User Guide

for

Design Advisor

Version 4

By

Donald E Malen
Department of Integrative Systems + Design
University of Michigan
Ann Arbor, MI

April 16, 2013

Prepared for

WorldAutoSteel

World Steel Association
Rue Colonel Bourg, 120
B-1140 Brussels
Belgium

Executive Summary

Making a material selection decision for an automotive component is complicated by several factors. First, it is generally recognized that such decisions should be based on the effect on the overall vehicle system rather than considering *only* effects of the component. Second, the decision criteria (what determines 'best') are multiple attributes. These attributes address such questions as: How is the vehicle system mass affected by the material selected: How is the vehicle system cost impacted: How will fuel economy be impacted? How will environmental stressors be impacted over the life cycle of the vehicle system? Since these criteria are not easily combined as a single objective number, the decision maker must be presented with several attributes (mass, cost, greenhouse gas) so any trade-offs between attributes may be recognized.

The objective of the *Design Advisor* software is to provide the decision-maker with a tool to evaluate these component material selection decisions at a vehicle system level, and using multiple attributes of vehicle mass, cost, and life cycle stress on the environment. Because these material selection decisions are often made very early in the vehicle design cycle, the *Design Advisor* is configured to operate in that context. First, only information which would be available during the vehicle planning stage is required as input. Second, to support quick decision making during meetings, Microsoft Excel was the chosen application because of its wide availability on laptops. Third, the interface is intended to be intuitive and visual as the assumed decision maker may be other than an analyst. Finally, because of the approximate nature of input data, a sensitivity analysis is included to allow varying the input values to evaluate the robustness of the estimates.

Primary updates for Version 4 (version shown in brackets after each item) include:

1) Functional and usability changes in response to comments from members and other users [version 4.0]
2) Updating mass influence coefficients with new data from EDAG [version 4.1]
3) Updating energy demand and Fuel Reduction Values for the corrected US schedule from fka [v4.1]
4) Updating benchmark charts with new data from EDAG [version 4.1]
5) Updating benchmark equations from EDAG [version 4.1]
6) Updating material list in Bill of Materials consistent with UCSB v4 [version 4.1]
7) Change material production GHG to include prompt scrap recycling consistent with UCSB v4 [v4.1]
8) Changing any parameters to be consistent with UCSB v4 [version 4.1]

Acknowledgements

The mathematical models used in the Design Advisor draw from several projects supported the American Iron and Steel Institute, the Auto-steel partnership, WorldAutoSteel, and USAMP.

Special thanks to Jody Shaw of United States Steel Corporation for spearheading and supporting the Design Advisor development work. Thanks also to George Coates and Russ Balzer of Phoenix Group, Kate Hickey of WorldAutoSteel, and Roland Geyer of UCSB in providing data and insight into the GHG model.

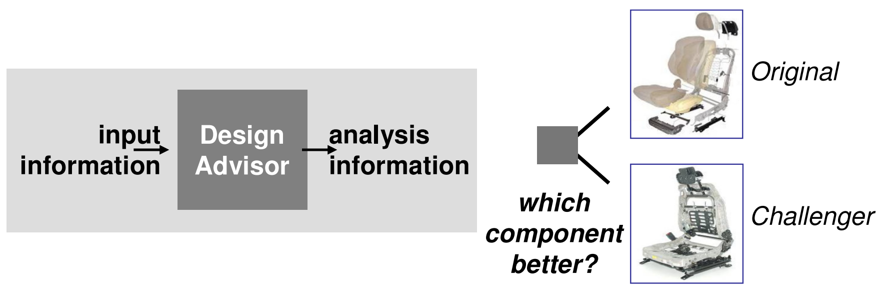
Several University of Michigan graduate students in Interdisciplinary Degree Programs have made significant contributions to the Design Advisor as part of their Capstone Projects. These include Yijun Zheng, Wooyoung Shin, Nicholas Capicotto, Faisal Shaikh, Chengtao Ye, and Charn Phenjati.

Table of Contents

1- Introduction

Making a material selection decision for an automotive component is complicated by several factors. First, it is generally recognized that such decisions should be based on the effect on the overall vehicle system rather than considering *only* how the component is affected. Second, the decision is based on multiple attributes. These attributes include such questions as: How is the vehicle system mass affected by the material selected; How is the vehicle system cost impacted; How will environmental stressors be impacted over the life cycle of the vehicle system? Often these attributes point to a differ preference and the decision maker must understand any tread-offs between attributes

This user guide describes a software tool called the *Design Advisor*. The purpose of the *Design Advisor* is to provide rapid, quantitative evaluation for a material selection decision for two alternative components. This evaluation is done at a vehicle system level, and considers mass, cost, and life cycle greenhouse gas.



Example selection context for Design Advisor

1.1 Description of the model- In the *Design Advisor*, the user is stepped through the process of building two vehicles; a nominal vehicle with the original component, and a resized vehicle with the competitor component. The performance of these two vehicles is then compared using several metrics.

Before describing the model, a few definitions are needed.

Component –The assembly under study.
Part–The part within the component whose material is varied. This may be a weldment of several pieces. The part is the primary focus of the analysis.

Original component/part–The component of the original material and design concept.
Competitor component/part –An alternative to the original. The decision on whether to use the original or competitor component is being made.

Nominal vehicle – The vehicle as defined by the user and having the original component.
Resized vehicle – The nominal vehicle with the competitor component substituted for the original component, and with subsystems resized due to differences in mass between the original and competitor components.

Primary changes –Changes in mass/cost/CO_2 between the original and competitor *components.*
Subsystem resizing changes –Changes in mass/cost/CO_2 between the nominal vehicle with original component and the resized vehicle with the competitor component. These are also called Secondary changes.

The overall calculation method is a five step sequence.

Step 1a—Define a nominal vehicle with the original component. A nominal vehicle is defined based on vehicle type (Sedan/Hatchback or SUV), the foot print area, the powertrain type, and the number of passengers and cargo. Based on benchmark data, vehicle mass and subsystem mass are determined for a typical vehicle of that size and class.

Step 1b- A powertrain is sized for the nominal vehicle by specifying fuel consumption, fuel type, driving schedule, and life time range.

Step 2a- The original and competitor component technology is input. This includes mass for the component and part, the part material, and the shaping process. It is assumed this information is available from a previous study of the component design concepts.

Step 2b- The component is scaled to fit in this nominal vehicle. Benchmark data is used to scale the component mass from the original study to the specific nominal vehicle. The user may choose to use scaling or to leave the component mass as originally input. A graph comparing the part mass to mass for other benchmark vehicles is also provided in this step.

Step 3- The nominal vehicle is resized by substituting the competitor component for the original. This substitution will require other vehicle systems to be resized in response to the mass difference in the original and competitor components. Secondary mass change is the primary tool used in this step. The user may choose the method for secondary mass change, and which subsystems are free to be resized.

At this point, two vehicles have been defined allowing a comparison at the vehicle system level.

Step 4- Several metrics are calculated and compared for the two vehicles. These are:

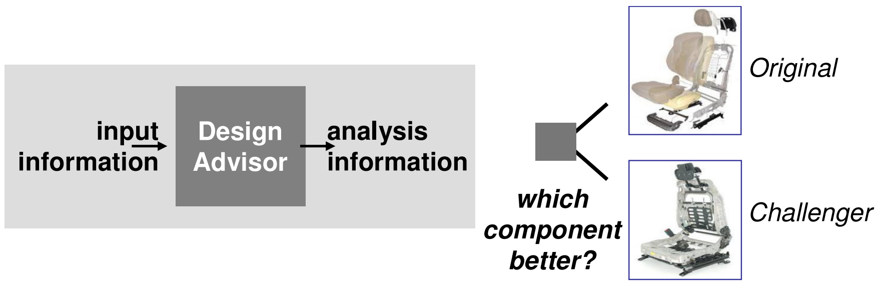
1. Mass change (primary and subsystem resizing)
2. Cost change (primary and subsystem resizing)
3. Changes in fuel use and greenhouse gas
    - Material production greenhouse gas
    - Use Phase greenhouse gas
    - Recycling greenhouse gas credit
    - Life cycle total greenhouse gas
    - Fuel consumption
    - Life time fuel use
    - Life time fuel cost

Because much of the information used in these calculations is approximate, a final step is provided:

Step 5- A sensitivity analysis of how the metrics change in response to small changes in several parameters.

2- Quick Start Application Example

As a sample application of the *Design Advisor*, consider a decision to use either a Steel driver's seat frame or a lighter mass magnesium seat frame. As is often the case in vehicle design, the decision must be made before complete information is available for the vehicle or the seat frames.



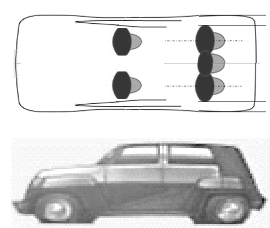
Context for use of Design Advisor

The available input information for this case study is shown below.

Component: Seat Frame

Original Component	**Competitor Component**
Steel	Magnesium,
Stamped	High pressure die cast
17 kg total seat mass	*13 kg* total seat mass
10 kg frame mass	*6 kg* frame mass

Vehicle Parameters

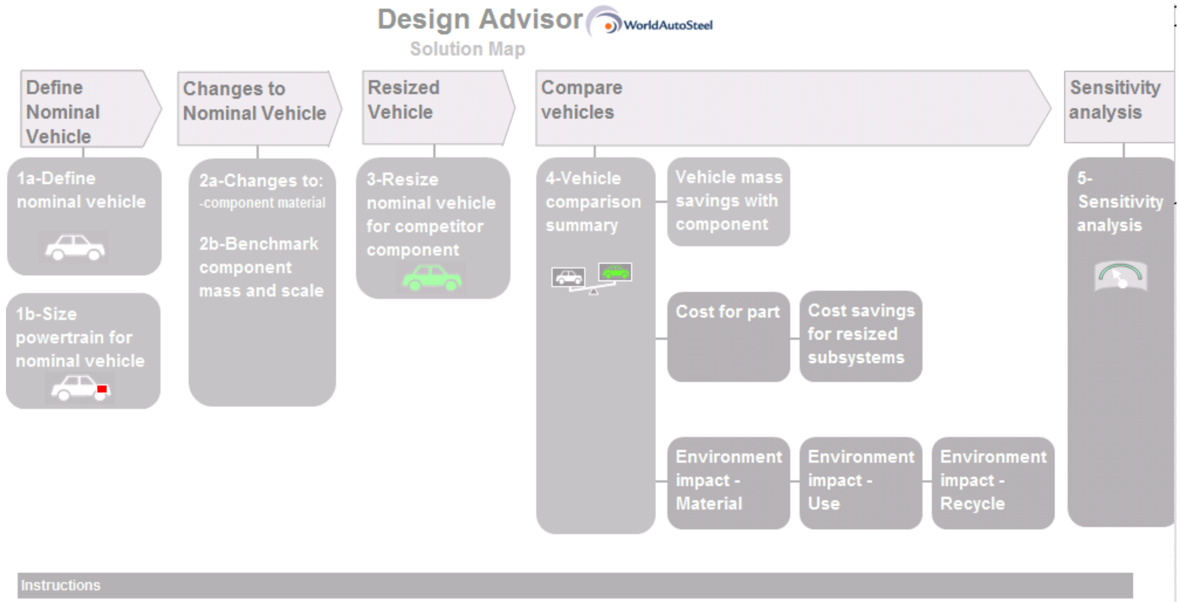


Sedan/Hatchback
5 passenger
100 kg cargo
OAL=*4.7 m*
OAW=*1.8 m*
New architecture
Internal Combustion-gasoline
Powertrain is fixed and will not change
6.8 liter/100 km (HYZEM schedule)
Life time range =*155,000 km*

Input information for example application

In subsequent sections, the *Design Advisor* will be used to estimate the mass, cost, and greenhouse gas impacts on the vehicle system.

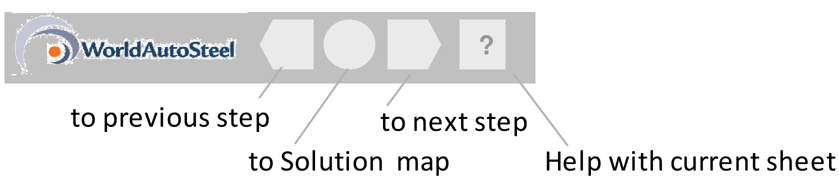
Solution Map for navigating through the Design Advisor- The first sheet of the *Design Advisor* is the *Solution Map*. This map shows the sequence of solution steps to be followed to arrive at the final results. The analysis is ordered by moving from left to right through all steps in numerical order.



Sheet: Solution Map

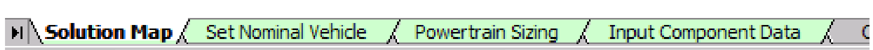
The user can use the *Solution Map* sheet to move through building process from left to right by clicking on the icons, inputting data, then using the 'Back to Solution Map' button found on each sheet.

An alternative method for navigation is to use the buttons found on each sheet in the upper right corner.



Navigation buttons

A final alternative is to use the sheet tabs at the bottom of the screen moving from left to right.

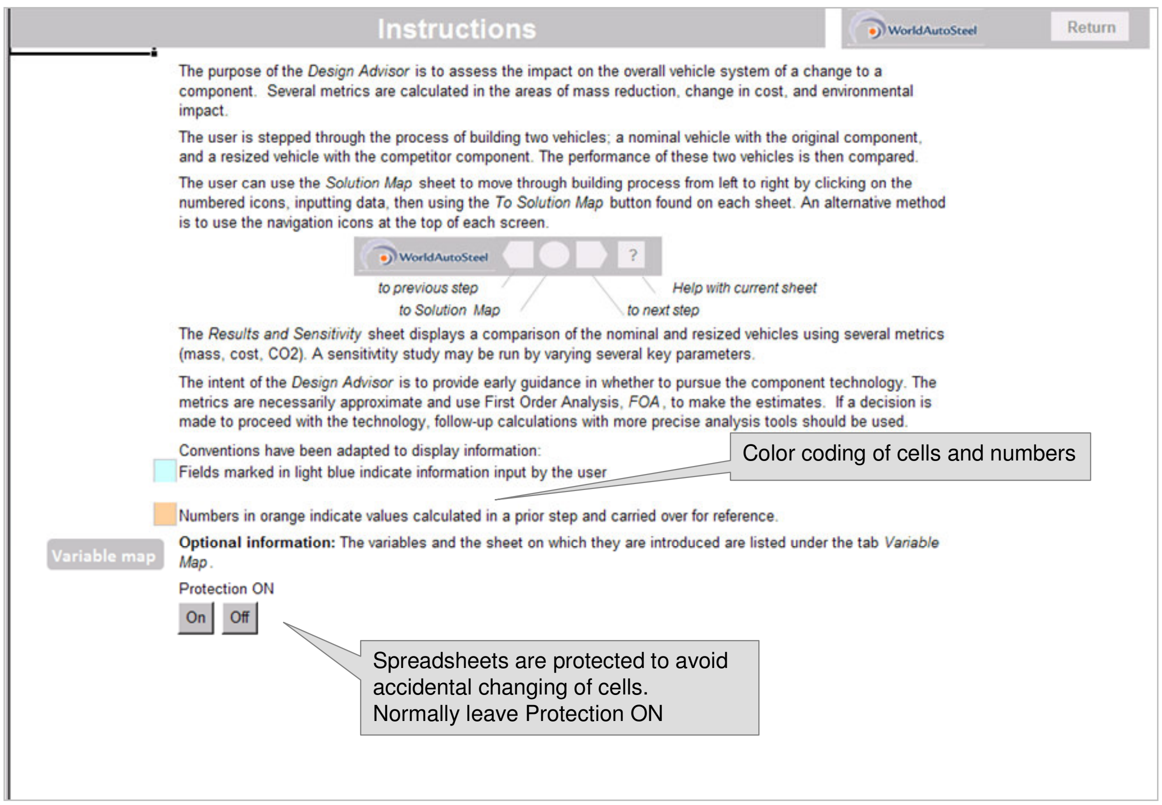


Sheet tabs

Conventions have been adapted to display information:

- Fields in ***light blue*** indicate information to be input by the user. In some cases, drop-down lists, check boxes, and slider bars are also provided for data input.
- Fields marked in ***orange*** indicate values calculated in that sheet or in a prior sheet. Pre-loaded parameter values are also shown in orange.
- On any sheet, by scrolling down, the pre-loaded parameter values may be found, there are also listed in the Appendix. With normal use, these parameters are not changed and there is no need to view this information.

These instructions are summarized on the *Instructions* sheet accessed from the *Solution Map*, bottom bar. Note also at the bottom of the *Instructions* sheet, the cell protection may be turned off. This allows selecting and changing any cell in the workbook. Under normal use, the protection should be *On to* prevent accidentally overwriting a formula.



