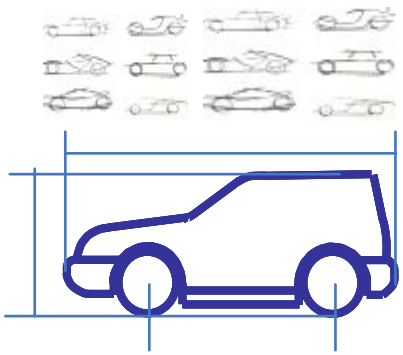
***What is mass if configuration is changed from typical vehicle?***

## Detail
*Engineering Factory*

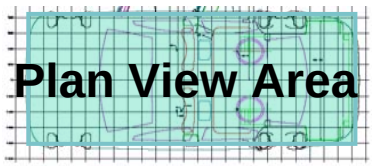


***Control mass growth to targets***

# Mass Estimation In The PreConfiguration Stage



- Type of Vehicle
- Number of Passengers
- Cargo Mass



Plan View Area

**Mass of *Nominal* Vehicle for Size and Vehicle Category**

# Vehicle Sample

2004 VW Touareg
2004 Nissan Murado
2004 Toyota Sienna
2004 Toyota Prius
2003 Toyota Camry (US)
2003 BMW 330i
2003 Infiniti G35
2003 Honda Accord
2003 Toyota Corolla Sedan
2002 Audi A4

2007
Cadillac SRX
Chevrolet HHR
Saturn Outlook
GMC Sierra Crew Cab
Chevrolet Colorado
Chevrolet Impala
Pontiac G6 SE1
Cadillac STS
GMC Yukon
Saturn Vue

2002 Honda Civic LX
2003 Honda Accord EX
2003 PT Cruiser
2003 Toyota Matrix XRS
2003 Toyota Tacoma 4x2
2004 Dodge Ram 4x4
2004 Nissan Titan LE
2004 Toyota Highlander Premium
2004 Toyota Sienna
2005 Honda Odyssey Touring
2005 Jeep Liberty
2005 Jeep Wrangler

| | |
|---|---|
| **Sedans:** | **14** |
| **SUV:** | **12** |
| **Pick Up:** | **5** |
| **Van:** | **2** |
| | **33** |

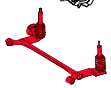
# Data for Each Vehicle

## Functional Subsystem


Body Non-Structure

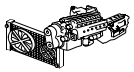

Body Structure


Front Suspension


Rear Suspension

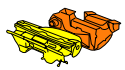

Steering


Brakes


Powertrain


Fuel and Exhaust


Wheels and tires


Air Conditioning


Electrical

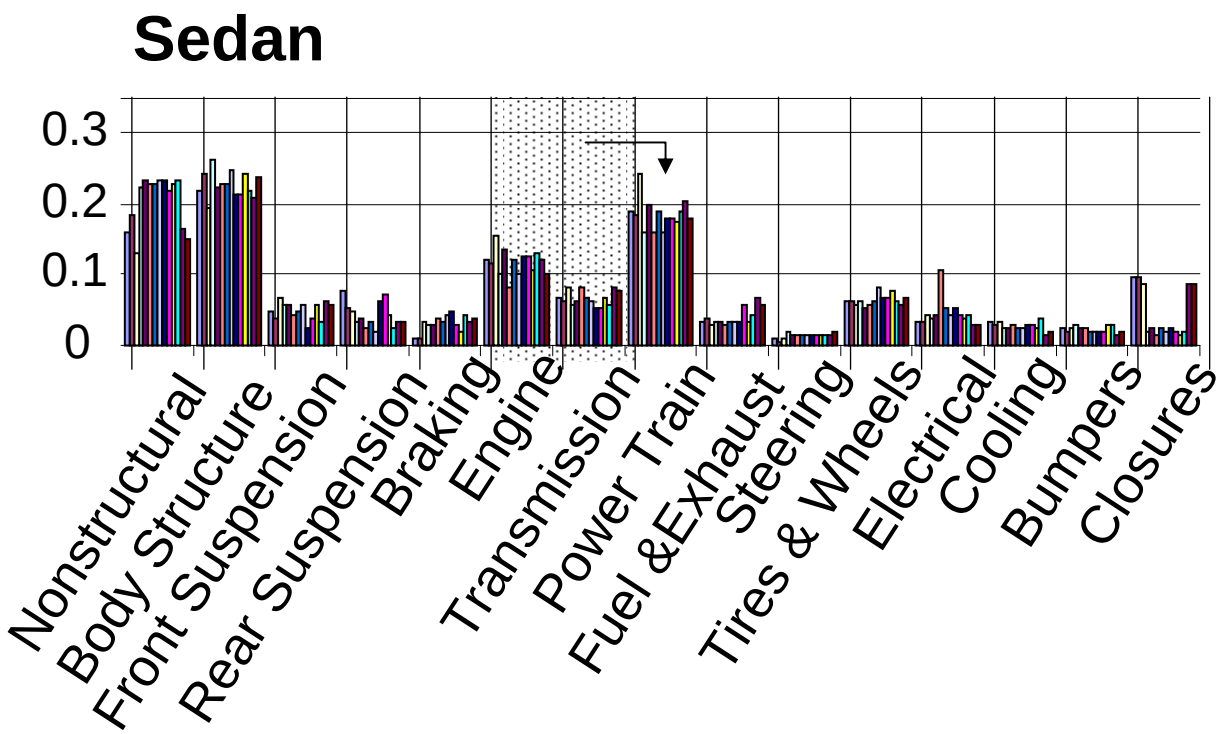

Bumpers


Closures

- **Vehicle Category**
- **Vehicle overall dimensions**
- **Curb Mass**
- **Number of Passengers**
- **Cargo Mass**
- **Gross Vehicle Mass**
- **Subsystem Mass**