Sheet: Instructions

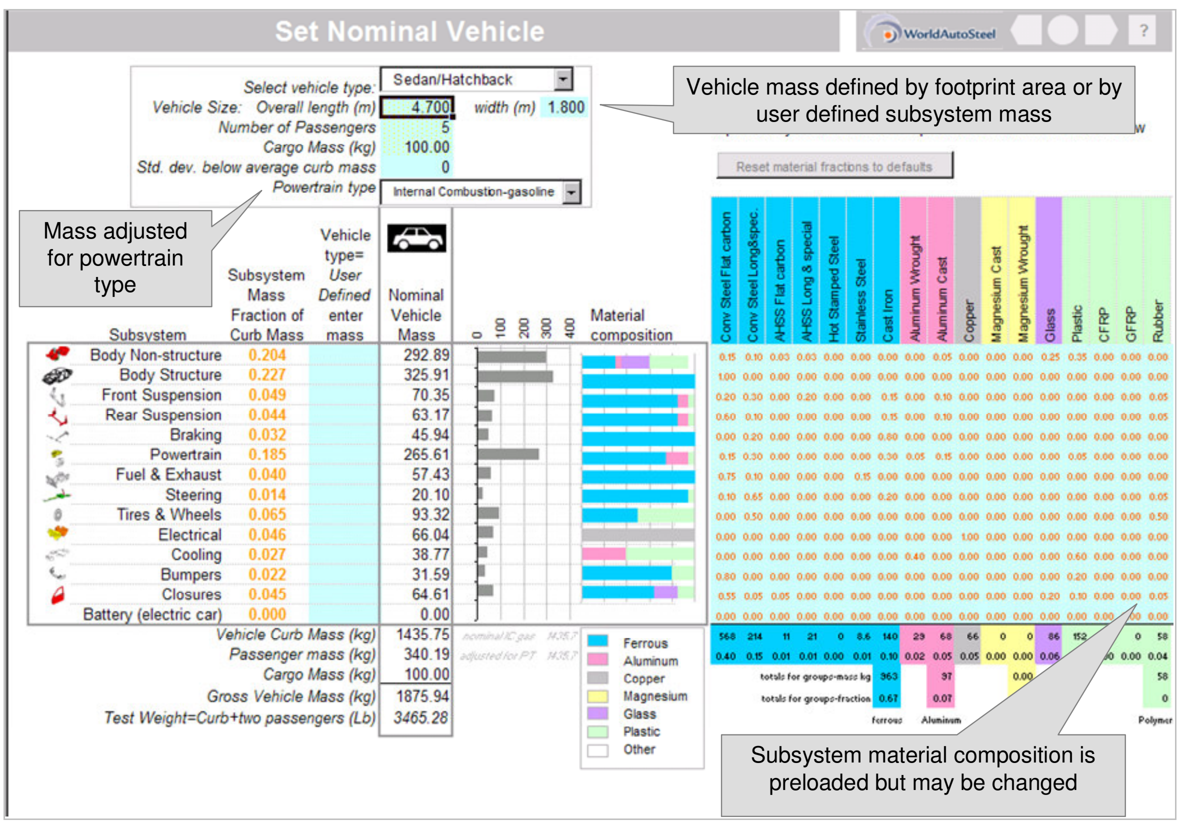
We will now step through the Seat Frame case study. Refer to the illustration at the beginning of Section 2 for the input information.

Step 1a: Create nominal vehicle- The user now defines the nominal vehicle on which to 'install' the original component. Selecting the left icon on the *Solution Map*, 'Define nominal vehicle', the user is taken to the sheet shown below.

Here the user identifies the vehicle type and size using length and width. The number of passengers and cargo mass are also input. A powertrain type is selected *(internal combustion-gasoline, internal combustion-diesel, parallel hybrid, fuel cell, plug-in electric, or battery electric)*. Based on these inputs, the mass for vehicle curb condition, for GVM, and for each subsystem are estimated. These estimates are for a nominal vehicle. If the user desires a lighter-than-average vehicle, the number of standard deviations below the nominal value may be entered.

To the right of this sheet is a large matrix—the vehicle Bill of Materials (BOM). This matrix indicates the material content for each subsystem. The default BOM represents a typical contemporary vehicle. This matrix may be altered by the user.

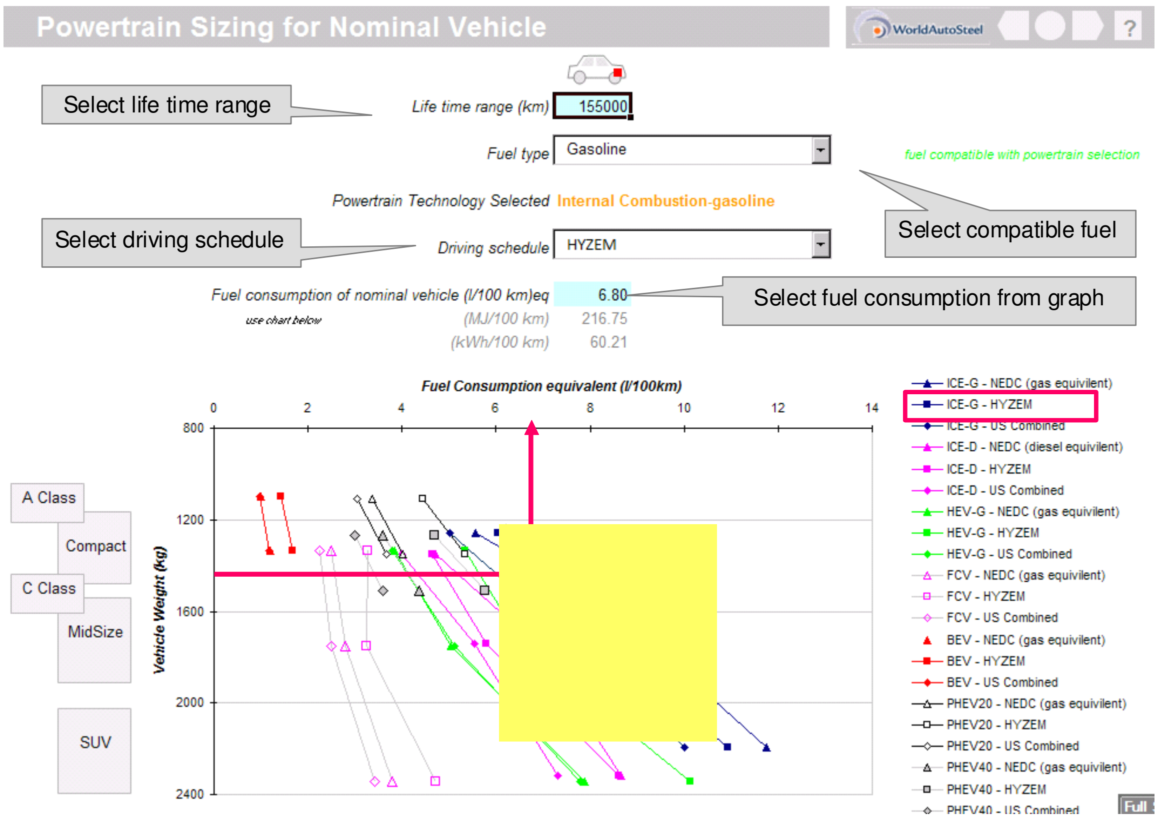
In the upper right corner of each sheet is a link back to the *Solution Map* (circle), a right facing arrow for the next step, a left facing arrow to go back to the previous step, or a question mark for help with this sheet.



Sheet: Set Nominal Vehicle

Step 1b: Size powertrain for nominal vehicle- As the final step in setting the nominal vehicle, the user sizes the powertrain. On this sheet the user enters life-time range, the fuel type consistent with the selected powertrain *(gasoline, diesel, E85, hydrogen, biodiesel, electricity)*, the driving schedule *(NEDC, HYZEM, US Combined)*, and the fuel consumption.

Results of simulations for the vehicle types, powertrain combinations and driving schedules have been loaded as parameters [5, 6, 7]. A chart of fuel consumption vs. vehicle mass is provided to select the appropriate fuel consumption consistent with this simulation data. Note that in these simulations vehicle mass is associated with a specific vehicle type (A & C class, Compact, Midsize, SUV). Front area, drag coefficient, and gradability are consistent with the vehicle type. For this example, note how the calculated vehicle mass (yellow dot on graph below) falls on the curve for Internal Combustion-gasoline, HYZEM schedule.



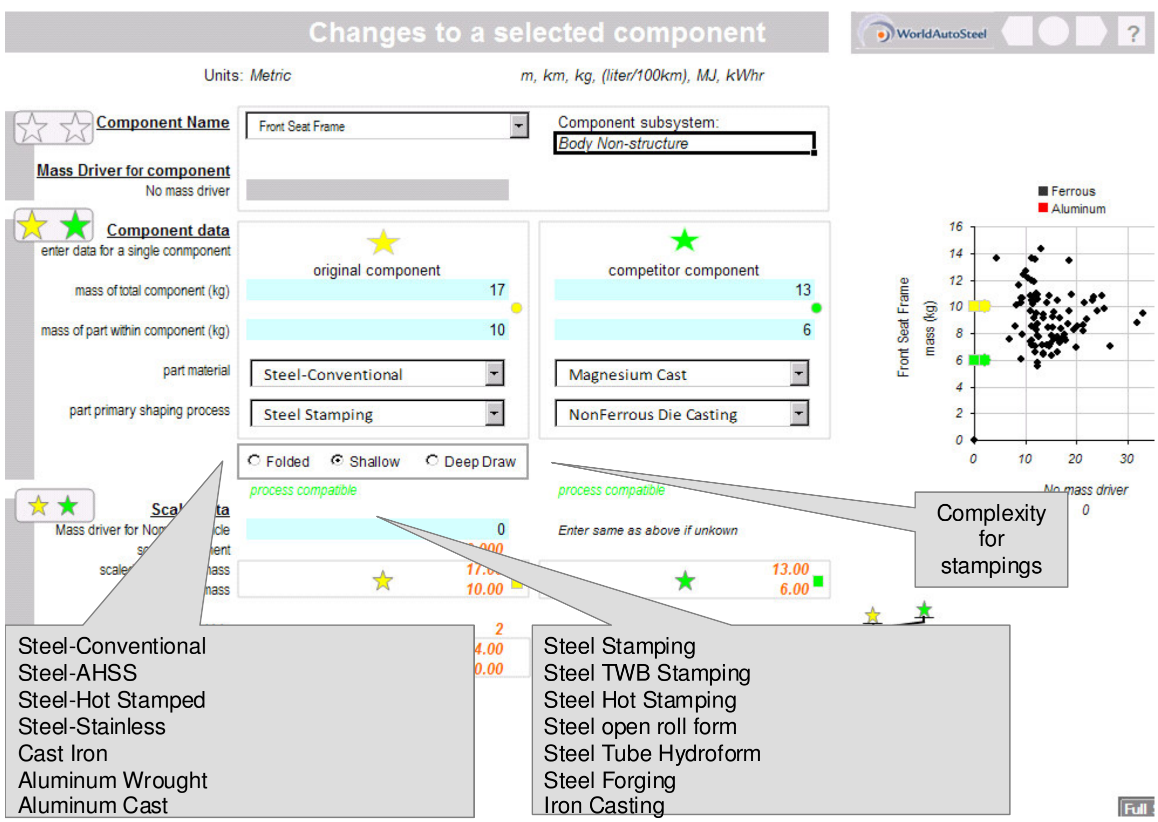
Sheet: Powertrain Sizing

Step 2a: Input component data for original and competitor component- The primary input data for the *Design Advisor* is a description of the original and competitor components. This required data includes component mass, mass of the part of interest within the component, the value of any mass drivers for this component, part material and primary shaping process. This set of data is required for both the original and the competitor design concepts.

In the screen print below, the user has navigated using the *Solution Map* by clicking the second from left icon 'Changes to Component'. All inputs are either list boxes, or indicated with a light blue field. This convention is used throughout the *Design Advisor*.

Metric units are used exclusively throughout the Design Advisor. The 'Front Seat Frame' has been selected from a list of 16 components for which benchmark data exists. Once the component name has been identified, the corresponding subsystem is shown to the right. Mass for the total component and for the part within the component is entered (the part may be a weldment or assembly of the same material.

Finally, the part material and the primary shaping process are selected from lists. These will be used for cost estimation and in the material and recycling estimates of greenhouse gas. Note the message on material/process compatibility. If a warning message is displayed, the results will not be valid.



Sheet: Input Component Data

Step 2b: Scale component for nominal vehicle- In the same input sheet, benchmark data is shown on the right side which allows comparison of the input mass data with data from several other vehicles.

Also, on this sheet, the component may be scaled based on mass drivers relevant to this component (for the case of the seat frame, there are no mass drivers). To illustrate the use of mass drivers and component scaling, below is an illustration for a hood. Here the mass driver is hood area. If the hood area on the nominal vehicle (*1.5* m^2 in this example) is different than that used in the input data (*2* m^2 in this example), the hood mass is scaled based on the mass driver. The scaled mass for components and parts shown at the bottom of the sheet will be used in subsequent calculations.

If the mass driver values are unknown, or if scaling is not desired, the user by enter the same arbitrary value for both and no scaling will be applied (for example *Hood Area used to size component=2*, and *Mass driver for Nominal Vehicle=2*).

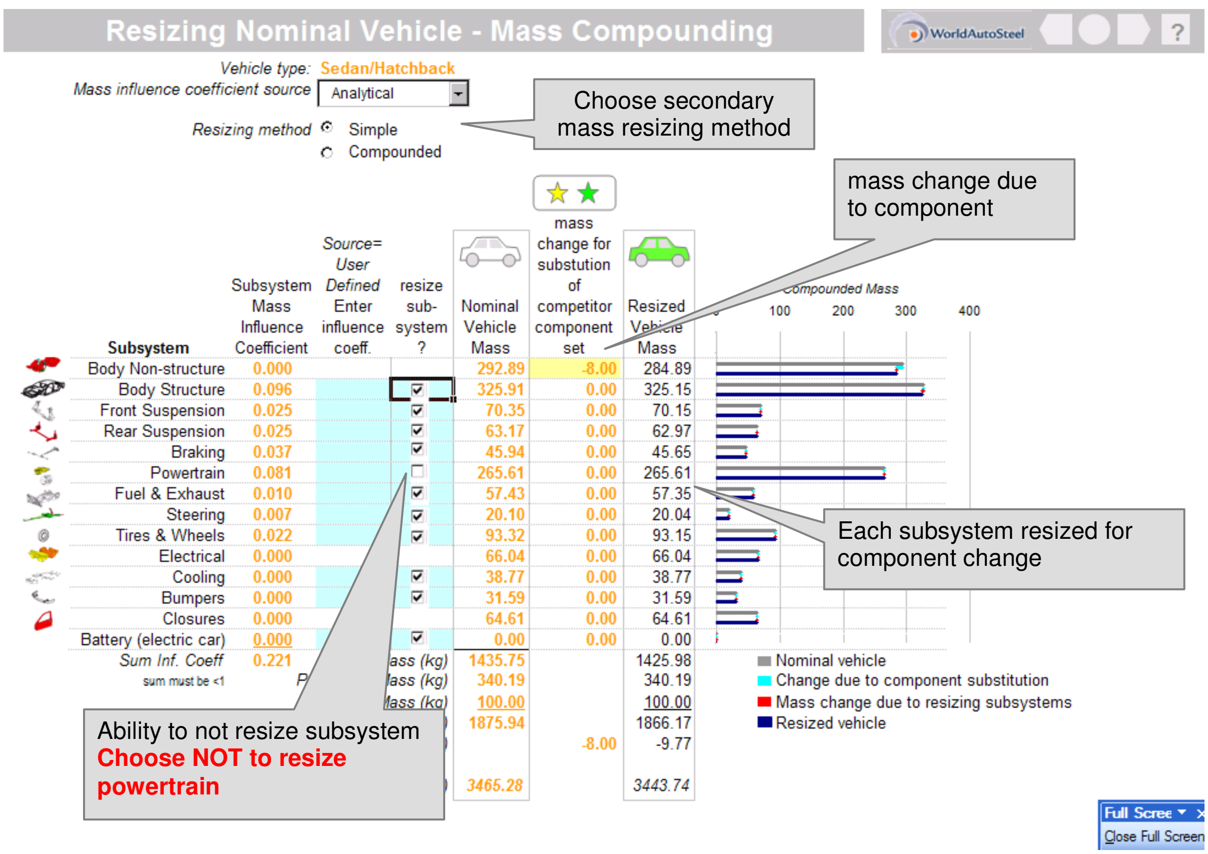
Note also that the part and component data are always entered for one unit. The Design Advisor will adjust the mass for the number of units per vehicle. For example, referring to the above illustration for the seat frame. The seat frame data is entered for one seat. The software will account for the fact that a vehicle will have two front seats as seen at the bottom of the sheet.

Sheet: Input Component Data
Example: Hood having Mass Driver of Area

Step 3: Define resized vehicle by resizing nominal vehicle- The previous steps have defined a nominal vehicle having the original component. In this sheet, that vehicle is resized for the competitor component. This includes adjusting the mass of some subsystems which are mass dependent. The primary tool used here is secondary mass analysis.

Little input is required of the user. The software inserts the primary mass change (the difference in the adjusted original component and competitor component masses) at the appropriate subsystem. The user enters the source for the secondary mass coefficients (*Analytical, Regression, Ratio, or User Defined)*, and the resizing method *(Simple, Compounded)*. The user can further specify which subsystems to consider in the resizing. For this example, the all subsystems can be resized <u>*with the exception*</u> of the powertrain.

Using mass influence coefficients the vehicle is resized. This resized vehicle will be compared with the nominal vehicle in subsequent steps.



Sheet: Mass Compounding

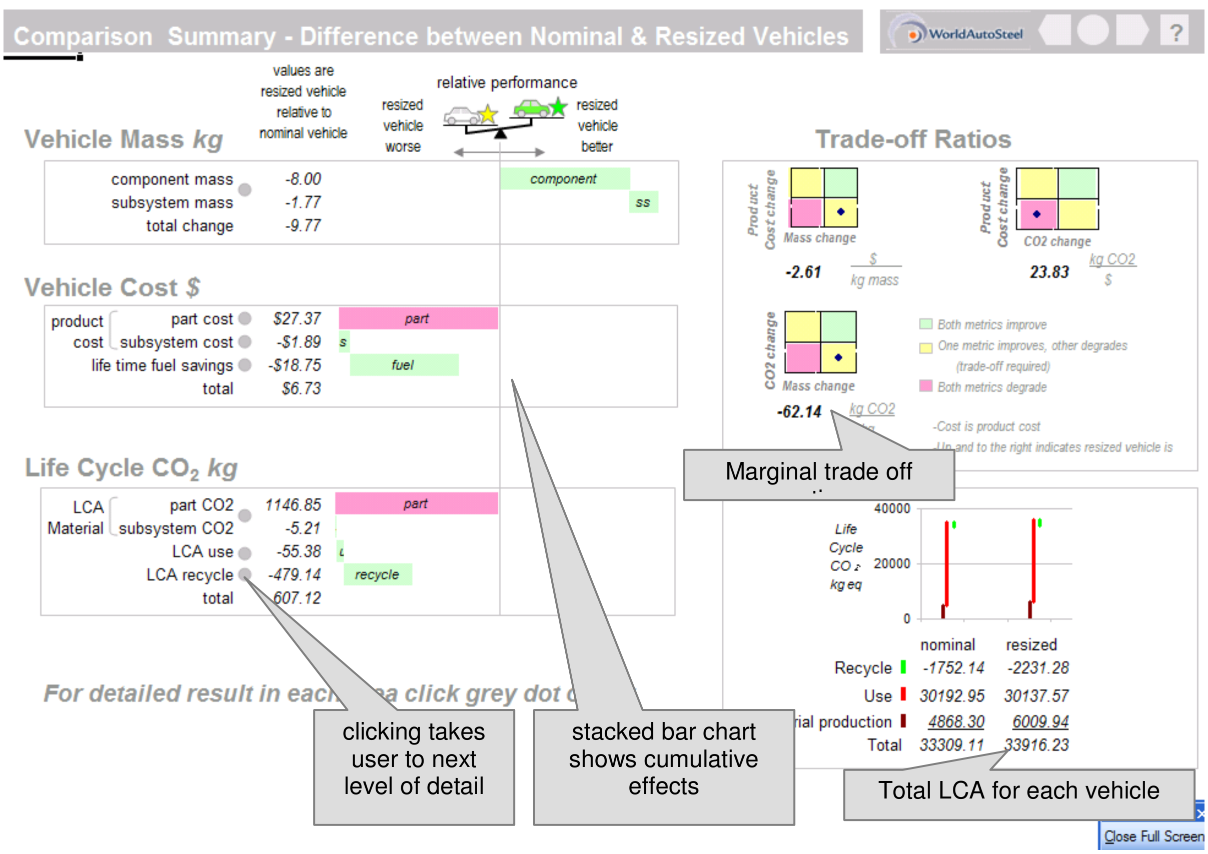
Step 4: Comparison summary – The Comparison Summary shows is a high-level summary of the results for mass, cost, and greenhouse gas. Each value shown on the left is the difference between the Resized vehicle and the Nominal vehicle. Negative values indicate the Resized vehicle is preferred to the Original vehicle.

Bar charts are provided in each area for a quick assessment of performance. The bars are additive as vectors, see illustration on next page. If the sequence of bars terminates on the right side, the resized vehicle is preferred; on the left side, the nominal vehicle is preferred. Green bars indicate that metric is favorable for the resized vehicle, red for the nominal vehicle.

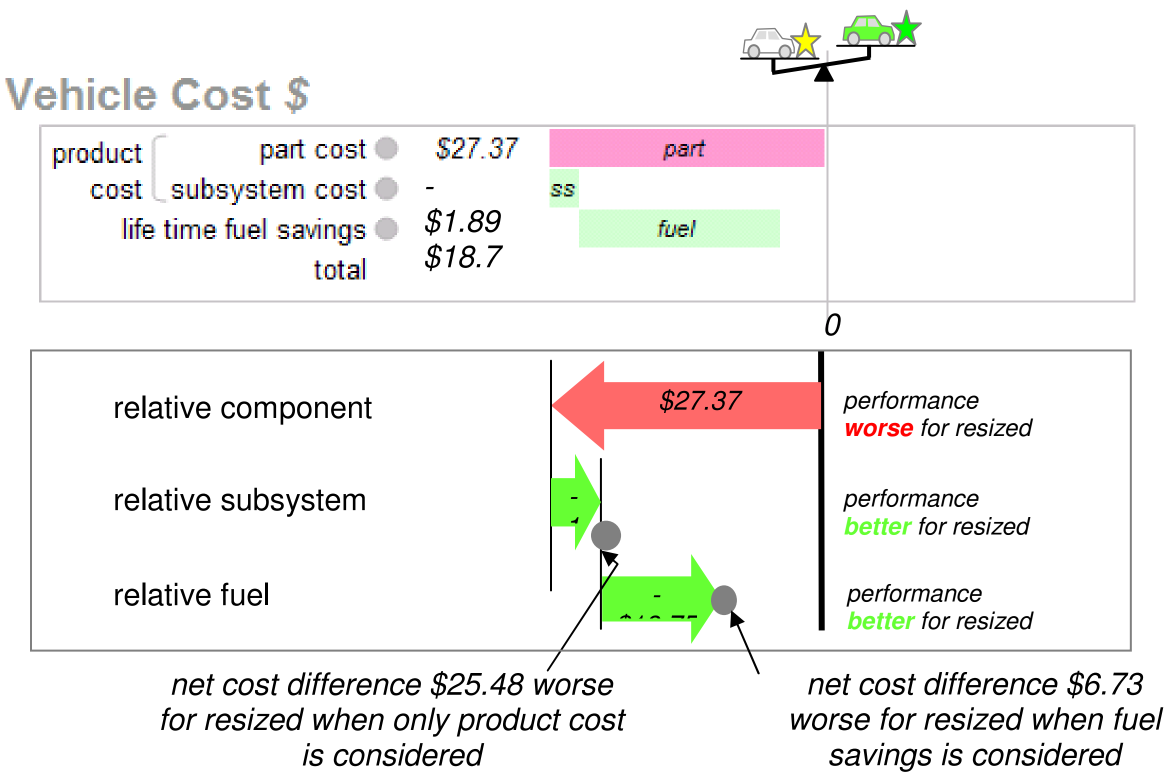
Often the individual metrics are in conflict: one improves while another degrades. To capture this behavior, trade-off ratios are provided. See the illustration at the bottom of the next page for a definition of trade-off ratios.

Finally in the lower right corner, life cycle greenhouse gas estimates are provided for each vehicle. We are primarily interested in the differences however these absolute values are useful for comparison with other sources.

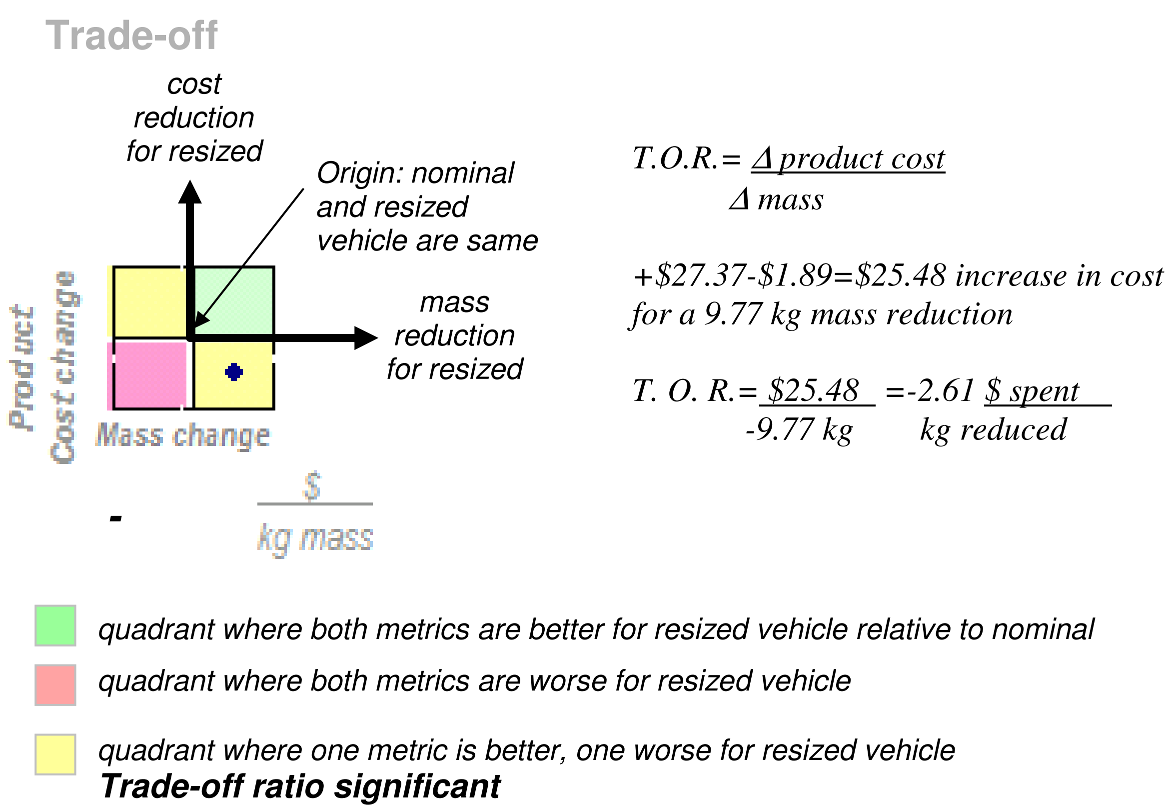
This sheet is a summary. By clicking either on a specific bar, or by clicking on the gray dot next to the metric name, a sheet with detailed results for that area will be brought up.



Sheet: Comparison Summary



Interpreting the bar graphs



Definition of Trade-off ratios

Detailed Results: Mass comparison- In this detailed results sheet, mass is compared for both primary changes (considering only component), as well as subsystem resizing changes between the nominal vehicle and resized vehicle. This sheet requires no inputs.

Results - Mass Comparison

Component Mass change

Original component	Component mass change	Competitor component
34.00	-8.00	26.00

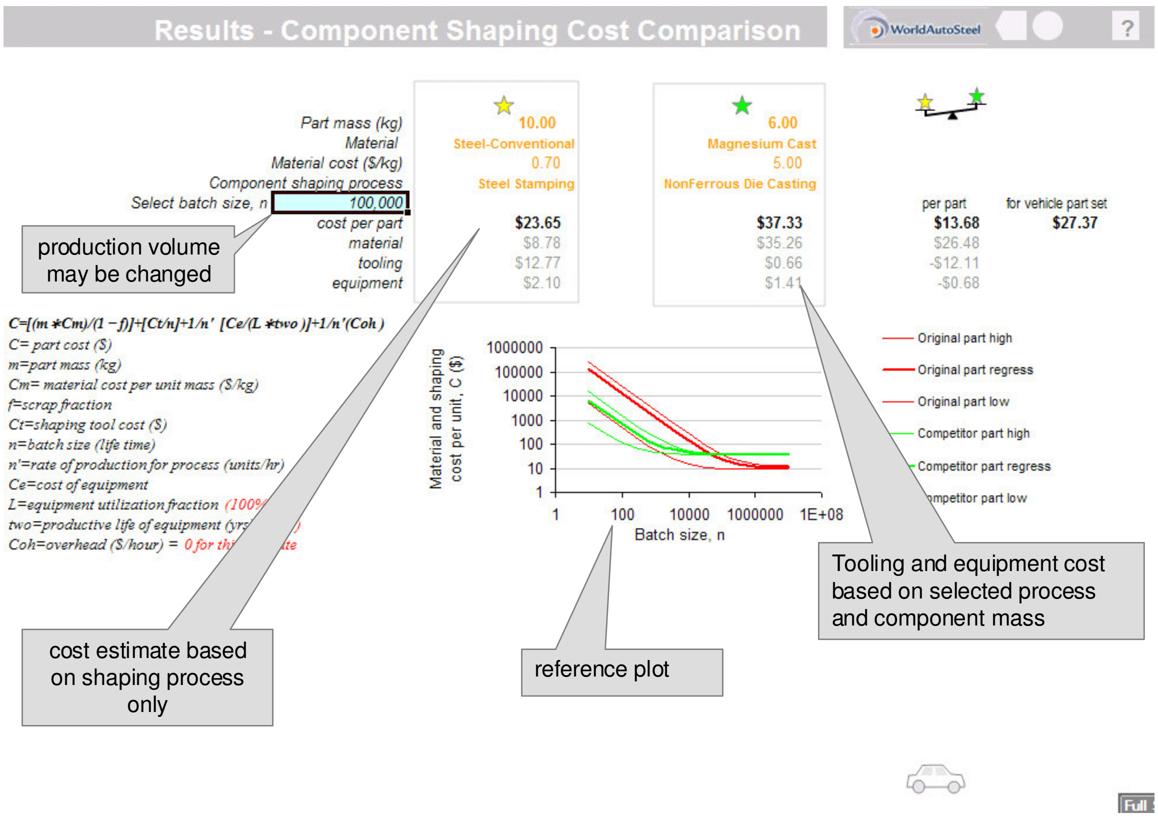
Subsystem mass changedue to resizing vehicle for component change

	Nominal Vehicle Mass	Component mass change	Subsystem Resizing Changes	Resized Vehicle Mass	Total Mass Change
Body Non-structure	292.89	-8.00	0.00	284.89	-8.00
Body Structure	325.91	0.00	-0.77	325.15	-0.77
Front Suspension	70.35	0.00	-0.20	70.15	-0.20
Rear Suspension	63.17	0.00	-0.20	62.97	-0.20
Braking	45.94	0.00	-0.29	45.65	-0.29
Powertrain	265.61	0.00	0.00	265.61	0.00
Fuel & Exhaust	57.43	0.00	-0.08	57.35	-0.08
Steering	20.10	0.00	-0.06	20.04	-0.06
Tires & Wheels	93.32	0.00	-0.17	93.15	-0.17
Electrical	66.04	0.00	0.00	66.04	0.00
Cooling	38.77	0.00	0.00	38.77	0.00
Bumpers	31.59	0.00	0.00	31.59	0.00
Closures	64.61	0.00	0.00	64.61	0.00
Battery (electric car)	0.00	0.00	0.00	0.00	0.00
Curb Mass (kg)	1435.75	-8.00	-1.77	1425.98	-9.77
Passenger Mass (kg)	340.19			340.19	0.00
Cargo Mass (kg)	100.00			100.00	0.00
Gross Vehicle Mass (kg)	1875.94			1866.17	-9.77
Curb+two passengers (Lb)	3465.28			3443.74	-21.54

Sheet: Mass Change

Detailed Results: Part shaping cost comparison- Cost is estimated for the original and competitor parts and includes material, tooling, and equipment cost for the primary shaping process only. All costs are based on the part mass, material, and shaping process. Therefore this is an approximate cost for comparison purposes only.

A graph showing part cost dependency on manufacturing batch size is included for both the original and competitor part. Often these will cross-over, and the user may enter a batch size other than the default 100,000 units.



Sheet: Primary Cost

Detailed Results: Cost savings for resized subsystems - Due to the primary change in component mass, the resized vehicle will have subsystem mass changes. These changes in mass will incur subsystem resizing cost changes. The resizing cost of changing a subsystem is estimated as a factor—($/ unit mass change). This factor will be different for each subsystem and is based only on material cost changes.

The user may define cost coefficients, and also decided which subsystem to consider resizing costs.

Results - Cost savings for resized subsystems

WorldAutoSteel ?

User defined cost coefficients? ☐

Subsystem	Subsystem Cost Coefficient ($/kg)	*User defined* cost coefficient ($/kg)	Consider Resizing Cost?	Nominal Vehicle Mass (kg)	Resized Vehicle Mass (kg)	Cost: Resized relative to nominal ($) ($)	Referenc Nominal Vehicle Material Cost
Body Non-structure	2.965			292.89	292.89	0.000	868.3
Body Structure	0.852		☑	325.91	325.15	-0.655	277.6
Front Suspension	1.268		☑	70.35	70.15	-0.251	89.2
Rear Suspension	1.161		☑	63.17	62.97	-0.230	73.3
Braking	0.666		☑	45.94	45.65	-0.195	30.5
Powertrain	1.586		☑	265.61	265.61	0.000	421.2
Fuel & Exhaust	0.905		☑	57.43	57.35	-0.073	51.9
Steering	0.998		☑	20.10	20.04	-0.056	20.0
Tires & Wheels	2.449		☑	93.32	93.15	-0.427	228.5
Electrical	5.143			66.04	66.04	0.000	339.6
Cooling	3.032		☑	38.77	38.77	0.000	117.5
Bumpers	.465		☑	31.59	31.59	0.000	77.8
Closures	036			64.61	64.61	0.000	131.5
Battery (electric car)	250			0.00	0.00	0.000	0.0
			otals	1435.75	1433.98	**-1.888**	2727.6

Subsystem cost change per kg based on material cost

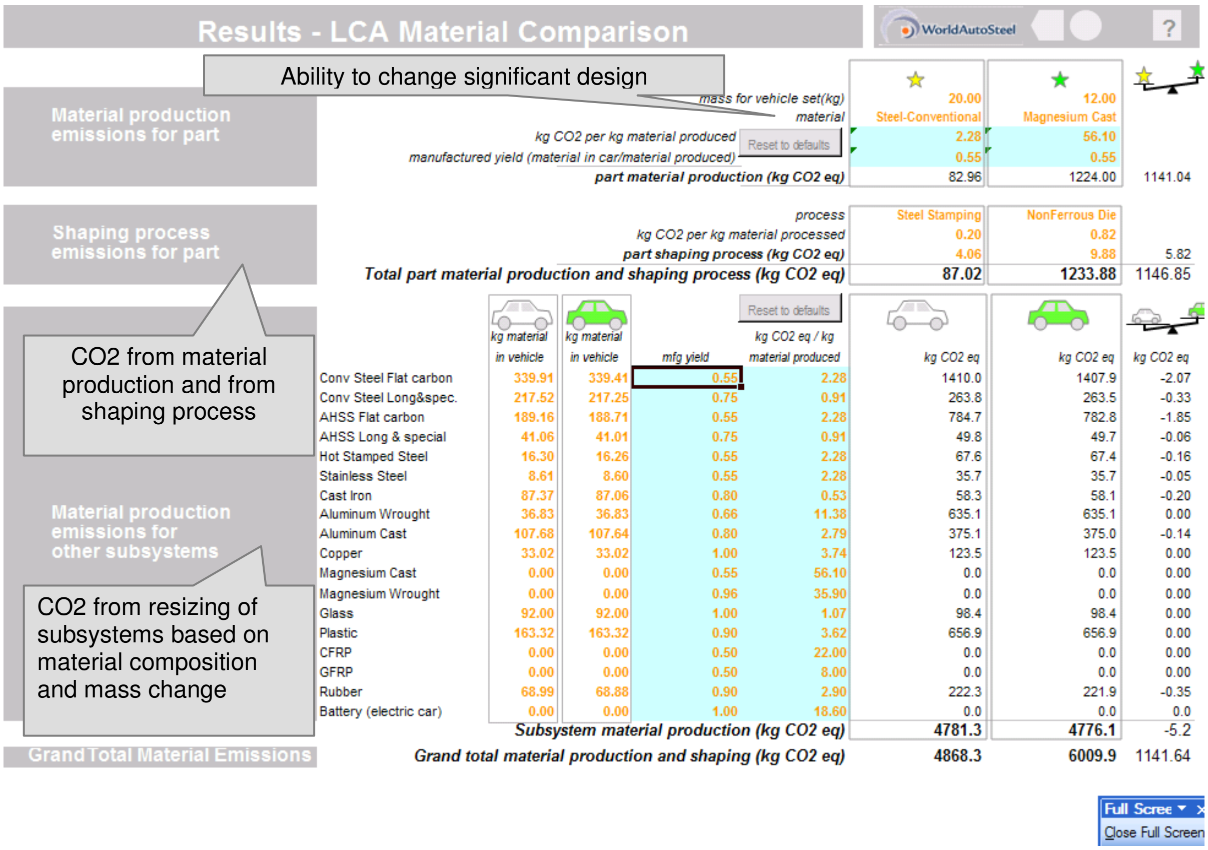
ability to include cost change or not include

Full Scree ▾ ×
Close Full Screen

Sheet: Subsystem resizing Cost

Detailed Results: LCA Material comparison- Greenhouse gas—CO_2—in the production of the vehicle material is calculated. The part CO_2 is estimated based on the materials in the original and competitor components. CO_2 for the primary shaping process is also estimated. A subsystem resizing CO_2 value is based on the material content for each subsystem. The grand total CO_2 for material production is the sum of the part, shaping process, and subsystem resizing values. For this example, CO_2 has been increased for the resized vehicle.