# Subsystem Mass as a Fraction of Curb Mass

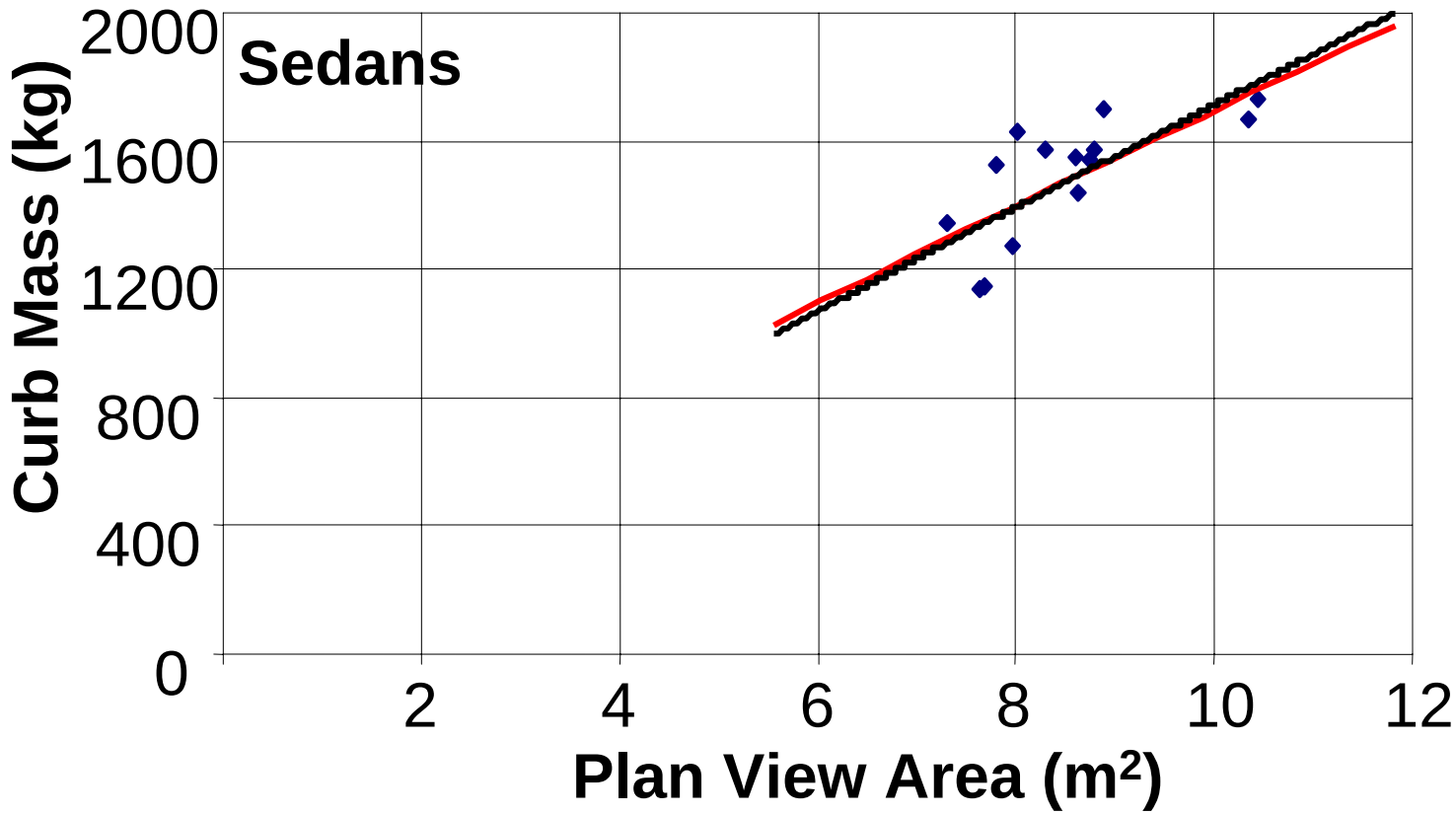
| | |
|---|---|
| Body Non-structural | 0.204 |
| Body Structure | 0.227 |
| Front Suspension | 0.049 |
| Rear Suspension | 0.044 |
| Braking | 0.032 |
| Engine | 0.118 |
| Transmission | 0.067 |
| Power Train | 0.185 |
| Fuel and Exhaust | 0.040 |
| Steering | 0.014 |
| Tires & Wheels | 0.065 |
| Electrical | 0.046 |
| Cooling | 0.027 |
| Bumpers | 0.022 |
| Closures | 0.046 |



# Curb Mass vs. Plan View Area

$$curb\ mass = 147.75(PVA) + 229.59$$

$$curb\ mass = 206.11(PVA)^{0.9212}$$



# An Example

A new vehicle is in the planning stage (*pre-configuration*).