Key parameters of CO_2/unit of material mass and manufacturing yield may be changed by the user.

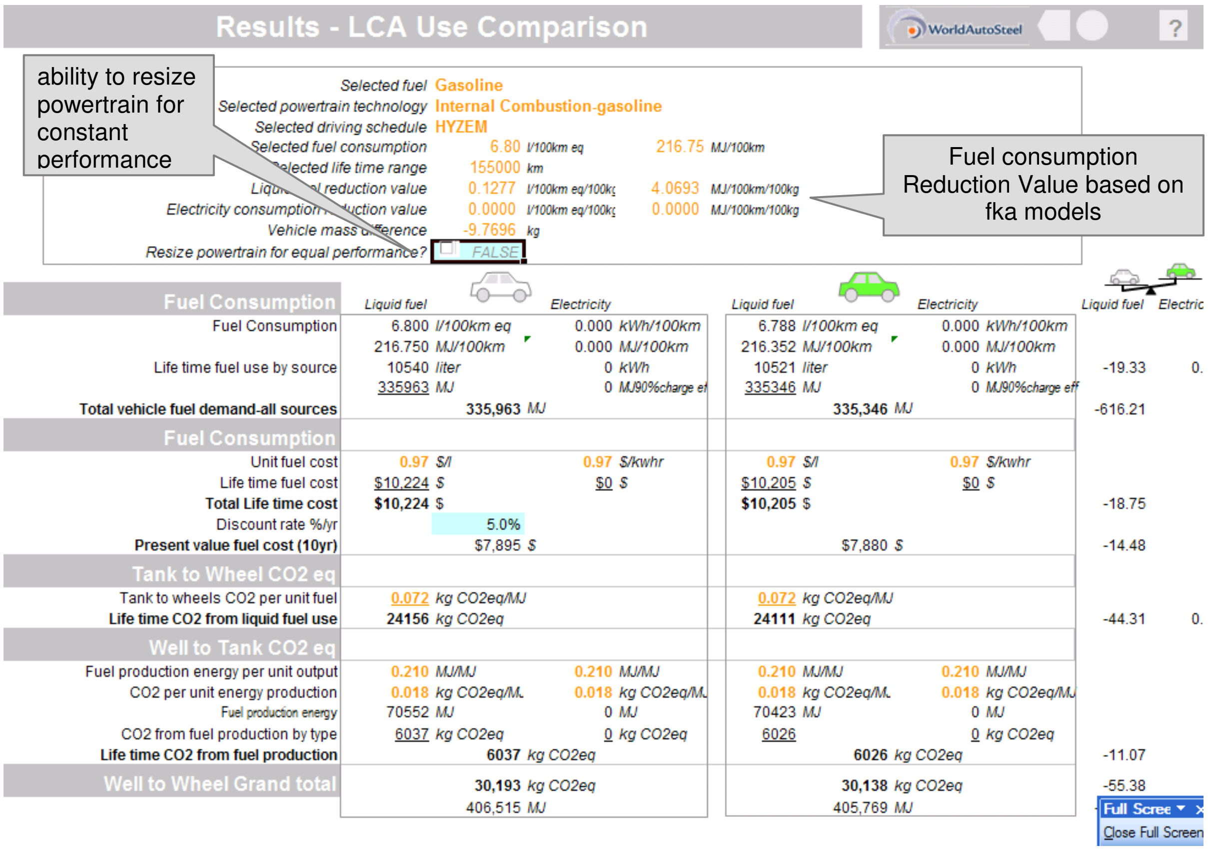


mass for vehicle set(kg)	20.00	12.00	
material	Steel-Conventional	Magnesium Cast	
kg CO2 per kg material produced	2.28	56.10	
manufactured yield (material in car/material produced)	0.55	0.55	
part material production (kg CO2 eq)	82.96	1224.00	1141.04
process	Steel Stamping	NonFerrous Die	
kg CO2 per kg material processed	0.20	0.82	
part shaping process (kg CO2 eq)	4.06	9.88	5.82
Total part material production and shaping process (kg CO2 eq)	87.02	1233.88	1146.85

	kg material in vehicle	kg material in vehicle	mfg yield	kg CO2 eq / kg material produced	kg CO2 eq	kg CO2 eq	kg CO2 eq
Conv Steel Flat carbon	339.91	339.41	0.55	2.28	1410.0	1407.9	-2.07
Conv Steel Long&spec.	217.52	217.25	0.75	0.91	263.8	263.5	-0.33
AHSS Flat carbon	189.16	188.71	0.55	2.28	784.7	782.8	-1.85
AHSS Long & special	41.06	41.01	0.75	0.91	49.8	49.7	-0.06
Hot Stamped Steel	16.30	16.26	0.55	2.28	67.6	67.4	-0.16
Stainless Steel	8.61	8.60	0.55	2.28	35.7	35.7	-0.05
Cast Iron	87.37	87.06	0.80	0.53	58.3	58.1	-0.20
Aluminum Wrought	36.83	36.83	0.66	11.38	635.1	635.1	0.00
Aluminum Cast	107.68	107.64	0.80	2.79	375.1	375.0	-0.14
Copper	33.02	33.02	1.00	3.74	123.5	123.5	0.00
Magnesium Cast	0.00	0.00	0.55	56.10	0.0	0.0	0.00
Magnesium Wrought	0.00	0.00	0.96	35.90	0.0	0.0	0.00
Glass	92.00	92.00	1.00	1.07	98.4	98.4	0.00
Plastic	163.32	163.32	0.90	3.62	656.9	656.9	0.00
CFRP	0.00	0.00	0.50	22.00	0.0	0.0	0.00
GFRP	0.00	0.00	0.50	8.00	0.0	0.0	0.00
Rubber	68.99	68.88	0.90	2.90	222.3	221.9	-0.35
Battery (electric car)	0.00	0.00	1.00	18.60	0.0	0.0	0.0
Subsystem material production (kg CO2 eq)					4781.3	4776.1	-5.2
Grand total material production and shaping (kg CO2 eq)					4868.3	6009.9	1141.64

Sheet: LCA-Material

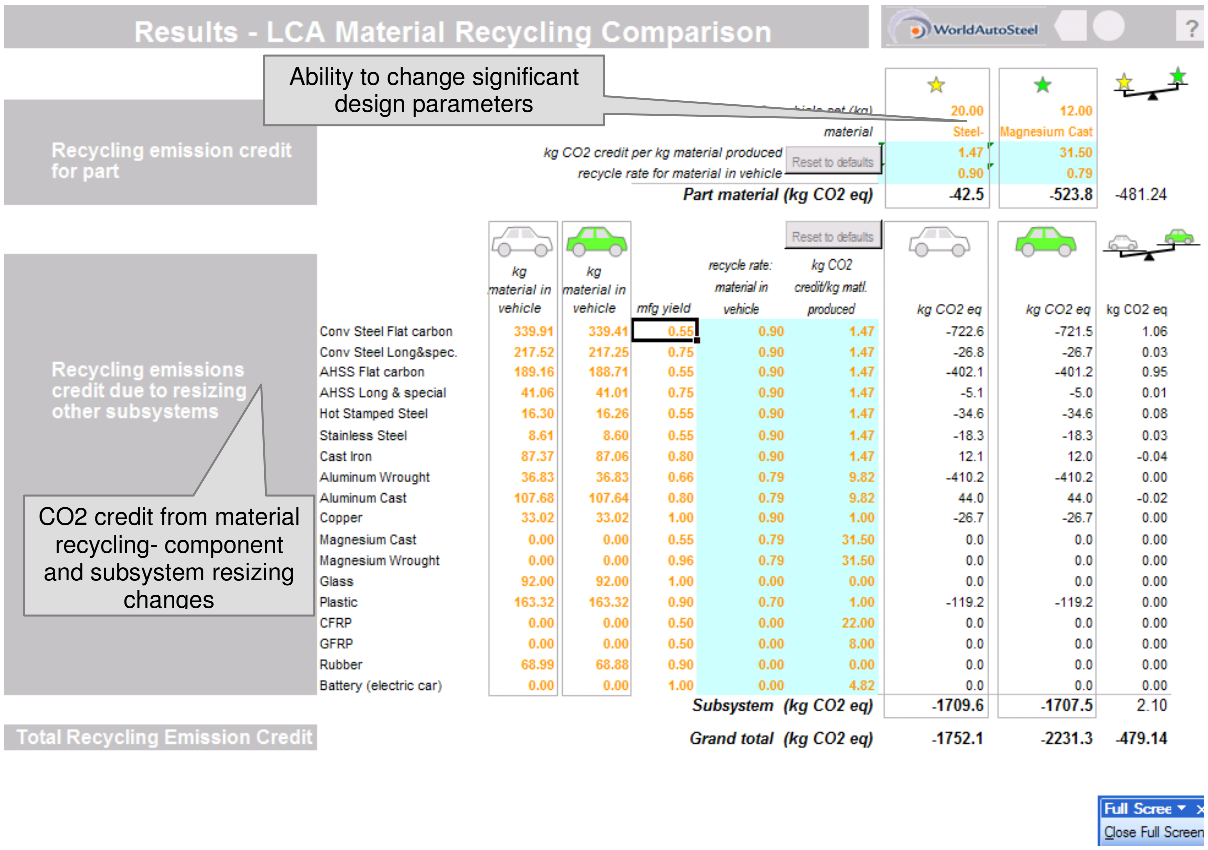
Detailed Results: LCA Use comparison- The greenhouse gas generated during the use phase are estimated, as well as energy use. The user may keep powertrain size fixed between the nominal and resized vehicle, or may resize the powertrain to achieve the same acceleration performance between the two vehicles. In both cases, the fuel consumption changes are based on a fuel consumption mass reduction value which is determined by simulation [5, 6, 7].



Sheet: LCA-Use

Detailed Results: LCA Material Recycling comparison- Greenhouse gas credit due to recycling of the vehicle material is calculated. As in the material production calculation, the primary CO_2 is estimated based on the materials in the original and competitor components. A subsystem resizing CO_2 value is based on the material content for each subsystem (the same content is used as in the material production CO_2 estimate). The total CO_2 credit for material recycling is the sum of the part and subsystem resizing values.

Key parameters of CO_2 credit/unit of material mass and recycle rate may be changed by the user.



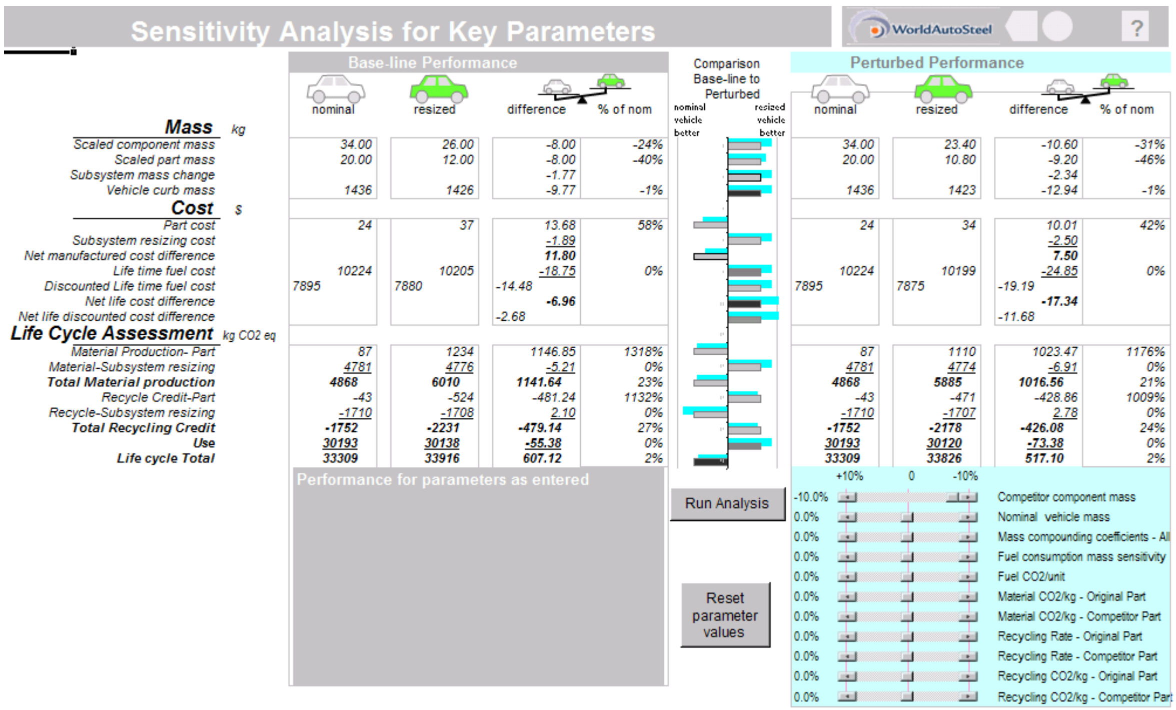
material	Steel-	Magnesium Cast	
	20.00	12.00	
kg CO2 credit per kg material produced	1.47	31.50	
recycle rate for material in vehicle	0.90	0.79	
Part material (kg CO2 eq)	-42.5	-523.8	-481.24

	kg material in vehicle	kg material in vehicle	mfg yield	recycle rate: material in vehicle	kg CO2 credit/kg matl. produced	kg CO2 eq	kg CO2 eq	kg CO2 eq
Conv Steel Flat carbon	339.91	339.41	0.55	0.90	1.47	-722.6	-721.5	1.06
Conv Steel Long&spec.	217.52	217.25	0.75	0.90	1.47	-26.8	-26.7	0.03
AHSS Flat carbon	189.16	188.71	0.55	0.90	1.47	-402.1	-401.2	0.95
AHSS Long & special	41.06	41.01	0.75	0.90	1.47	-5.1	-5.0	0.01
Hot Stamped Steel	16.30	16.26	0.55	0.90	1.47	-34.6	-34.6	0.08
Stainless Steel	8.61	8.60	0.55	0.90	1.47	-18.3	-18.3	0.03
Cast Iron	87.37	87.06	0.80	0.90	1.47	12.1	12.0	-0.04
Aluminum Wrought	36.83	36.83	0.66	0.79	9.82	-410.2	-410.2	0.00
Aluminum Cast	107.68	107.64	0.80	0.79	9.82	44.0	44.0	-0.02
Copper	33.02	33.02	1.00	0.90	1.00	-26.7	-26.7	0.00
Magnesium Cast	0.00	0.00	0.55	0.79	31.50	0.0	0.0	0.00
Magnesium Wrought	0.00	0.00	0.96	0.79	31.50	0.0	0.0	0.00
Glass	92.00	92.00	1.00	0.00	0.00	0.0	0.0	0.00
Plastic	163.32	163.32	0.90	0.70	1.00	-119.2	-119.2	0.00
CFRP	0.00	0.00	0.50	0.00	22.00	0.0	0.0	0.00
GFRP	0.00	0.00	0.50	0.00	8.00	0.0	0.0	0.00
Rubber	68.99	68.88	0.90	0.00	0.00	0.0	0.0	0.00
Battery (electric car)	0.00	0.00	1.00	0.00	4.82	0.0	0.0	0.00
Subsystem (kg CO2 eq)						-1709.6	-1707.5	2.10
Grand total (kg CO2 eq)						-1752.1	-2231.3	-479.14

Sheet: LCA-Recycle

Step 5: Sensitivity Analysis- The Sensitivity Analysis sheet provides a summary of all estimates (Base line performance on left side of sheet for input values). It also allows the user to see how small variations in select parameters affect performance (Perturbed Performance on the right side of the sheet). In the graph, gray bars indicate directionally the base-line analysis values while the blue bars indicate the perturbed values.

To perform a sensitivity analysis, first click the *Reset parameter values*, then click *Run Analysis*. This will make Perturbed Performance the same as the base. Now change key parameters using the sliders, then click *Run Analysis*. The Perturbed Performance will now reflect the changes made. This analysis is particularly useful in seeing if a result will 'flip' in preference—the blue bar will be on the opposite side of the center line. This indicates that the preference for the components is not strong and that further detailed analysis is needed.



	Base-line Performance: nominal	resized	difference	% of nom	Perturbed Performance: nominal	resized	difference	% of nom
Mass kg								
Scaled component mass	34.00	26.00	-8.00	-24%	34.00	23.40	-10.60	-31%
Scaled part mass	20.00	12.00	-8.00	-40%	20.00	10.80	-9.20	-46%
Subsystem mass change			-1.77				-2.34	
Vehicle curb mass	1436	1426	-9.77	-1%	1436	1423	-12.94	-1%
Cost $								
Part cost	24	37	13.68	58%	24	34	10.01	42%
Subsystem resizing cost			-1.89				-2.50	
Net manufactured cost difference			**11.80**				**7.50**	
Life time fuel cost	10224	10205	-18.75	0%	10224	10199	-24.85	0%
Discounted Life time fuel cost	7895	7880	-14.48		7895	7875	-19.19	
Net life cost difference			**-6.96**				**-17.34**	
Net life discounted cost difference			-2.68				-11.68	
Life Cycle Assessment kg CO2 eq								
Material Production- Part	87	1234	1146.85	1318%	87	1110	1023.47	1176%
Material-Subsystem resizing	4781	4776	-5.21	0%	4781	4774	-6.91	0%
Total Material production	**4868**	**6010**	**1141.64**	23%	**4868**	**5885**	**1016.56**	21%
Recycle Credit-Part	-43	-524	-481.24	1132%	-43	-471	-428.86	1009%
Recycle-Subsystem resizing	-1710	-1708	2.10	0%	-1710	-1707	2.78	0%
Total Recycling Credit	**-1752**	**-2231**	**-479.14**	27%	**-1752**	**-2178**	**-426.08**	24%
Use	**30193**	**30138**	**-55.38**	0%	**30193**	**30120**	**-73.38**	0%
Life cycle Total	**33309**	**33916**	**607.12**	2%	**33309**	**33826**	**517.10**	2%

Sheet: Sensitivity Analysis

The table below is a summary of the specific information input on each sheet of the *Design Advisor*. Bold font indicates required inputs. Red indicates important parameters which can be changed from Results Summary sheet.

Excel Sheet	Information input on sheet
1a. Set Nominal Vehicle	**•vehicle type** **•length and width** **•number of passengers** **•cargo mass** •(optional) standard deviation from average curb mass **•powertrain type** •(optional) subsystem masses
1b. Powertrain Sizing	**•life time range** **•fuel type** **•driving schedule** **•nominal vehicle fuel consumption**
2a. Input Component Data **2b. Size Component for nominal vehicle**	**•component name** **•mass driver value used to size component** **•component and part mass** **•component material** **•shaping process** **•mass driver for nominal vehicle**
3. Resizing Nominal Vehicle (sheet Mass Compounding)	**•influence coefficient source** **•resizing method** **•resize specific subsystems (yes/no)** •(optional) subsystem influence coefficients
Results-Component Shaping Cost (sheet Component Cost)	•batch size
Results-Cost savings for resized subsystem (sheet Subsystem Cost)	•(optional) consider cost for specific subsystems (yes/no) •(optional) subsystem cost coefficients
Results-LCA Material Comparison (sheet LCA-Material)	•(optional) manufacturing yield •(optional) GHG/unit material coefficient
Results-LCA Use Comparison (sheet LCA-Use)	•Resize powertrain for equal performance (yes/no) •(optional) Discount rate for fuel cost
Results-LCA Recycling Comparison (sheet LCA-Recycle)	•(optional) manufacturing yield •(optional) GHG/unit recycle coefficient

3- Technical Description

In this section, the models used to in the *Design Advisor* are described. These first order analysis models were selected to provide enough accuracy to support the A vs. B selection decision, and also because they require only that input information which would be available during the early design stages.

3.1 Mass Estimation for the Nominal Vehicle- Often the curb mass for the vehicle is unknown and must be estimated. The plan view area of the vehicle (Length x Width) can be used to make this estimation,

$$(\text{Curb mass}) = \beta_1 \, (\text{plan view area}) + \beta_0 \;\;)$$

where

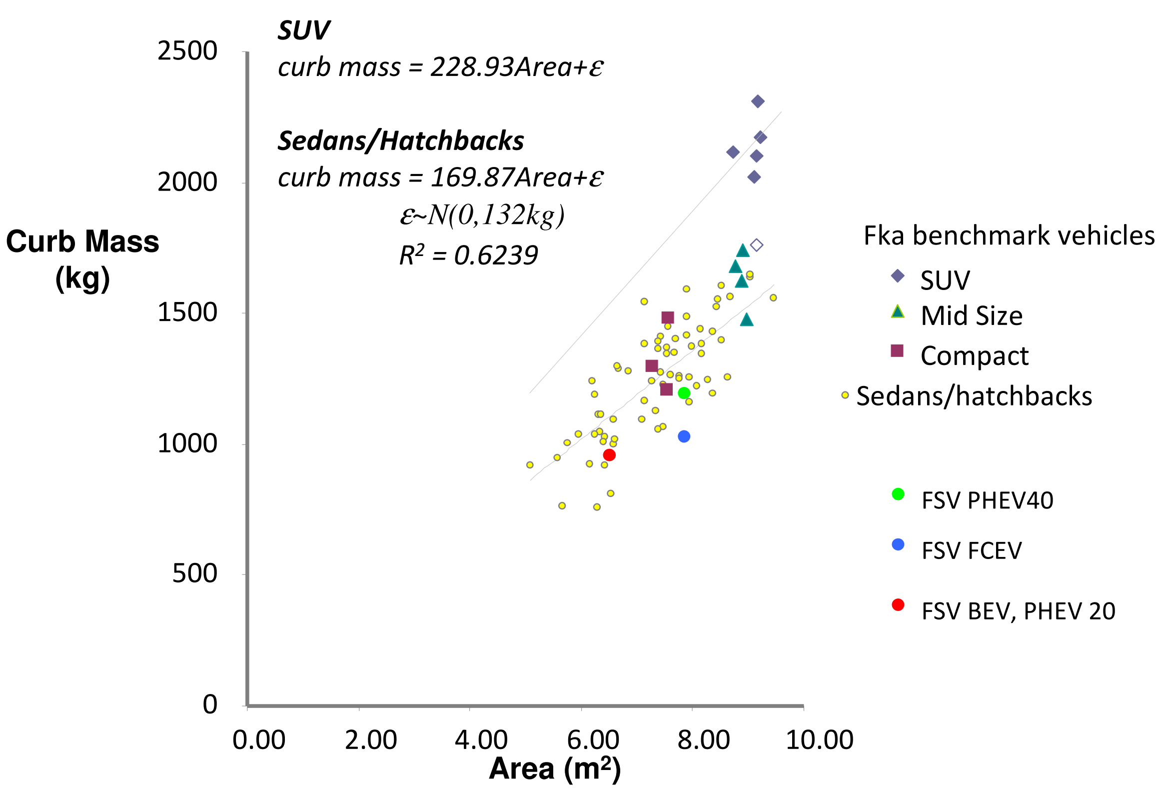
m'_{CURB} =*estimated curb mass (kg) for base gasoline IC, sedan/hatchback, FWD, BFI*

A_{PLAN} =*Plan view area of vehicle (length x width)* (m^2)

β_0, β_1 =*coefficients estimated by regression*

ε =*residual error* $N(0,\sigma)$

Data from several sources were used to fit the above expression, see below [1, 4, 5, 11, 12].



Curb mass estimated using Plan view area

With curb mass determined, the mass for each subsystem may be taken as a fraction of the estimated curb mass.

$$\bar{\phi} = \begin{bmatrix} \phi_1 \\ \phi_2 \\ . \\ \phi_n \end{bmatrix}, \qquad m'_{CURB}\,\bar{\phi} = \begin{bmatrix} m_1 \\ m_2 \\ . \\ m_n \end{bmatrix}$$

where

ϕ_i =*mass fraction relative to curb mass for subsystem i*

for the reference vehicle (IC gasoline), $\Sigma\phi_i=1$

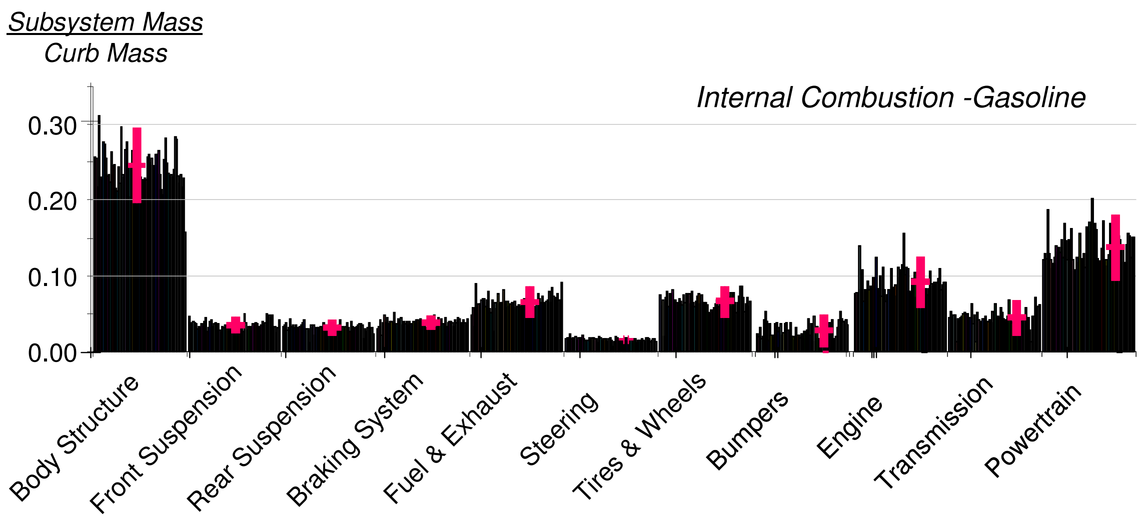
for other powertrain types, $\Sigma\phi_i$ *may be smaller or larger than one*

m'_{CURB} =*curb mass (kg) of reference IC-gasoline vehicle estimated by plan view area*

m_i =*subsystem mass (kg)*

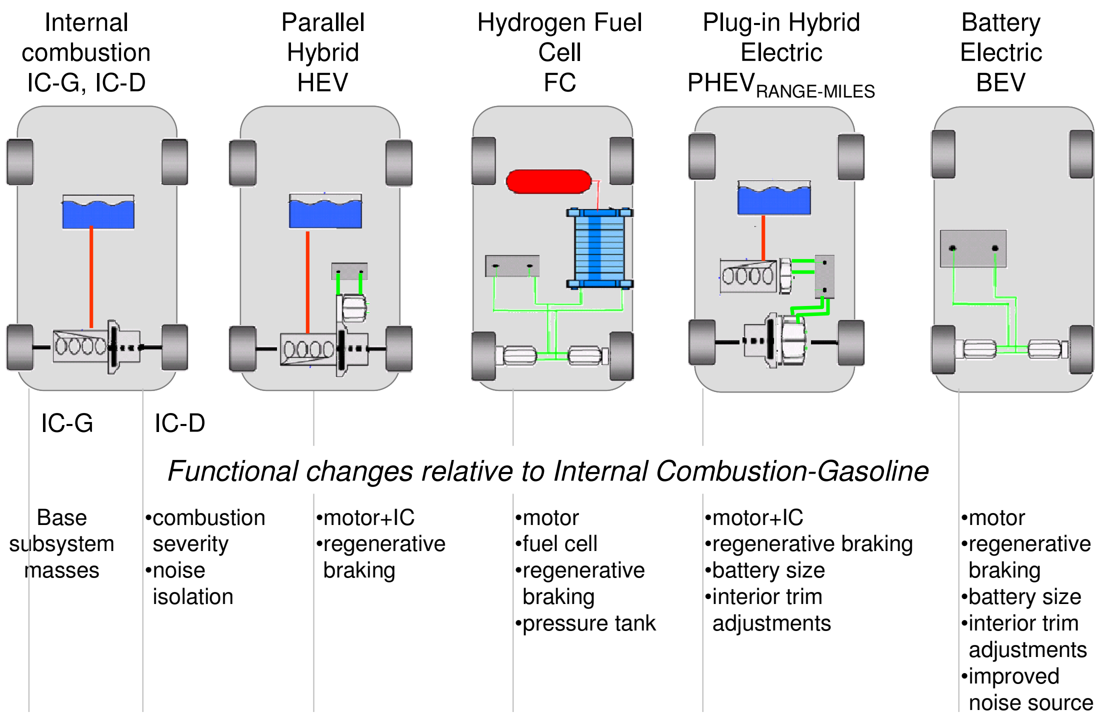
m_{CURB} =*curb mass (kg) for vehicle with specific powertrain* $m_{CURB} = \sum m_i$

Data to evaluate the subsystem mass fraction were obtained from vehicle teardowns [1]. The illustration below shows subsystem mass data for several vehicles (sedan/hatchback FWD, integral body, gasoline internal combustion engines). The average values for each subsystem was used to estimate the mass fraction, ϕ_i , for the reference IC-gasoline case.



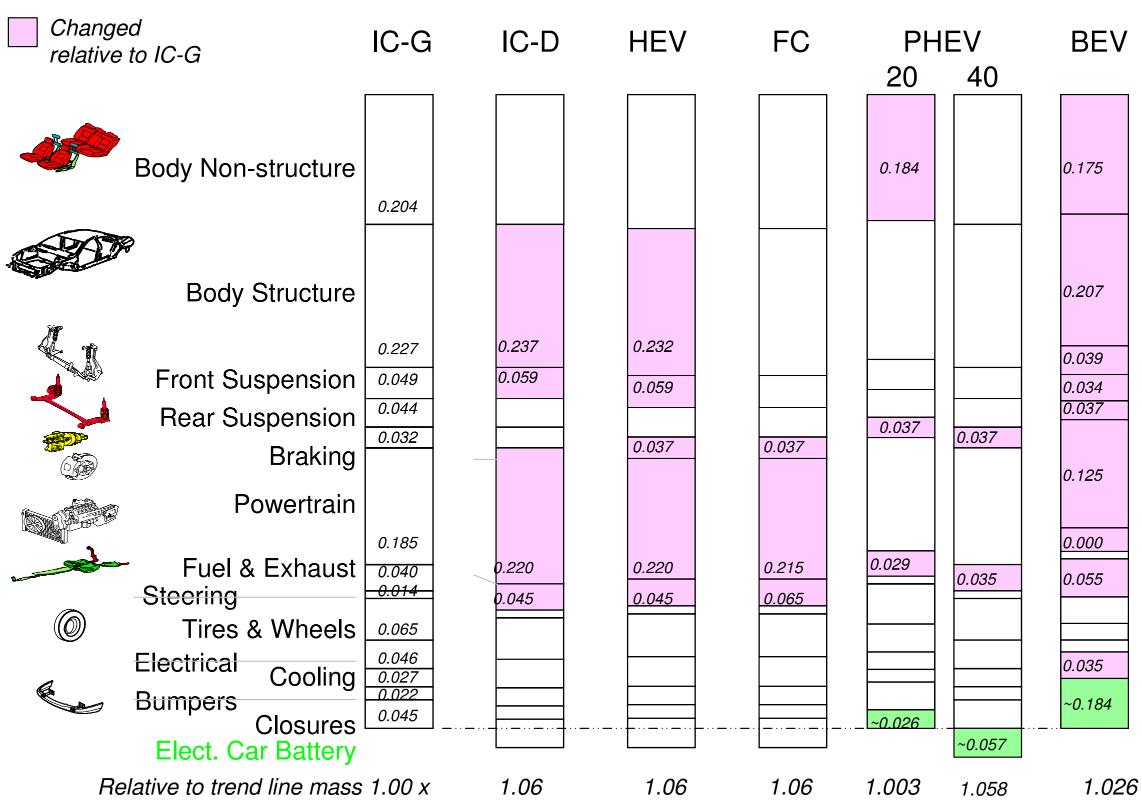
Subsystem mass/curb mass

To evaluate the mass fractions for other powertrain types, the functional changes needed to replace a IC-gasoline with the alternative powertrain were considered, see illustration below. These functional changes then lead to changes in subsystems and a resulting change in subsystem mass fraction.



Functional changes required for various powertrains

Based on these functional changes, the subsystem mass fractions are adjusted depending on the powertrain selected, illustration below.



Subsystem mass fractions for a given powertrain

The electric car battery sizing model is shown below and depends on frontal area, range, and curb mass [10]. Once the required battery power is determined, the battery mass is determined using energy density for a particular battery technology.

Power required

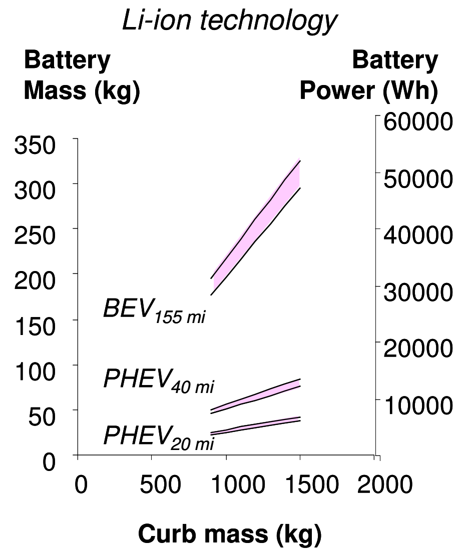
$$P_{BATTERY} = 0.0623 A_f \cdot R \cdot M_{CURB}$$

$P_{BATTERY}$ =*required battery power (Wh)*
A_f =*vehicle frontal area (m²)*
R =*range with fully charged battery (km)*
M_{CURB} =*vehicle curb mass (kg)*

Battery Mass

$$m_{BATTERY} = \frac{P_{BATTERY}}{e_{DENSITY}}$$

$m_{BATTERY}$ =*battery mass (kg)*
$e_{DENSITY}$ =*battery energy density (Wh/kg)*
for Li-ion technology, $e_{DENSITY}$*=155 Wh/kg*

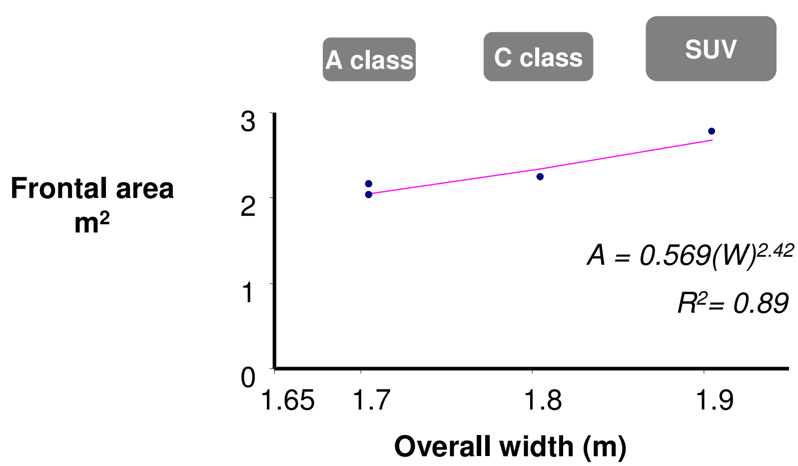


	Battery mass
BEV	20-22 % curb
$PHEV_{40}$	5.1-5.6 %
$PHEV_{20}$	2.5-2.8 %
	$2.03\ m^2 < A_f < 2.24\ m^2$

User Guide for Version 3 of the WorldAutoSteel Energy and GHG Model, Roland Geyer, WorldAutoSteel, 1/6/2011, page 24.