Target Specifications

| | |
|---|---|
| **5** | passengers |
| **120 kg** | cargo capacity. |
| **1815 mm** | Vehicle width |
| **4732 mm** | length |
| **2250 Lb** | test weight class for fuel economy |

(~**885kg** curb mass)

# Step 1: Pre Configuration Mass Estimation

**For Sedans**

***Vehicle Curb Mass***

$$curb\ \ mass\ \ (kg)\ \ = 147.75\,A(m^2) + 229.59$$

$$A = (1.815\ m)(4.732\ m) = 8.59m^2$$

$$curb\ \ mass\ \ = \sim 1500kg$$ ⟺ **Target: 885kg**

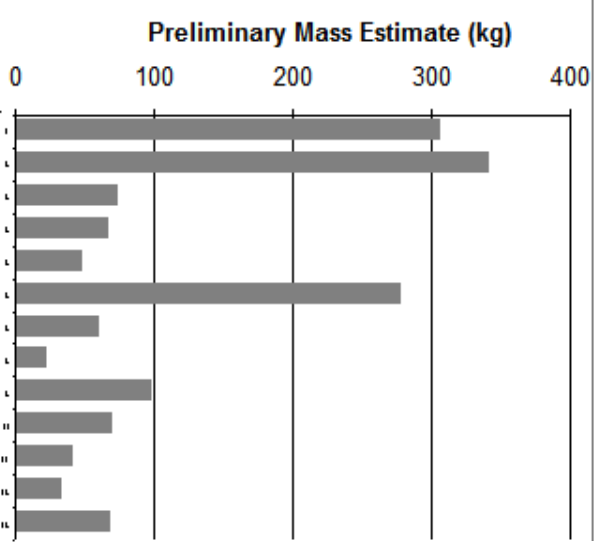
***Subsystem Mass***

$$(Body\ Non\text{-}structure\ mass) = 0.204\ (Curb\ Mass)$$

$$(Body\ Non\text{-}structure\ mass) = \sim 306\ kg$$

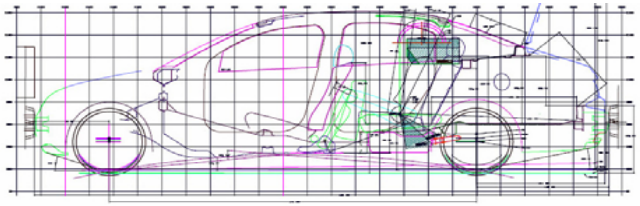
# Software Tool: Pre Configuration Mass Estimation

| | B | C | D |
|---|---|---|---|
| 1 | Select Data set: | Sedan | |
| 2 | | | |
| 3 | Subsystem | Subsystem Mass Fraction of Curb Mass | User Defined Mass (optional) | Preliminary Subsystem Mass (kg) |
| 4 | Body Non-structure | 0.204 | | 305.70 |
| 5 | Body Structure | 0.227 | | 340.17 |
| 6 | Front Suspension | 0.049 | | 73.43 |
| 7 | Rear Suspension | 0.044 | | 65.94 |
| 8 | Braking | 0.032 | | 47.95 |
| 9 | Powertrain | 0.185 | | 277.23 |
| 10 | Fuel & Exhaust | 0.040 | | 59.94 |
| 11 | Steering | 0.014 | | 20.98 |
| 12 | Tires & Wheels | 0.065 | | 97.41 |
| 13 | Electrical | 0.046 | | 68.93 |
| 14 | Cooling | 0.027 | | 40.46 |
| 15 | Bumpers | 0.022 | | 32.97 |
| 16 | Closures | 0.045 | | 67.43 |
| 17 | | | | |
| 18 | Vehicle Plan View Area (m2) | | 8.58858 | |
| 19 | Vehicle Curb Mass (kg) | | | 1498.55 |
| 20 | | | | |
| 21 | Number of Passengers | | 5 | 350.00 |
| 22 | Cargo Mass (kg) | | | 120.00 |
| 23 | | | | |
| 24 | Gross Vehicle Mass | | | 1968.55 |




***Mass of Nominal Vehicle for Size and Vehicle Category***

# Mass Estimation In The Configuration Stage



*What is mass if configuration is changed from **typical** vehicle (mass saving materials or technology)?*

**Mass of *Nominal* Vehicle**

**Subsystem Mass reductions from nominal vehicle enabled by technologies**

Mass of Vehicle resized for alternative subsystems

# Step 2: Mass Reduction Technologies
# Step 3: Sort Technologies by Cost

***For a vehicle with curb mass=1500kg, what are mass reduction technologies?***

| subsystem | mass reduction technology | mass savings |
|---|---|---|
| | | kg |
| Tire& wheel | Min. cap. wheels and tires | 20.00 |
| non structure | sound treatment opt | 19.45 |
| Braking | optimized pedal bracket | 3.00 |
| rear susp | shape optimization | 6.59 |
| body struct | joint improvements | 15.00 |
| closures | hardware: bar stock | 10.00 |
| front susp | shape optimization | 7.34 |
| body struct | AHSS optimization | 70.00 |
| non structure | reduce glass thickness | 5.00 |
| non structure | IP substrate optimization | 21.43 |
| Braking | tubular pedals | 4.00 |
| non structure | seat frame shape optimization | |
| closures | AHSS optimization | |
| Fuel&Exhaust | lower gage of exhaust | |

***Include all technologies with marginal cost ≤0.1***

# Primary Mass Reduction

| Subsystem | Mass reduction |
|---|---|
| Non Structure | 100.88kg |
| Body Structure | 85.00 |
| Front Suspension | 7.34 |
| Rear Suspension | 6.59 |
| Braking | 7.00 |
| Powertrain | 27.72 |
| Fuel and exhaust | 5.99 |
| Steering | 2.00 |
| Tire & Wheels | 20.00 |
| Bumper | 4.95 |
| Closures | 22.46 |
| | 289.93kg |

*This configuration of technologies provides a primary mass reduction total of ~290kg.*

| | |
|---|---|
| Curb Mass from Pre-Configuration= | 1500 |
| Primary Mass Savings from alternative configurations | -290 |
| | 1210 |

**Target: 885**

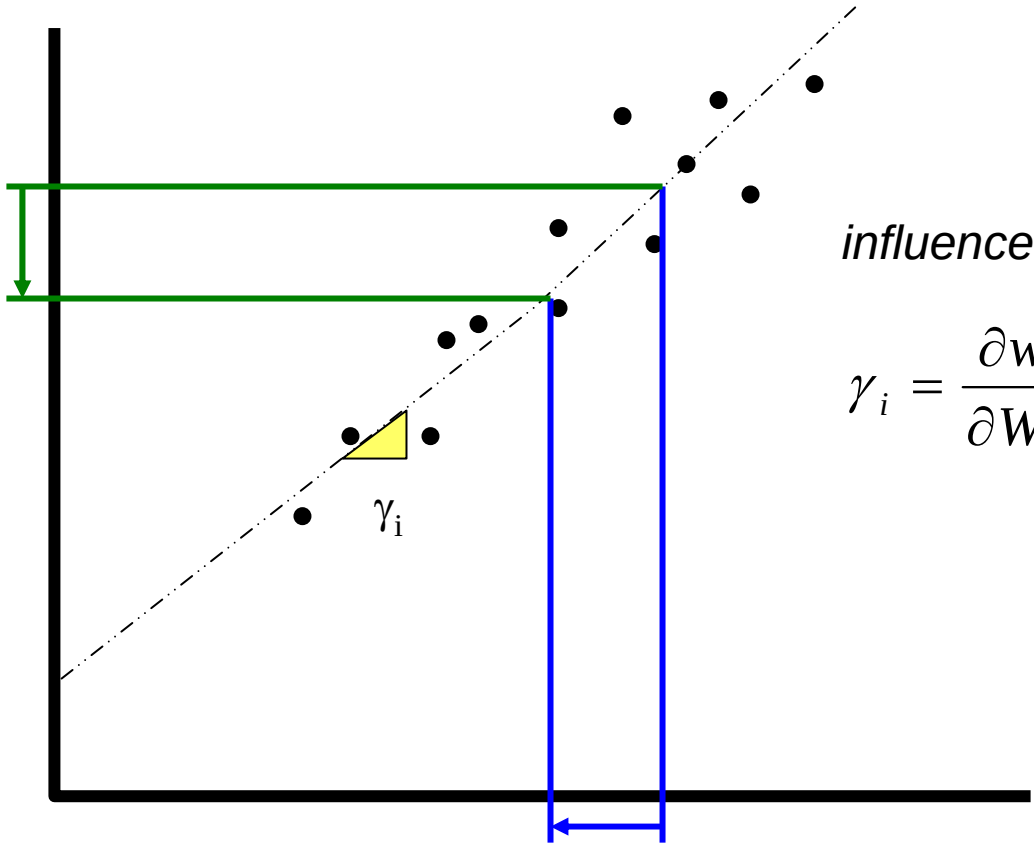
# Mass Compounding

**An unplanned mass increase in a component during vehicle design has a ripple effect throughout the vehicle;**

**other components need to be resized increasing vehicle mass even more.**

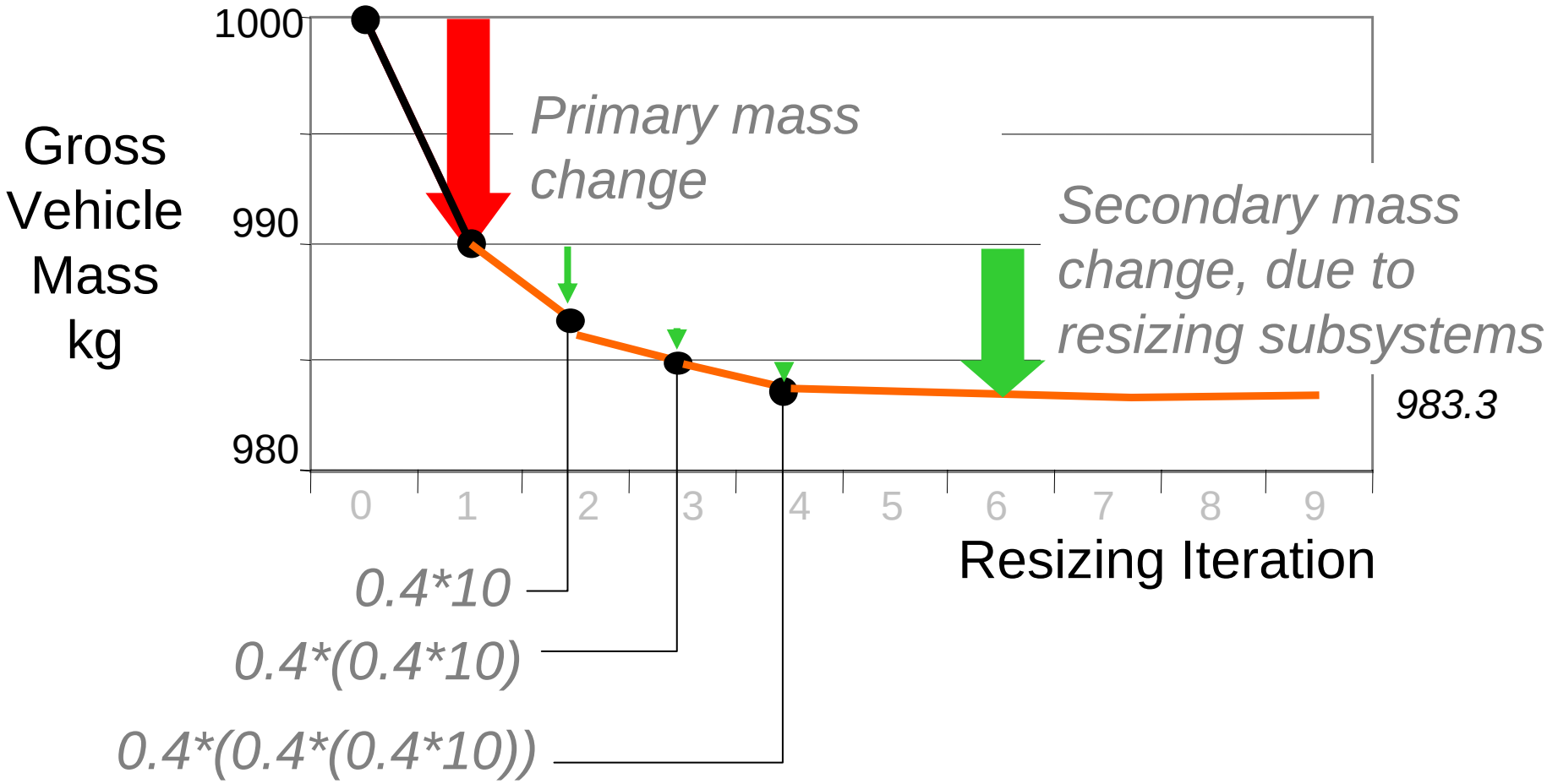
***mass begets mass***

# Subsystem Mass Influence Coefficient



# Example of Mass Compounding

- *1000 kg GVM*
- *10 kg of initial mass change*
- *vehicle mass influence coefficient = 0.4*



# Mass Compounding Formula

**Compounded Vehicle Mass**

Initial Vehicle Mass

Mass Change (primary)