Battery Sizing Model

To implement this model, the vehicle frontal area is required. As this parameter is often unknown in the early design stage, overall width was used as an estimator for frontal area, see illustration below.



Estimating frontal area using overall width

3.1.1 Vehicle Bill of Material and Material Mass- To capture the material use in the vehicle, the Bill of Materials—BOM—is used. This is a matrix with each element being the fraction of a particular subsystem composed of a particular material,

BOM $$\bar{\alpha} = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \ldots \\ \alpha_{21} & \alpha_{ij} & \ldots \\ \ldots & \ldots & \ldots \end{bmatrix}$$

where

α_{ij}=*fraction of subsystem i composed of material j*

Note that rows will sum to 1

Subsystem mass vector $$\bar{m} = \begin{bmatrix} m_1 \\ m_i \\ \ldots \end{bmatrix}$$

where

m_i =*mass of subsystem i*

Total mass of material j in vehicle $$\bar{\mathrm{m}} = [\mathrm{m}_1 \quad \mathrm{m}_j \quad \ldots] = [m_1 \quad m_i \quad \ldots] \begin{bmatrix} \alpha_{11} & \alpha_{12} & \ldots \\ \alpha_{21} & \alpha_{ij} & \ldots \\ \ldots & \ldots & \ldots \end{bmatrix} = (\bar{m})^T (\bar{\alpha})$$

where

m_j =*total mass of material j in vehicle*

The *Design Advisor* is pre-loaded with a conventional BOM resulting in 67% Ferrous material, 7% Aluminum, 5% Copper, 6% glass, 11% Plastics, 4% Rubber, and <1% other. This default may be changed by the user.

Vehicle Bill of Materials

IC-gasoline	Conv Steel Flat carbon	Conv Steel Long&spec.	AHSS Flat carbon	AHSS Long & special	Hot Stamped Steel	Stainless Steel	Cast Iron	Aluminum Wrought	Aluminum Cast	Copper	Magnesium Cast	Magnesium Wrought	Glass	Plastic	CFRP	GFRP	Rubber	
Body Non-structure	0.15	0.10	0.03	0.03	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.25	0.35	0.00	0.00	0.00	
Body Structure	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Front Suspension	0.20	0.30	0.00	0.20	0.00	0.00	0.15	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	
Rear Suspension	0.60	0.10	0.00	0.00	0.00	0.00	0.15	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	
Braking	0.00	0.20	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Powertrain	0.15	0.3	0	0	0	0	0.3	0.05	0.15	0	0	0	0	0.05	0	0	0	100%
Fuel & Exhaust	0.75	0.10	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Steering	0.10	0.65	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	
Tires & Wheels	0.00	0.50	0.00	0.00	0.00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.50	
Electrical	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.00	
Cooling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.00	0.00	0.00	0.00	0.00	0.60	0.00	0.00	0.00	
Bumpers	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	
Closures	0.55	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.10	0.00	0.00	0.05	
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

fraction of powertrain made of Cast Iron

Default BOM

3.2 Scaling Component Mass **-** In general, the component data input has been sized for a specific vehicle. Attributes of the nominal vehicle may be different than this, and the component should be resized based on its specific mass driver. As an example, benchmark data for hood mass can be expressed as,

$$\hat{m}_{HOOD}(kg) = 11.06(Area\ \ m^2)^{0.867}$$

In this expression, the hood mass depends on hood Area—a mass driver for the hood. If we have mass data for a hood B with area $1.0\ m^2$, we can scale that hood to estimate the mass of hood A with area $1.5m^2$,

$$m_A = m_B\left(\frac{1.5\ \ m^2}{1.0\ \ m^2}\right)^{0.867}$$

or in general,

$$\frac{m_A}{m_B} = \left[\frac{MassDriver_A}{MassDriver_B}\right]^{\beta}$$

$$m_A = \left[\frac{MassDriver_A}{MassDriver_B}\right]^{\beta} m_B$$

where

m_A =*mass of component A to be determined*

m_B =*mass of reference component B*

β =*exponent for the significant mass driver*

Mass drivers for components in the *Design Advisor* are summarized below.

Component name	Mass-Driver
Front Suspension Knuckle	Gross vehicle mass
Front Suspension lower control arm	Gross vehicle mass
Body Structure	Gross vehicle mass
Deck Lid Frame	Projected Area
Exhaust System	Engine displacement
Front Bumper Beam	Curb mass
Front Door Frame	Projected Area
Front Seat Frame	No mass driver
Front Suspension	Gross vehicle mass
Hatchback Frame	Projected Area
Hood Frame	Projected Area
Instrument Panel Beam	No mass driver
Lift Gate Frame	Projected Area
Other	User defined
Rear Bumper Beam	Curb mass
Rear Suspension	Gross vehicle mass
Wheels	Swept volume (circular area x width)

Mass Drivers

3.3 Powertrain Sizing for the Nominal Vehicle- To determine fuel consumption (energy demand), simulations were done for the 18 vehicles shown below *[5, 6, 7, 17]*.

		Compact		Midsize		SUV	
		mass	power	mass	power	mass	power
Internal combustion	IC-G	1260 kg	(85 kW)	1640	(181)	2195	(235)
	IC-D	1350	(100)	1740	(170)	2320	(220)
Parallel Hybrid	HEV	1335	(85)	1752	(181)	2345	(235)
Hydrogen Fuel Cell	FCV	1335	(64-73)	1752	(116-131)	2345	(173-195)
	0-100km/h time=	9.8 s		6.9 s		6.5 s	

	A class		C class	
	mass	power	mass	power
$PHEV_{20}$	1107kg	(50/45)	1349	(85/75)
$PHEV_{40}$	1268	(50/47)	1512	(85/75)
BEV_{155}	1097	(45)	1334	(75)
0-100km/h time=	11-13 s		11-13 s	

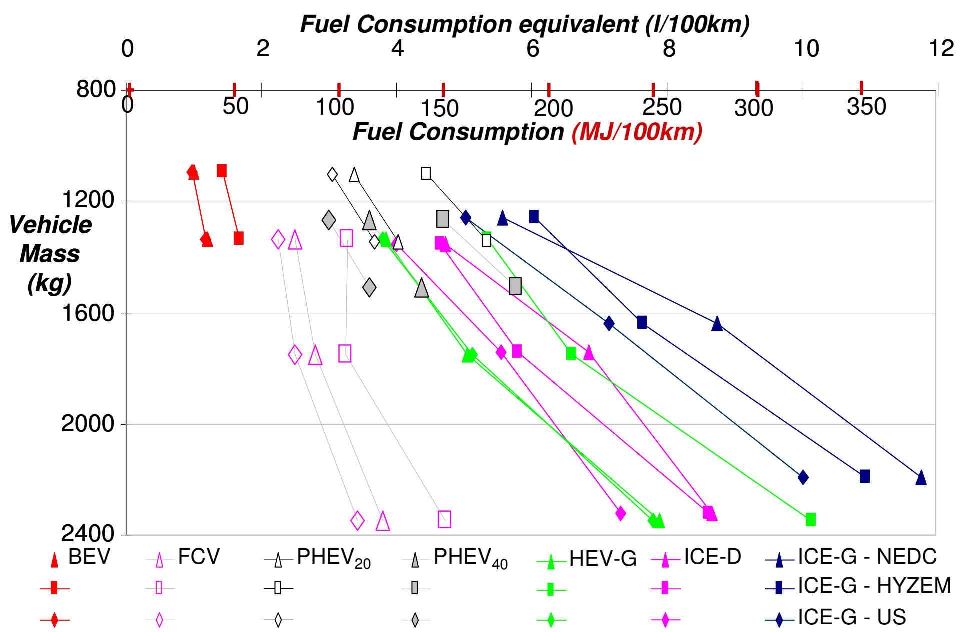
Plug-in Hybrid Electric $PHEV_{RANGE-MILES}$

Battery Electric

power kW (ICE/Motor)

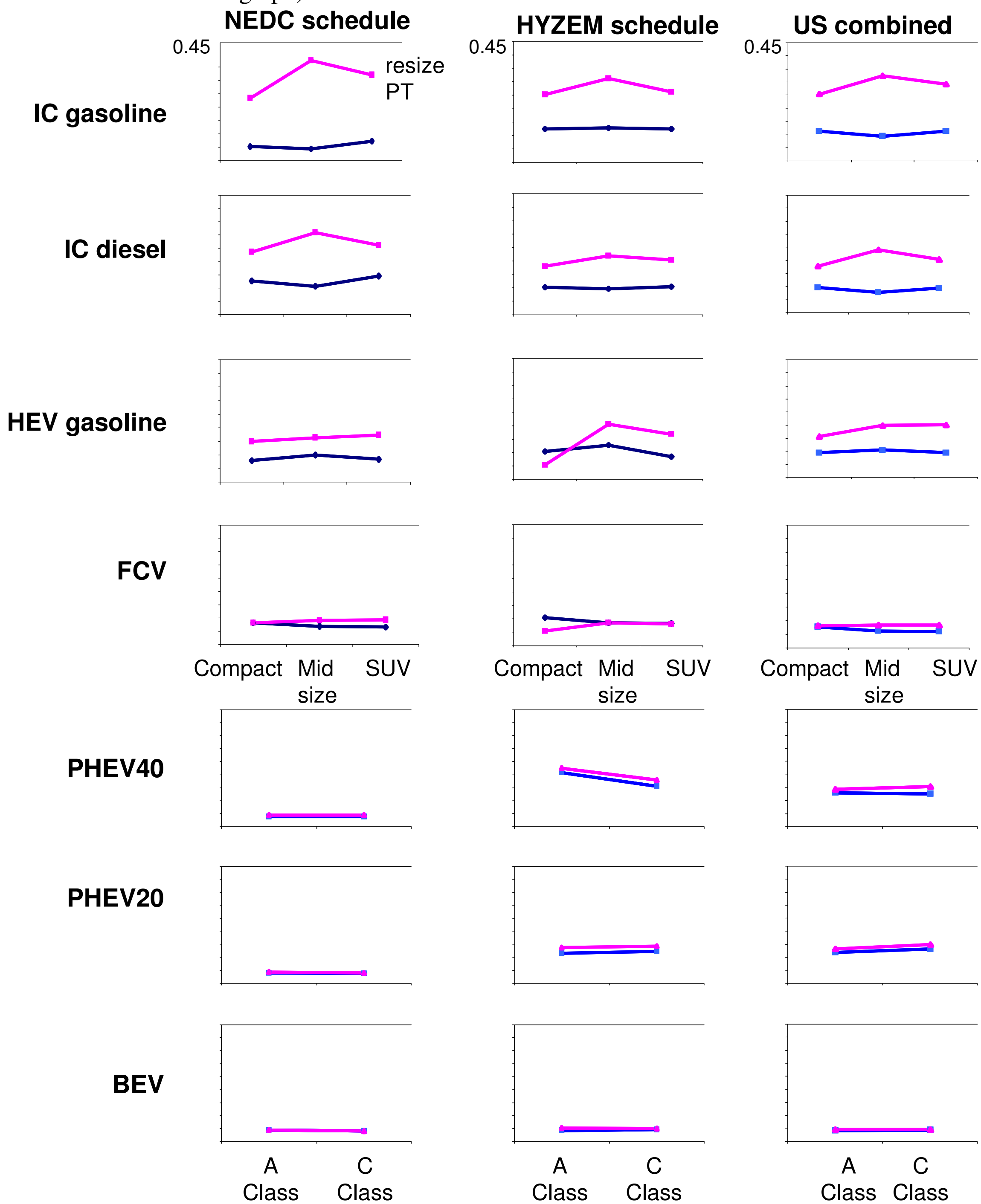
Vehicles Simulated [5, 6, 7, 17]

The resulting fuel consumption (energy demand) is summarized on the chart below. This data is used to estimate the fuel consumption of the nominal vehicle.



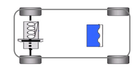
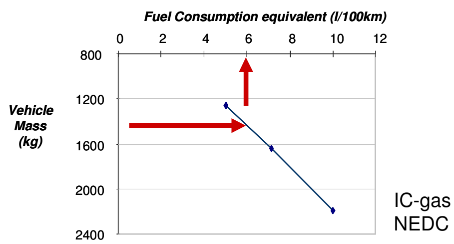
Energy Demand as a functional of vehicle mass

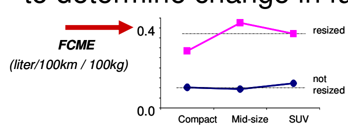
To estimate how fuel consumption changes due to mass reduction, a fuel consumption mass reduction value is applied. This value is defined as the reduction in energy consumption (*MJ/100 km*) per *100 kg* of vehicle mass reduction. In the thumbnail graphs below, the fuel reduction value, FRV, is expressed in equivalent liters gasoline rather than energy. Note that the FRV is greatest for pure internal combustion powertrains, and is largest when the powertrain is resized—red line at top of each graph—to achieve constant acceleration performance (rather than keeping the same displacement—blue lines at bottom of each graph).



Fuel Reduction Value (l/100km/100kg)

Using the energy demand and the Fuel Reduction Value, the calculation methodology to determine vehicle fuel consumption for the nominal and resized vehicles is as follows,

Calculation steps	Example values
1. set nominal vehicle mass	*1400 kg*
2. select powertrain technology	 *IC-g*
3. select fuel consumption schedule	*NEDC*
4. select a consistent base fuel consumption (energy demand)	
using energy demand graphs 	*6 l/100km*
5. resize nominal vehicle for component mass change	*1410 kg*
6. calculate change in vehicle mass between nominal and resized, ΔM	*10 kg*
7. use *FRV* to determine change in fuel consumption *Δ fuel consumption=*	*FRV*ΔM*



Δfc=(0.4 L/100km/100kg)10 kg= 0.04 L/100km

resized fuel consumption=6+0.04= 6.04 L/100km

Fuel consumption calculation steps

3.4 Mass Estimation of the Resized Vehicle (mass compounding)- When the mass of a component is changed during vehicle design, other subsystems are also affected.. This effect is known as the secondary mass effect, and is captured in the following equations. For the overall vehicle mass,

$$M_{RS} = M_0 + \Delta + \Delta\Gamma$$

M_0 =Initial vehicle mass for which the subsystems are sized

Δ =Initial total mass change (primary mass change)

M_{RS} =Resized vehicle mass

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

$\Gamma = \gamma_V$ for simple secondary mass

$\Gamma = \frac{\gamma_V}{1-\gamma_V}$ for compounded secondary mass

γ_V =Mass influence coefficient for the vehicle given by $\gamma_V = \Sigma \gamma_i$

γi =Mass influence coefficient for subsystem *i*

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

$$mi_{RS} = mi_0 + \Delta_i + \Delta\tau$$

$\tau = \gamma i$ for simple secondary mass

$\tau = \frac{\gamma i}{1-\gamma_V}$ for compounded secondary mass

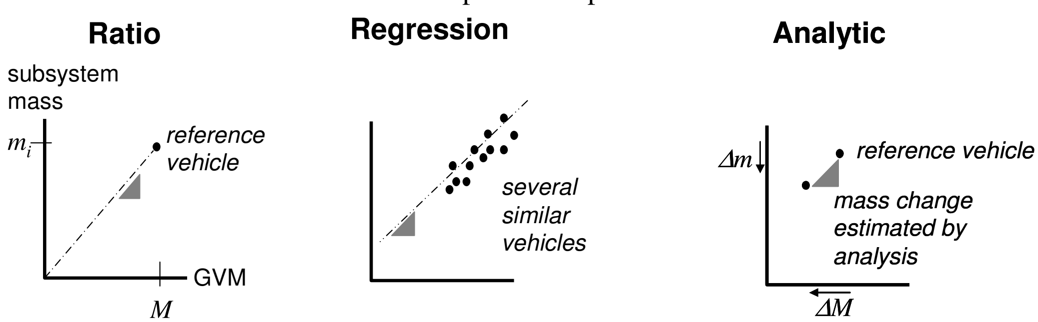
mi_0 =Initial subsystem i mass

Δ_i =Initial mass change in subsystem i

mi_{RS} =Resized subsystem i mass

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

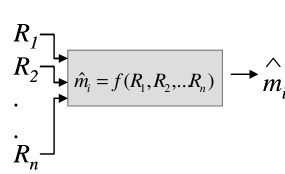
Three methods to estimate mass influence coefficients are shown below. The *Design Advisor* allows the user to select the method and to select simple or compounded mass.



$\gamma_i = m/M$

$\hat{m} =$
$\beta_0 + \beta_1(GVM) + \beta_2(MassDriver_2) + ... + \varepsilon$
or
$\hat{m} = \beta_0 (GVM)^{\beta 1} (massdriver_2)^{\beta 2} ...$

$\gamma_i = \frac{\partial \hat{m}}{\partial GVM}$



R: set of requirements believed to be dominate

Methods to estimate secondary mass influence coefficients

3.5 Primary Cost Estimation- The primary cost change is limited here to material cost and tooling and equipment cost for the primary shaping process. This is modeled by the following equation,

$$C = \left[\frac{m\,C_M}{1-f}\right] + \left[\frac{(C_T)}{n}\right] + \frac{1}{\dot{n}}\left(\frac{C_C}{L \cdot t_{WO}}\right) + \frac{1}{\dot{n}}\dot{C}_{OH}$$

C =Cost per part ($)
C_M =Cost of material ($/kg)
f =Scrap fraction *note: (yield=1-f)*
C_C =Cost of equipment ($)
C_T =Cost of tooling ($)
$\acute{n}$ =Production rate (number of units made per year)
n =Batch size
m =Part mass (kg)
t_{WO} =Capital write-off time (years equipment will be productive)
L =Load factor (fraction of time equipment is productive)
C_{OH} =Overhead rate ($/yr)
(all other costs of production not allocated directly to part)
$C_{OH}=0$ for this analysis

Tooling cost and equipment cost are taken as dependent on part mass. For example, for steel the expressions are shown below.