Mass Change from resizing (secondary)

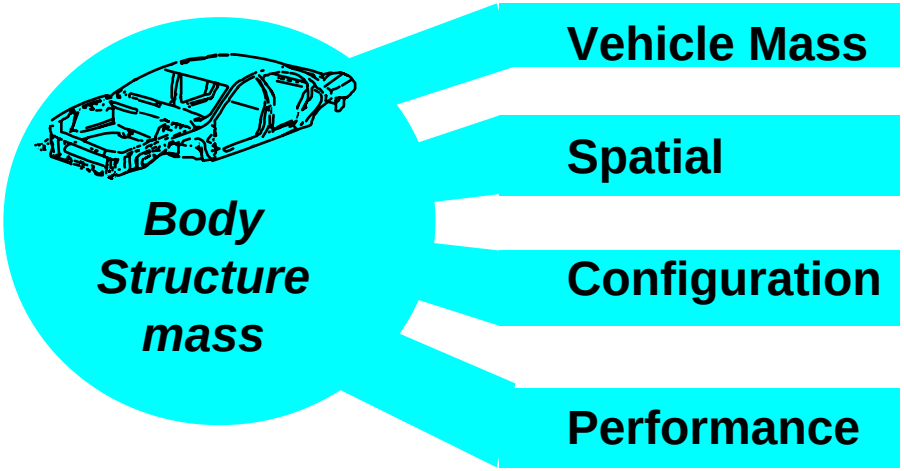
$$W_{V\infty} = W_0 + \Delta + \Delta\Gamma_V$$

$$\Gamma_V = \left[\frac{\gamma_V}{(1-\gamma_V)}\right]$$

$$\gamma_V = \sum_{i=1}^{n} \gamma_i$$

Vehicle influence coefficient is sum of subsystem influence coefficients

# Modeling Subsystem Mass Dependency




- ● *strong dependence*
- ○ *moderate dependence*

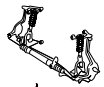
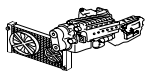
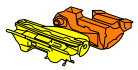
- *BFI, BOF*
- *refinement level*

*subsystem mass = f (gross vehicle mass, vehicle area, configuration, performance)*

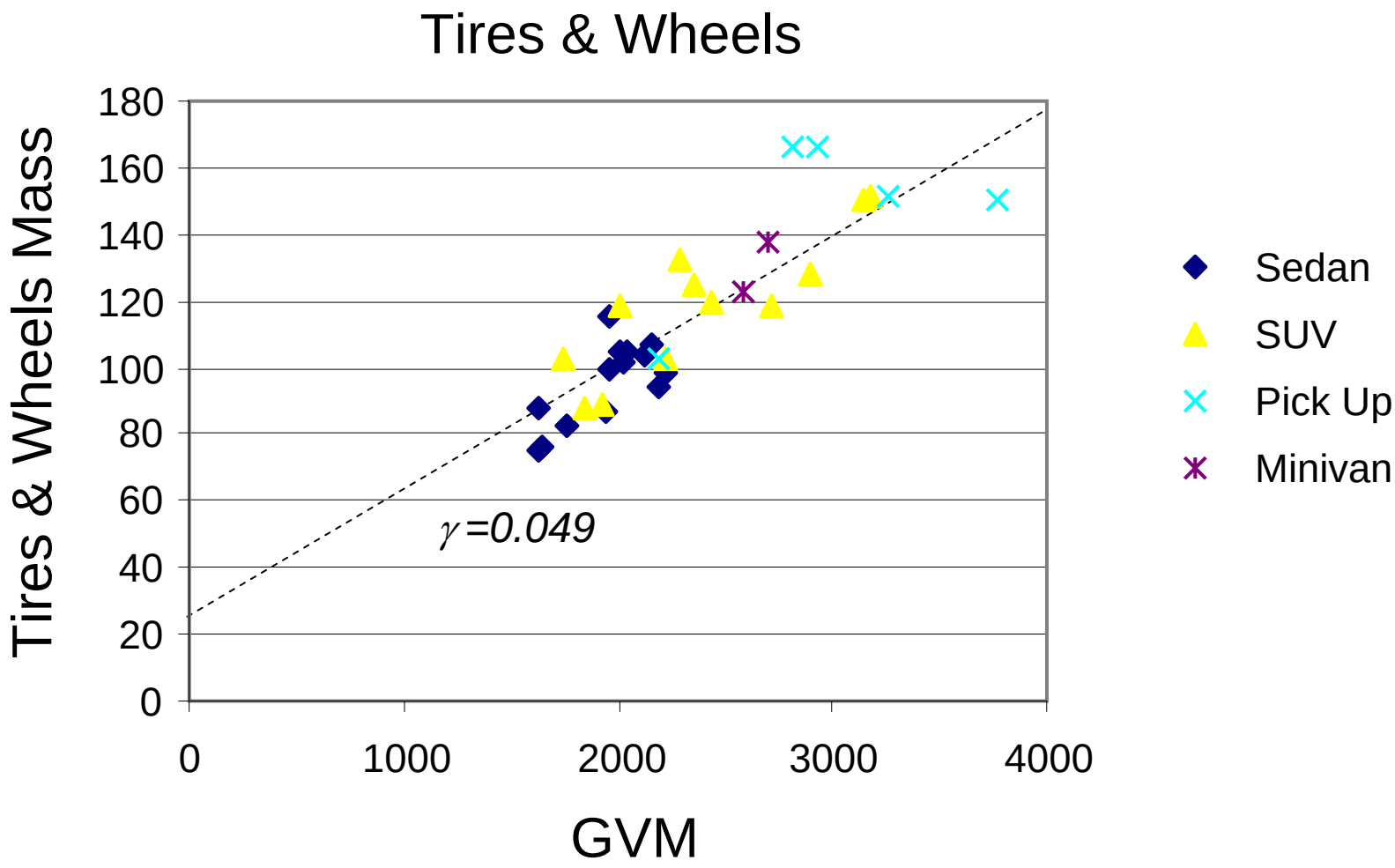
***Reduced linear model***

$$subsystem\ mass = C_0 + C_1(gross\ vehicle\ mass) + \varepsilon$$

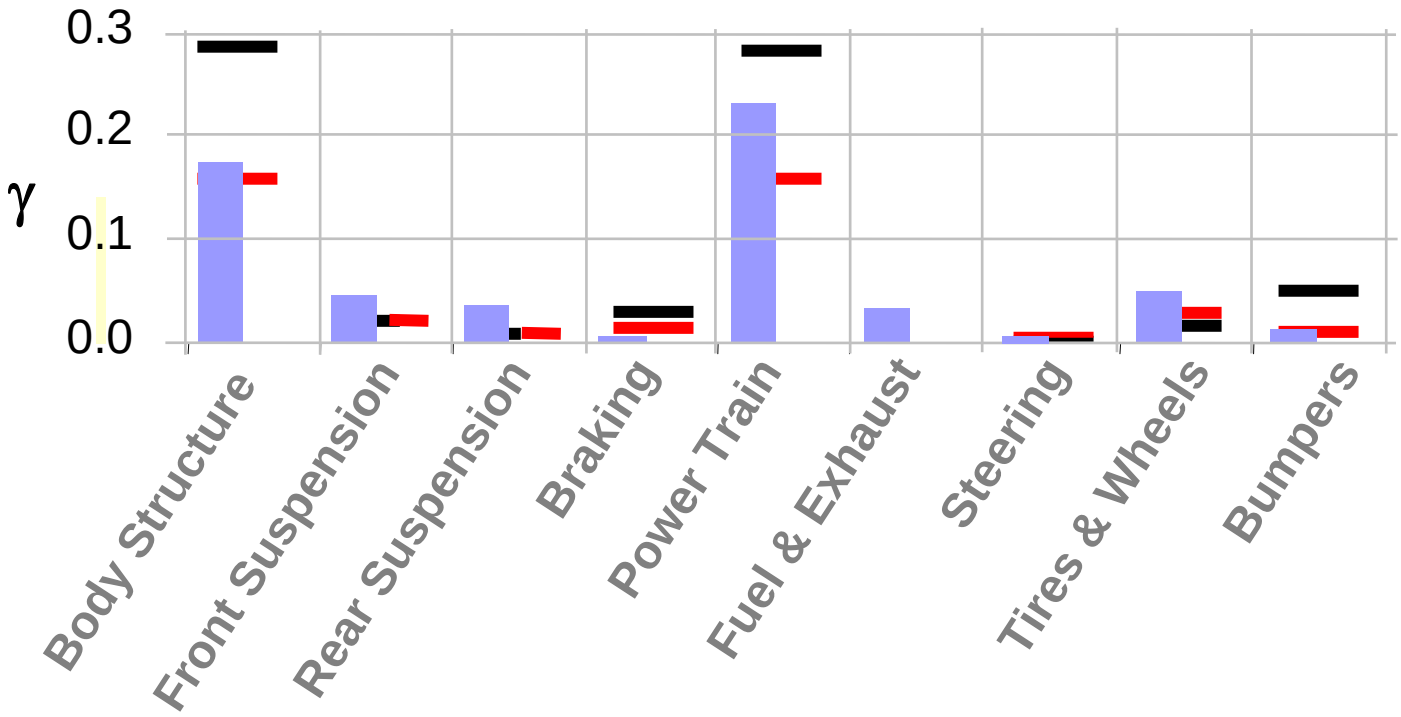
# Subsystem Mass Dependency

| Functional Subsystem | Vehicle Mass | Spatial (veh.vol, area) | Config. | Performance Level |
|---|---|---|---|---|
|  Body Non-Structure | ○ | ● | | •refinement level |
|  Body Structure | ● | ◎ | •BFI, BOF | •safety star rating |
|  Front Suspension | ● | ○ | •Strut, SLA | •handling / isolation level |
|  Rear Suspension | ● | ○ | •Ind, etc. | •handling / isolation level |
|  Steering | ◎ | ○ | •Mech, Rack | |
|  Brakes | ◎ | ○ | | |
|  Powertrain | ● | ○ | •FW, RW, AW<br>•Long, Trans. | •acceleration level<br>•fuel economy level<br>•range |
|  Fuel and Exhaust | ◎ | ○ | | •noise level |
|  Wheels and tires | ● | ○ | | •styling level |
|  Air Conditioning | ○ | ● | | •time-to-cool |
|  Electrical | ○ | ◎ | | •option loading level |