Process	$\hat{Y} = \beta_0 (Mass)^{\beta_1} + \beta_2$
Equipment Cost	
Steel Stamping	$\hat{Y} = 2478928(Mass^{0.2282})(0.6494^{Shallow})(1.2202^{DeepDraw})$
Hot Stamping	$\hat{Y} = 2478928(Mass^{0.2282})(0.6494^{Shallow})(1.2202^{DeepDraw}) + 1.0E06$
Tailor Welded Blank Stamping	$\hat{Y} = 2478928(Mass^{0.2282})(0.6494^{Shallow})(1.2202^{DeepDraw}) + 3.8E06$
Non Ferrous Stamping	$\hat{Y} = 3167177(Mass^{0.2282})(0.6494^{Shallow})(1.2202^{DeepDraw})$
Tooling Cost	
Steel Stamping	$\hat{Y} = 506037(Mass^{0.402})(0.5081^{Shallow})(1.2643^{DeepDraw})$
Hot Stamping	$\hat{Y} = 506037(Mass^{0.402})(0.5081^{Shallow})(1.2643^{DeepDraw}) + 1.0E06$
Tailor Welded Blank Stamping	$\hat{Y} = 506037(Mass^{0.402})(0.5081^{Shallow})(1.2643^{DeepDraw}) + 3.8E06$
Non Ferrous Stamping	$\hat{Y} = 779106(Mass^{0.402})(0.5081^{Shallow})(1.2643^{DeepDraw})$

Example relationships to determine equipment and tooling cost as a function of part mass

The parameters used for tooling and equipment costs, material utilization and production rate, and material costs are found in the Appendix.

3.6 Subsystem Resizing Cost Estimation-When changing a component, other subsystems of the vehicle may be resized due to mass compounding. This causes a subsystem resizing cost,

subsystem cost change = (subsystem mass change)(subsystem cost/unit subsystem mass)

The subsystem cost/unit mass is determined by the material cost for the subsystem given by the following expressions.

Vehicle Bill of Material, $$\bar{\alpha} = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \dots \\ \alpha_{21} & .\alpha_{ij} & \dots \\ \dots & \dots & \dots \end{bmatrix}$$

where
α_{ij}=*fraction of subsystem i composed of material j*
Note that rows will sum to 1

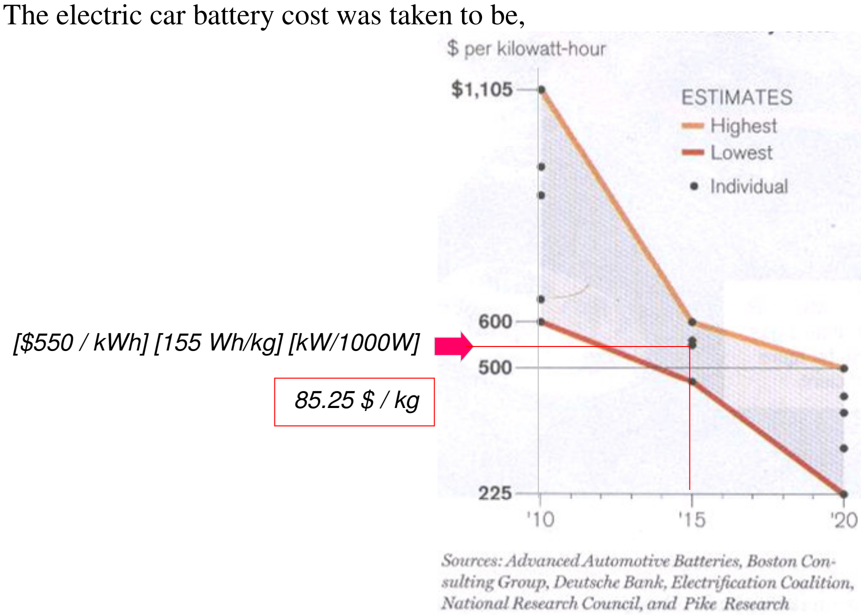
Vector of material costs $$\bar{c} = \begin{bmatrix} c_1 \\ c_j \\ \dots \end{bmatrix}$$

where
c_j=*cost per unit mass of material j ($/kg)*

Material cost of subsystem i in vehicle $$\bar{\mathbf{C}} = \begin{bmatrix} \mathbf{C}_1 \\ \dots \\ \mathbf{C}_i \end{bmatrix} = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \dots \\ \alpha_{21} & \alpha_{ij} & \dots \\ \dots & \dots & \dots \end{bmatrix} \begin{bmatrix} c_1 \\ c_j \\ \dots \end{bmatrix} = (\bar{\alpha})(\bar{c})$$

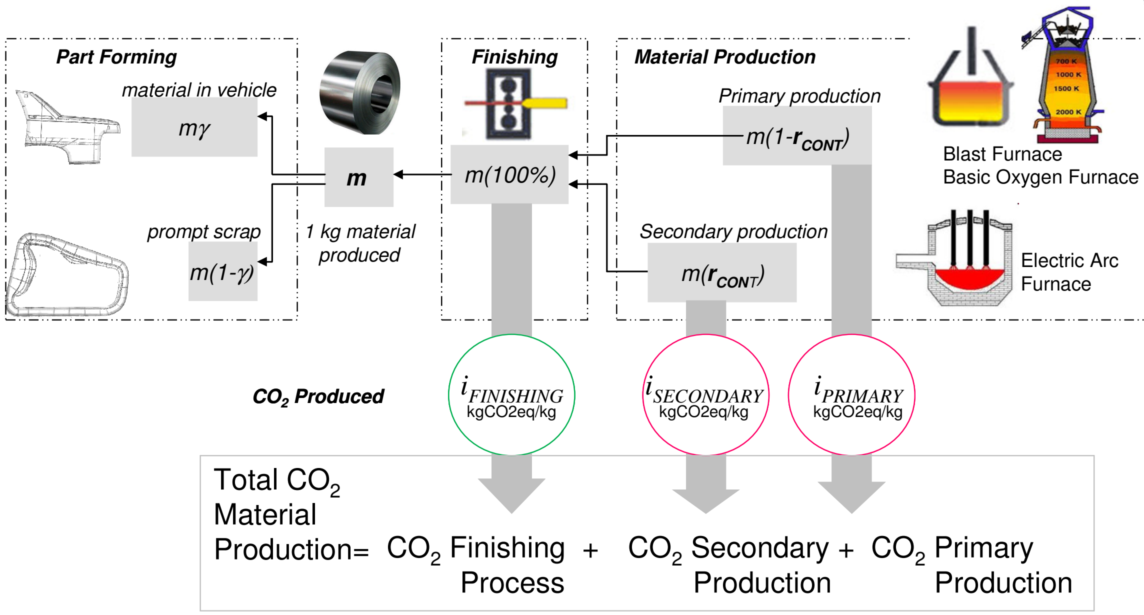
where
$\mathbf{C}_i$=*total material cost of subsystem i in vehicle*

The electric car battery cost was taken to be,



Battery Cost

3.7 Life Cycle Assessment: Material Production- A typical material production sequence is shown below. Material is produced by both a primary production process using basic ore, and also a secondary process using recycled material. After production, the material enters a finishing process (cold rolling in this example) resulting in one unit of material entering the vehicle manufacturing process. Green house gas is produced in the finishing, secondary, and primary production steps. The greenhouse gas calculation is indicated below.



Material Production Flow

$$Total\ CO_2\ Material\ Production =$$
$$[CO_2\ \ Primary\ Production] + [CO_2\ \ Secondary\ Production] + [CO_2\ \ Finishing\ Process]$$
$$I_{MAT} = [m(1 - r_{CONT})i_{PRIMARY}] + [mr_{CONT}i_{SECONDARY}] + [mi_{FINIFSHING}]$$
$$I_{MAT} = m[(1 - r_{CONT})i_{PRIMARY} + r_{CONT}i_{SECONDARY} + i_{FINIFSHING}]$$

$$I_{MAT} = m[i_{TOTAL\_PRODUCTION}]$$

Where

m =*mass of material produced*

I_{MAT} =CO_2 *resulting from production of m kg of finished material (kg* CO_2eq*)*

r_{CONT} =*fraction of material from secondary production*

$i_{PRIMARY}$ =CO_2 *resulting from primary production of 1 kg (kg* CO_2eq*/kg material)*

$i_{SECONDARY}$ =CO_2 *resulting from secondary production of 1 kg (kg* CO_2eq*/kg material)*

$i_{FINISHING}$ =CO_2 *resulting from finishing process of 1 kg (kg* CO_2eq*/kg material)*

$i_{TOTAL\_PRODUCTION}$=CO_2 *resulting from complete production of 1 kg (kg* CO_2eq*/kg material) (resource extraction (cradle) to factory gate)*

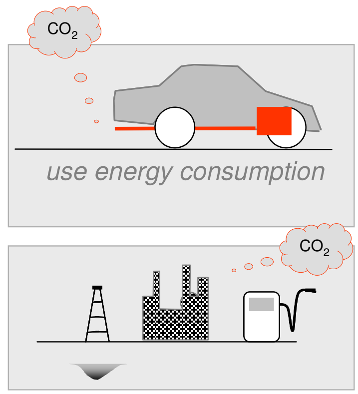
Part shaping process GHG $I_{SHAPE}=m\ i_{SHAPE}$

Where

m =*Mass of material to shaping process (kg)*

i_{SHAPE}=*CO2/kg material*

3.8 Life Cycle Assessment: Use Phase- Greenhouse gas produced during the use phase falls in two areas, the GHG due to fuel consumed in using the vehicle (tank to wheels), and the GHG due to producing the fuel (wheel to tank). Both sources are accounted for in the Design Advisor using the following expressions.



Use phase GHG areas

$$I_{USE} = I_{WELL\_TANK} + I_{TANK\_WHEELS}$$

$$I_{WELL\_TANK} = [i_{FUEL\_PRODUCTION}]R_L(ED)$$

$$I_{TANK\_WHEELS} = [i_{FUEL\_COMBUSTION}]R_L(ED)$$

Where

ED =*Energy demand per unit distance (MJ/100km)*

$ED_{NOMINAL\ VEHICLE}$=*f(vehicle mass, schedule) from fka simulations*

$ED_{RESIZED\ VEHICLE}=(ED)_{NOM}+(\Delta m)(FCME)$

(Δm) =*Difference in mass between resized and nominal vehicles (kg)*

(FCME)=*Fuel Consumption mass elasticity (MJ/100kg)*

R_L =*life time range (km)*

I_{USE} =CO_2 *resulting from vehicle use over life (kg* CO_2*eq)*

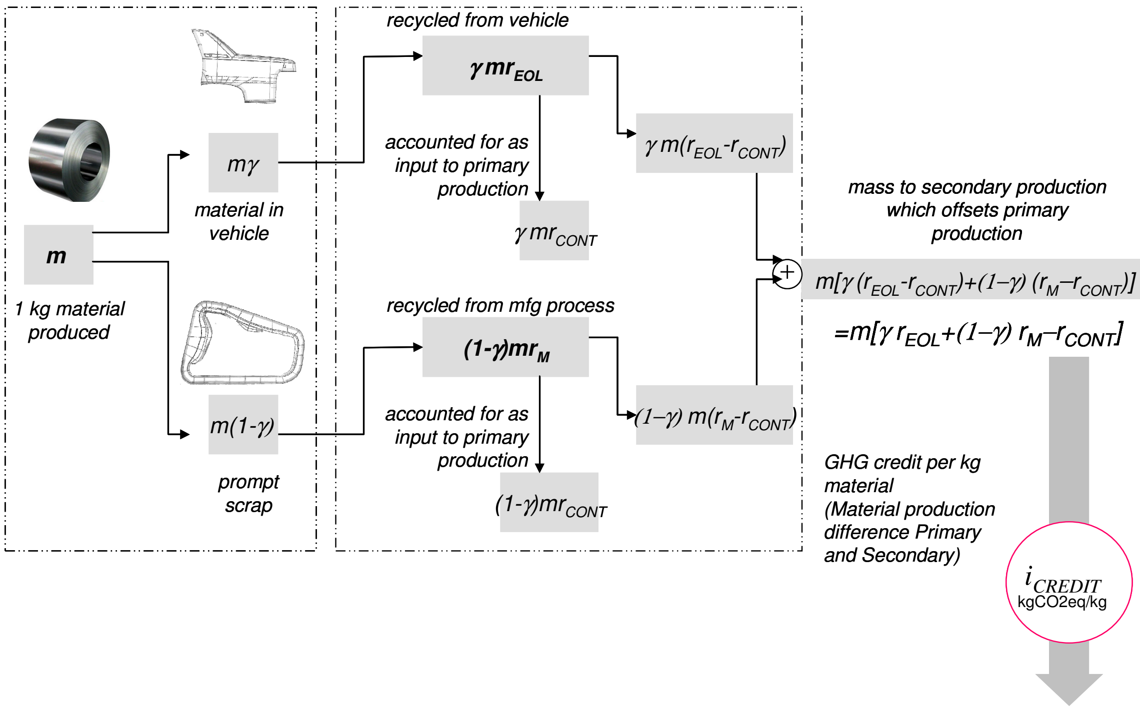
$i_{FUEL\_PRODUCTION}$ =CO_2 *resulting from production of 1 unit of fuel (kg* CO_2*eq/MJ)*

$i_{FUEL\_COMBUSTION}$=CO_2 *resulting from combustion of 1 unit of fuel (kg* CO_2*eq/MJ)*

note: Gasoline equivalent energy demand (liter/100km)=ED/ Q_{LHV}

Q_{LHV} =*Lower Heating Value of fuel (MJ/liter) (for gasoline* Q_{LHV}*=31.88 MJ/liter)*

3.9 Life Cycle Assessment: Recycle- The flow of a unit of material is shown below at the end-of-life stage. A greenhouse gas credit results by displacing a unit of primary material production with a unit of secondary production.



Material Recycling Flow

$$I_{RECYCLE}=(1-\alpha)m[\gamma(r_{EOL}-r_{CONT})+(1-\gamma)(r_M-r_{CONT})](i_{SECONDARY}-i_{PRIMARY})$$

Where

m =*mass of material produced (kg)*

$I_{RECYCLE}$=*CO_2 credit from end of life of ($m\gamma$) kg of material from vehicle (kg CO_2eq)*

r_M =*Prompt scrap recycling rate*

r_{EOL} =*End of Life recycle rate for vehicle*

r_{CONT} =*Scrap input to primary production*

γ =*Vehicle production forming yield (from material mass of m, part mass of $m\gamma$ results)*

i_{CREDIT} =*GHG credit per kg material (Material production difference between Secondary and Primary)*

$i_{PRIMARY}$ =*Environmental impact of primary material production*

$i_{SECONDARY}$ =*Environmental impact of secondary material production*

$(1-\alpha)$ =*Factor for Consequential System Expansion method*

References

1. A2mac1.com Automotive benchmarking, Ypsilanti, MI.

2. Anderson, M., *Course notes for Global Vehicle Integration*, AUTO 501, University of Michigan, 2010.

3. CES EduPack 2012 Version 11.9.9, Grant Design Limited, www.grantadesign.com, Cambridge, UK.

4. EDAG, *WorldAutoSteel - Future Steel Vehicle Phase 2—Report*, April 20, 2011.

5. fka, Wohlecker, Roland, et al., *Determination of Weight Elasticity of Fuel Economy for Conventional ICE Vehicles, Hybrid Vehicles and Fuel Cell Vehicles*, fka, Report 55510, June 2007.

6. fka, Schulte-Corne, Claus, et al., *Determination of weight influence on the energy consumption of battery electric vehicles and plugin hybrid vehicles*, fka, Report 99280, January, 2010.

7. fka, Schulte-Corne, Claus, et al., *Determination of weight influence on the energy consumption according to US regulations*, fka, Report 105620, April 2011.

8. Fuchs, Hannes, *A/SP Lightweight Suspension Front Lower Control Arm Design Optimization,* Great Designs in Steel Seminar, 2010.

9. Geyer, R., *Life Cycle Greenhouse Gas Emission Assessments of Automotive Materials, Methodology Report*, UCSB, WorldAutoSteel, December, 2007

10. Geyer, R, *User Guide for Version 3 of the WorldAutoSteel Energy and GHG Model*, UCSB, WorldAutoSteel, January 6, 2012.

11. Malen D. & Reddy, K., *Preliminary Vehicle Mass Estimation Using Empirical Subsystem Influence Coefficients,* Auto/Steel Partnership, June 26, 2007

12. Malen D., *Automotive Mass Benchmarking*, Auto/Steel Partnership and USAMP, May 15, 2010

13. http://www.epa.gov/nvfel/testing/dynamometer.htm , US Driving Schedules, US EPA.

14. http://www.epa.gov./otaq/tcldata.htm, Test car data files, US EPA.

15. http://greet.es.anl.gov/main, *Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation*, *Argonne Nat. Lab, US DOE.*

16. *USLAB-AVC, Engineering Report*, Porsche Engineering Services, Oct, 2001, Chapter 15: CO_2 and vehicle performance.

17. fka, Scholz-Starke, et al, Determination of Weight Influence on Energy Consumption under EPA Conditions, Report 124960, November 2012.