|  Bumpers | ● | ◎ | | •low speed impact level |
|  Closures | ○ | ● | | |

# Subsystem Mass vs. GVM



# Influence Coefficient Summary




All Vehicles category

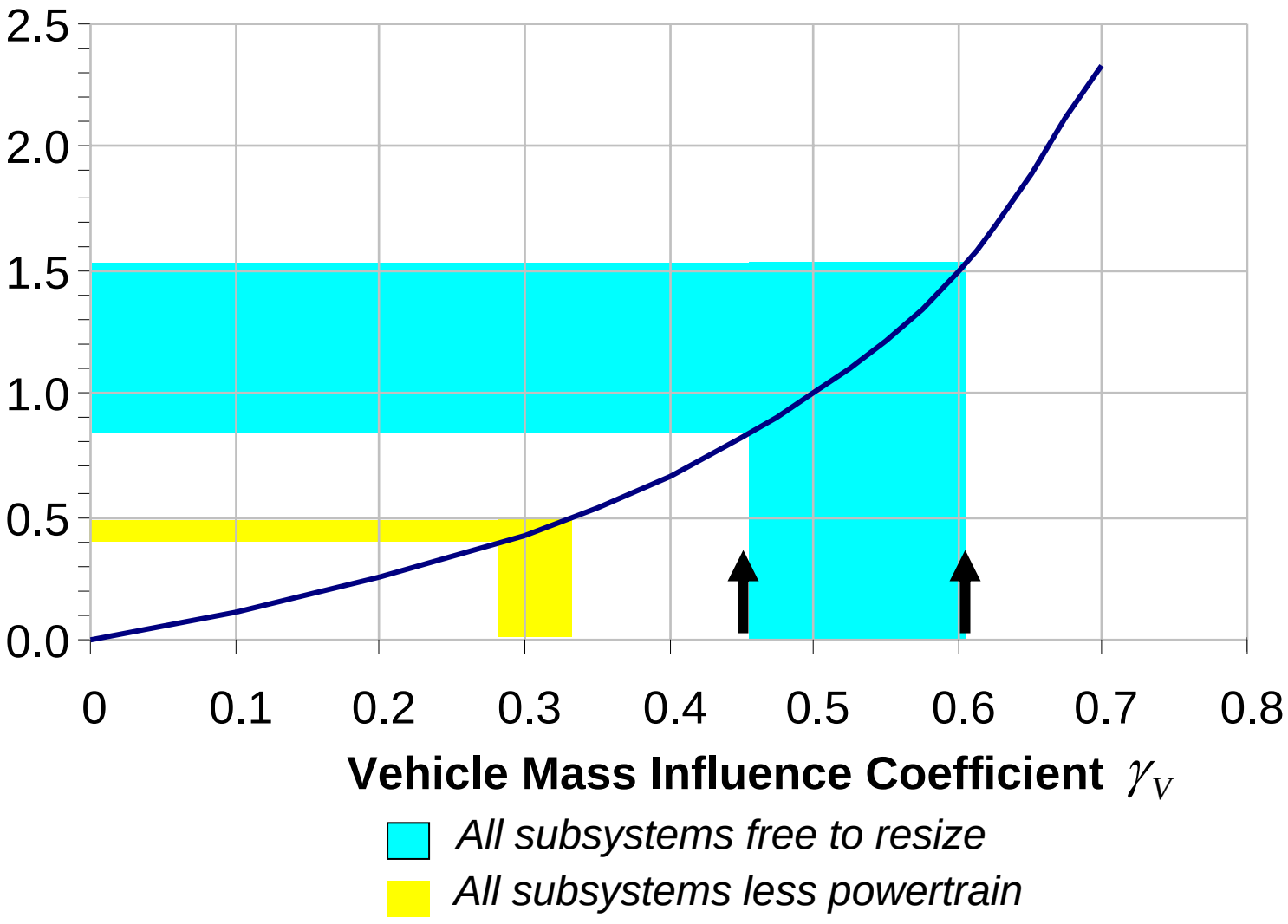
1975 Study

1981 Study

# Secondary Mass Savings

***Secondary Mass Savings per unit primary change***

$$\left(\Gamma_V = \frac{\gamma_V}{1-\gamma_V}\right)$$



# Step 4: Estimate Vehicle Mass Using Mass Compounding

*Primary mass savings* $\Delta = 290kg$

*Secondary mass savings* = $\Delta\left[\frac{\gamma_V}{(1-\gamma_V)}\right]$

*Taking a nominal value for the vehicle influence coefficient;* $\gamma_V = 0.53$

$$\left[\frac{\gamma_V}{(1-\gamma_V)}\right] = 1.128$$

*for a secondary mass savings = (1.128) 290kg = 327kg*

| | | |
|---|---|---|
| *Curb Mass from Pre-Configuration* | = | *1500* |
| *Primary Mass Savings from alternative configurations* | | *-290* |
| *Secondary Mass Savings from resizing to new GVM* | | *-327* |
| | | *883* |

***Target: 885kg***

# Software Tool: Mass Compounding

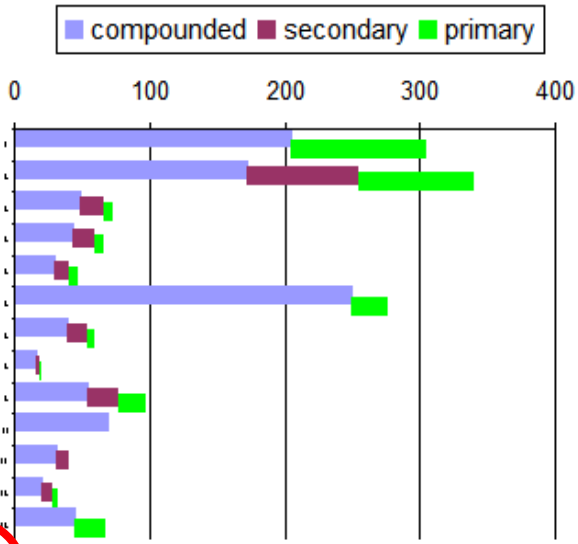
*Resize all subsystems with GVM dependency*

| | A | B | C | D |
|---|---|---|---|---|
| 1 | Select data set: | Ratio | | |
| 2 | | | | |
| 3 | Subsystem | Influence Coefficient | resize sub-system ? | Pre-Config. Subsystem Mass (kg) |
| 4 | Body Non-structure | 0.000 | | 305.70 |
| 5 | Body Structure | 0.173 | ☑ | 340.17 |
| 6 | Front Suspension | 0.037 | ☑ | 73.43 |
| 7 | Rear Suspension | 0.033 | ☑ | 65.94 |
| 8 | Braking | 0.024 | ☑ | 47.95 |
| 9 | Powertrain | 0.141 | ☑ | 277.23 |
| 10 | Fuel & Exhaust | 0.030 | ☑ | 59.94 |
| 11 | Steering | 0.006 | ☑ | 20.98 |
| 12 | Tires & Wheels | 0.049 | ☑ | 97.41 |
| 13 | Electrical | 0.000 | | 68.93 |
| 14 | Cooling | 0.021 | ☑ | 40.46 |
| 15 | Bumpers | 0.017 | ☑ | 32.97 |
| 16 | Closures | 0.000 | | 67.43 |
| 17 | *Sum Inf. Coeff* | 0.532 | | |
| 18 | Vehicle Curb Mass | | | **1498.55** |
| 19 | | | | |
| 20 | Passenger Mass | | | 350.00 |
| 21 | Cargo Mass | | | 120.00 |
| 22 | | | | |
| 23 | Gross Vehicle Mass | | | **1968.55** |
| 24 | | | | |
| 25 | Delta Mass from Pre-Config. | | | |

# Software Tool: Mass Compounding

*What is effect if Powertrain cannot be resized?*

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | Select data set: | Ratio | | | | |
| 2 | | | | | | |
| 3 | Subsystem | Influence Coefficient | resize sub-system ? | Pre-Config. Subsystem Mass (kg) | Adjustments to Pre-Config. Mass | Compounded Subsystem Mass (kg) |
| 4 | Body Non-structure | 0.000 | | 305.70 | -100.88 | 204.82 |
| 5 | Body Structure | 0.173 | ☑ | 340.17 | -85.00 | 172.88 |
| 6 | Front Suspension | 0.037 | ☑ | 73.43 | -7.34 | 48.33 |
| 7 | Rear Suspension | 0.033 | ☑ | 65.94 | -6.59 | 43.40 |
| 8 | Braking | 0.024 | ☑ | 47.95 | -7.00 | 29.35 |
| 9 | Powertrain | 0.000 | ☐ | 277.23 | -27.72 | 249.51 |
| 10 | Fuel & Exhaust | 0.030 | ☑ | 59.94 | -5.99 | 39.45 |
| 11 | Steering | 0.006 | ☑ | 20.98 | -2.00 | 16.12 |
| 12 | Tires & Wheels | 0.049 | ☑ | 97.41 | -20.00 | 53.84 |
| 13 | Electrical | 0.000 | | 68.93 | | 68.93 |
| 14 | Cooling | 0.021 | ☑ | 40.46 | | 30.67 |
| 15 | Bumpers | 0.017 | ☑ | 32.97 | -4.95 | 20.05 |
| 16 | Closures | 0.000 | | 67.43 | -22.46 | 44.97 |
| 17 | *Sum Inf. Coeff* | 0.391 | | | | |
| 18 | **Vehicle Curb Mass** | | | **1498.55** | | **1022.32** |
| 19 | | | | | | |
| 20 | **Passenger Mass** | | | 350.00 | | 350.00 |
| 21 | **Cargo Mass** | | | 120.00 | | 120.00 |
| 22 | | | | | | |
| 23 | **Gross Vehicle Mass** | | | **1968.55** | | **1492.32** |



# Mass Estimation In Preliminary Vehicle Design

- ***Rational approach to preliminary mass allocation***
- ***Effects of mass reduction technologies taken into account***
- ***Based on contemporary vehicles***
- ***Estimation requires only sparse data available***
- ***Adequate precision for decision making***
- ***Fast***

CD available from AISI with Spreadsheet and technical report

# Acknowledgments

•**Work sponsored by**

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•**Contributions**

*Kundan Reddy, UM Masters Candidate*

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