Appendix A. Notation

A_f	Vehicle frontal area (m^2)
c_j	Cost per unit mass of material j (\$/kg)
C_i	Total material cost of subsystem i in vehicle (\$)
C	Cost per part (\$)
C_C	Cost of equipment (\$)
C_M	Cost of material (\$/kg)
C_{OH}	Overhead rate (\$/yr)
C_T	Cost of tooling (\$)
$e_{DENSITY}$	Battery energy density (Wh/kg)
ED	Energy demand (MJ/100km)
(FCME)	Fuel Consumption mass elasticity (MJ/100kg)
f	Scrap fraction note: (yield=1-f)
i	Subscript for subsystem
$i_{FUEL\_PRODUCTION}$	GHG resulting from production of 1 unit of fuel (kg CO_2eq/MJ)
$i_{FUEL\_COMBUSTION}$	GHG resulting from combustion of 1 unit of fuel (kg CO_2eq/MJ)
i_{CREDIT}	GHG credit per kg material (Material production difference between Secondary and Primary)
$i_{PRIMARY}$	GHG for primary material production per unit mass (kg CO_2eq/kg)
$i_{SECONDARY}$	GHG for secondary material production per unit mass (kg CO_2eq/kg)
$I\_$	GHG total (kg CO_2eq), subscript for USE, MATERIAL PRODUCTION, RECYCLE
j	Subscript for material
L	Vehicle length (m)
L	Load factor (fraction of time equipment is productive)
m_{CURB}	Curb mass (kg)
m_i	Subsystem mass (kg)
m_j	total mass of material j in vehicle
m_{i_0}	Initial subsystem i mass
$m_{i_{RS}}$	Resized subsystem i mass
M_0	Initial vehicle mass for which the subsystems are sized
M_{RS}	Resized vehicle mass
$\acute{n}$	Production rate (number of units made per year)
n	Batch size (number of parts made over life of design)
m	Part mass (kg)
$P_{BATTERY}$	Required battery power (Wh)
r_M	Prompt scrap recycling rate
r_{EOL}	End of Life recycle rate for vehicle
r_{CONT}	Scrap input to primary production
R	Range with fully charged battery (km)
R_L	Life time range (km)
T_{WO}	Capital write-off time (years equipment will be productive)
Q_{LHV}	Lower Heating Value of fuel (MJ/liter) (for gasoline Q_{LHV}=31.88 MJ/liter)
W	Vehicle width
α_{ij}	fraction of subsystem i composed of material j
β	Regression coefficient
Δ	Initial total mass change (primary mass change)
Δ_i	Initial mass change in subsystem i
(Δm)	Difference in mass between resized and nominal vehicles (kg)
ϕ_i	Mass fraction relative to curb mass for subsystem i
γ	Forming yield (from material mass of m, part mass of $m\gamma$ results)
γi	Mass influence coefficient for subsystem *i*

Appendix B. Parameters loaded in spreadsheets

Input Component Data Sheet

Table of vehicle subsystems
B59:B71

Body Non-structure
Body Structure
Front Suspension
Rear Suspension
Braking
Powertrain
Fuel & Exhaust
Steering
Tires & Wheels
Electrical
Cooling
Bumpers
Closures

Table of Part materials
B93:B104

Steel-Conventional
Steel-AHSS
Steel-Hot Stamped
Steel-Stainless
Cast Iron
Aluminum Wrought
Aluminum Cast
Magnesium Wrought
Magnesium Cast
CFRP
GFRP
SMC

Table of Part shaping processes
G94:G106

Steel Stamping
Steel Tailor Welded Blank Stamping
Steel Hot Stamping
Steel Open Roll Form
Steel Tubular Hydroforming
Steel Forging
Iron Casting
NonFerrous Stamping
NonFerrous Extrusion
NonFerrous Die Casting
NonFerrous Forging
Composite Sheet Molding Compound
Composite Resin Transfer

Table of benchmarked components and mapping:
Component to vehicle subsystem, mass driver, units, scaling exponent, and mass benchmark equation
G59:P74

Body Structure	Body Structure	GVM	kg	0.44	Picture 6695
Front Door Frame	Closures	Door Area	m^2	0.87	Picture 6680
Hood Frame	Closures	Hood Area	m^2	1.24	Picture 6681
Deck Lid Frame	Closures	Deck Lid Area	m^2	1.18	Picture 6682
Hatchback Frame	Closures	Hatchback Area	m^2	0.55	Picture 6683
Lift Gate Frame	Closures	Liftgate Area	m^2	0.44	Picture 6684
Instrument Panel Beam	Body Structure	No mass driver		1.00	Picture 6691
Front Bumper Beam	Bumpers	Curb Mass	kg	0.55	Picture 6692
Rear Bumper Beam	Bumpers	Curb Mass	kg	0.87	Picture 6693
Front Seat Frame	Body Non-structure	No mass driver		1.00	Picture 6690
Front Suspension Knuckle	Front Suspension	GVM	kg	0.48	Picture 6686
Front Suspension Lower Control Arm-McPherson	Front Suspension	GVM	kg	0.90	Picture 6687
Front Suspension Lower Control Arm-SLA	Front Suspension	GVM	kg	1.04	Picture 6687
Wheels	Tires & Wheels	Swept Volume	mm^3	0.63	Picture 6689
Exhaust System	Fuel & Exhaust	Engine Disp.	liter	1.00	Picture 6694
Other	N/A	No mass driver		1.00	Picture 6792

Input Component Data Sheet-continued

Table of compatible materials and processes
G130:R135

Steel-Conventional	**Steel-AHSS**	**Steel-Hot Stamped**	**Steel-Stainless**	**Cast Iron**
Steel Stamping	Steel Stamping	Steel Hot Stamping	Steel Stamping	Iron Casting
Steel Tailor Welded Blank Stamping	Steel Tailor Welded Blank Stamping		Steel Tailor Welded Blank Stamping	
Steel Open Roll Form	Steel Open Roll Form		Steel Open Roll Form	
Steel Tubular Hydroforming	Steel Tubular Hydroforming		Steel Tubular Hydroforming	
Steel Forging	Steel Forging		Steel Forging	

Table continued

Aluminum Wrought	**Aluminum Cast**	**Magnesium Wrought**	**Magnesium Cast**	**CFRP**	**GFRP**	**SMC**
NonFerrous Stamping	NonFerrous Die Casting	NonFerrous Stamping	NonFerrous Die Casting	Composite Sheet Molding Compound	Composite Sheet Molding Compound	Composite Sheet Molding Compound
NonFerrous Extrusion		NonFerrous Extrusion		Composite Resin Transfer	Composite Resin Transfer	
NonFerrous Forging		NonFerrous Forging				

Set Nominal Vehicle Sheet

Table of subsystem mass fractions for various powertrain selections
A51:L66

Sub-system	IC-gasoline	IC-diesel	Parallel hybrid-gasoline	Fuel Cell	Plug in Hybrid-20 mile range	Plug in Hybrid-40 mile range	Battery Electric-140 mile range	
1	0.204	0.204	0.204	0.204	**0.184**	0.204	**0.175**	Body Non-structure
2	0.227	**0.237**	**0.232**	0.227	0.227	0.227	**0.207**	Body Structure
3	0.049	**0.059**	**0.059**	0.049	0.049	0.049	**0.039**	Front Suspension
4	0.044	0.044	0.044	0.044	0.044	0.044	**0.034**	Rear Suspension
5	0.032	0.032	**0.037**	**0.037**	**0.037**	**0.037**	**0.037**	Braking
6	0.185	**0.220**	**0.220**	**0.215**	0.185	0.185	**0.109**	Powertrain
7	0.040	0.045	**0.045**	**0.065**	**0.029**	**0.035**	**0.000**	Fuel & Exhaust
8	0.014	0.014	0.014	0.014	0.014	0.014	0.014	Steering
9	0.065	0.065	0.065	0.065	0.065	0.065	**0.055**	Tires & Wheels
10	0.046	0.046	0.046	0.046	0.046	0.046	0.046	Electrical
11	0.027	0.027	0.027	0.027	0.027	0.027	0.027	Cooling
12	0.022	0.022	0.022	0.022	0.022	0.022	0.022	Bumpers
13	0.045	0.045	0.045	0.045	0.045	0.045	**0.035**	Closures
14	0.000	0.000	0.000	0.000	0.029 Depends on curb mass	0.058 Depends on curb mass	0.226 Depends on curb mass	Battery (electric car)
total	1.000	1.060	1.060	1.060	1.003	1.058	1.026	

Table for curb mass estimate for Nominal gasoline IC vehicle
B67:E70

Vehicle Type	Slope: Curb Mass to Area (kg/m^2)	Intercept: Curb Mass to Area Intercept (kg)	standard error (kg)
Sedan/Hatchback	169.71	0.00	132.00
SUV	229.00	0.00	132.00
User Defined	0	0	0

Set Nominal Vehicle Sheet –continued

Table for default material mass fractions for each subsystem and materials in the vehicle Bill of Materials
N73:AF86

	Conv Steel Flat carbon	Conv Steel Long&spec.	AHSS Flat carbon	AHSS Long & special	Hot Stamped Steel	Stainless Steel	Cast Iron	Aluminum Wrought	Aluminum Cast	Copper	Magnesium Cast	Magnesium Wrought	Glass	Plastic	CFRP	GFRP	Rubber	Battery (electric car)	other (no GHG)
Body Non-struc	0.15	0.1	0.03	0.03	0	0	0	0	0.1	0	0	0	0.3	0.4	0	0	0	0	0.1
Body Struct	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Front Susp	0.2	0.3	0	0.2	0	0	0.15	0	0.1	0	0	0	0	0	0	0	0.1	0	0
Rear Susp	0.6	0.1	0	0	0	0	0.15	0	0.1	0	0	0	0	0	0	0	0.1	0	0
Brake		0.2	0	0	0	0	0.8	0	0	0	0	0	0	0	0	0	0	0	0
Pwrtrn	0.15	0.3	0	0	0	0	0.3	0.1	0.2	0	0	0	0	0.1	0	0	0	0	0
Fuel & Exh	0.75	0.1	0	0	0	0.15	0	0	0	0	0	0	0	0	0	0	0	0	0
Steer	0.1	0.65	0	0	0	0	0.20	0	0	0	0	0	0	0	0	0	0.1	0	0
Tires & Wheel	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0
Elect	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Cool	0	0	0	0	0	0	0	0.4	0	0	0	0	0	0.6	0	0	0	0	0
Bmpr	0.8	0.0	0.0	0.0	0.0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0
Clsure	0.55	0.05	0.05	0.0	0.0	0	0	0	0	0	0	0	0.2	0.1	0	0	0.1	0	0
Battry elcCar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

Table for electric car range
D73:G79

Internal Combustion-gasoline	0
Internal Combustion-diesel	0
Parallel hybrid-gasoline	0
Fuel Cell	0
Plug in Hybrid-20 mile range	20
Plug in Hybrid-40 mile range	40
Battery Electric- 155 mile range	155

Battery energy density
D89

Battery energy density	*Wh/kg*	155

Battery cost /kWh
D98

Battery cost projected 2015	*$/kWh*	550

Component Mass Benchmarking Sheet

Table of benchmark data for all components
P53:CH179
Refer to Excel sheet

List of component mass equations
A73:A145
Refer to Excel sheet

Powertrain Sizing Sheet

Table of compatible powertrains and fuels
J85:P91

Internal Combustion-gasoline	Internal Combustion-diesel	Parallel hybrid-gasoline	Fuel Cell	Plug in Hybrid-20 mile range	Plug in Hybrid-40 mile range	Battery Electric-140 mile range
Gasoline	Diesel	Gasoline	Hydrogen	Electricity-USA	Electricity-USA	Electricity-USA
E85	BioDiesel	E85		Electricity-Europe	Electricity-Europe	Electricity-Europe
				Electricity-China	Electricity-China	Electricity-China
				Electricity-Japan	Electricity-Japan	Electricity-Japan
				Electricity-India	Electricity-India	Electricity-India
				Electricity-Coal	Electricity-Coal	Electricity-Coal

Table of energy demands for various powertrains and vehicle mass
E219:M280
Refer to Excel sheet

Mass Compounding sheet

Table of secondary mass coefficients
D53:J68

sub-system	not used	Analytical	Regression	Ratio	User Defined	
1		0.0000	0.0000	(varies with specific case)		Body Non-structure
2		0.0961	0.1267			Body Structure
3		0.0248	0.0272			Front Suspension
4		0.0248	0.0276			Rear Suspension
5		0.0367	0.0238			Braking
6		0.0813	0.0929			Powertrain
7		0.0101	0.0607			Fuel & Exhaust
8		0.0070	0.0086			Steering
9		0.0218	0.0497			Tires & Wheels
10		0.0000	0.0000			Electrical
11		0.0000	0.0000			Cooling
12		0.0000	0.0347			Bumpers
13		0.0000	0.0000			Closures
14		0.0000	0.0000			Battery (electric car)
Sum		0.3025	0.4519			

Component Cost Sheet

Table of material cost for component
B176:C188

Material	Typical $/kg
Steel-Conventional	0.7025
Steel-AHSS	0.9550
Steel-Hot Stamped	1.4800
Steel-Stainless	1.8970
Cast Iron	0.5975
Aluminum Wrought	2.4650
Aluminum Cast	2.5600
Magnesium Wrought	4.9350
Magnesium Cast	4.9950
CFRP	42.1500
GFRP	20.4000
SMC	5.6250

Table of coefficients for equipment and tool cost
E174:O188

Process	tool	tool	tool	tool	tool	equipment	equipment	equipment	equipment	equipment
	param 1	param 2	param 3	opt 1	opt 2	param 1	param 2	param 3	Opti 1	opt 2
Steel Stamping	506037	0.402		0.5081	1.2643	2478928	0.2282		0.6494	1.2202
Steel Tailor Welded Blank Stamping	506037	0.402		0.5081	1.2643	2478928	0.2282	3800000	0.6494	1.2202
Steel Hot Stamping	506037	0.402		0.5081	1.2643	2478928	0.2282	1000000	0.6494	1.2202
Steel Open Roll Form	230.6	1	4897	1	1	6573.1	1	245343	1	1
Steel Tubular Hydroforming	-	1	690000	1	1		1	3350000	1	1
Steel Forging	947.46	1	7530.5	1	1	47206	1	376528	1	1
Iron Casting	0.3931	1	942.8	1	1	6.2836	1	18897	1	1
NonFerrous Stamping	779106	0.402		0.5081	1.2643	3167177	0.2282		0.6494	1.2202
NonFerrous Extrusion	314.18	1	939.86	1	1	141868	1	187581	1	1
NonFerrous Die Casting	9551.3	1	8384.5	1	1	62886	1	188371	1	1
NonFerrous Forging	3158.2	1	7530.5	1	1	157353	1	376528	1	1
Composite Sheet Molding Compound	2994.3	1	9340.2	1	1	8337.5	1	65750	1	1
Composite Resin Transfer	57.459	1	897.03	1	1	958.74	1	8663	1	1

Cost= (Param 1)(part mass, kg)$^{\text{Param 2}}$[(OPT1)$^{\text{SHALLOW}}$(OPT2)$^{\text{DEEP}}$]+(Param 3)

Where
The bracketed term is used only for stamping
SHALLOW=1 if selected, 0 otherwise
DEEP=1 if selected, 0 otherwise

Component Cost Sheet –continued

Equipment and tool cost equations dependent on coefficients

Process	
Equipment Cost	
Steel Stamping	$\hat{Y} = 2478928(Mass^{0.2282})(0.6494^{Shallow})(1.2202^{DeepDraw})$
Hot Stamping	$\hat{Y} = 2478928(Mass^{0.2282})(0.6494^{Shallow})(1.2202^{DeepDraw}) + 1.0E06$
Tailor Welded Blank Stamping	$\hat{Y} = 2478928(Mass^{0.2282})(0.6494^{Shallow})(1.2202^{DeepDraw}) + 3.8E06$
Non Ferrous Stamping	$\hat{Y} = 3167177(Mass^{0.2282})(0.6494^{Shallow})(1.2202^{DeepDraw})$
Tooling Cost	
Steel Stamping	$\hat{Y} = 506037(Mass^{0.402})(0.5081^{Shallow})(1.2643^{DeepDraw})$
Hot Stamping	$\hat{Y} = 506037(Mass^{0.402})(0.5081^{Shallow})(1.2643^{DeepDraw}) + 1.0E06$
Tailor Welded Blank Stamping	$\hat{Y} = 506037(Mass^{0.402})(0.5081^{Shallow})(1.2643^{DeepDraw}) + 3.8E06$
Non Ferrous Stamping	$\hat{Y} = 779106(Mass^{0.402})(0.5081^{Shallow})(1.2643^{DeepDraw})$

Tubular Hydroforming	
Equipment Cost	$\hat{Y} = 3.35E06$
Tooling Cost	$\hat{Y} = 6.90E05$

Process	**Equipment Cost**	**Tooling Cost**
Steel Open Roll Form	$\hat{Y} = 6573.1(Mass) + 245343$	$\hat{Y} = 230.6(Mass) + 4897$
Steel Forging	$\hat{Y} = 47206(Mass) + 376528$	$\hat{Y} = 947.46(Mass) + 7530.5$
Iron Casting	$\hat{Y} = 6.2836(Mass) + 18897$	$\hat{Y} = 0.3931(Mass) + 942.8$
Non Ferrous Extrusion	$\hat{Y} = 141868(Mass) + 187581$	$\hat{Y} = 314.18(Mass) + 939.86$
Non Ferrous Die Casting	$\hat{Y} = 62886(Mass) + 188371$	$\hat{Y} = 9551.3(Mass) + 8384.5$
Non Ferrous Forging	$\hat{Y} = 157353(Mass) + 376528$	$\hat{Y} = 3158.2(Mass) + 7530.5$
Sheet Molding Compound	$\hat{Y} = 8337.5(Mass) + 65750$	$\hat{Y} = 2994.3(Mass) + 9340.2$
Resin Transfer Method	$\hat{Y} = 958.74(Mass) + 8663$	$\hat{Y} = 57.459(Mass) + 897.03$

Subsystem Cost Sheet

Table of material cost for vehicle bill of materials
Y107:Z125

	Material price $/kg
Conv Steel Flat carbon	0.7025
Conv Steel Long&spec.	0.9385
AHSS Flat carbon	0.948375
AHSS Long & special	1.266975
Hot Stamped Steel	1.48
Stainless Steel	1.89675
Cast Iron	0.5975
Aluminum Wrought	3.16125
Aluminum Cast	2.56
Copper	7.285
Magnesium Cast	4.935
Magnesium Wrought	4.935
Glass	6.14
Plastic	3
CFRP	42.15
GFRP	20.4
Rubber	3.96
Battery (electric car)	85.25

LCA Material Sheet

Table of material production parameters for GHG for vehicle Bill of Materials B102:G119 (Reference UCSB Excel Model)

	Material Flows C97 Mat from secondary production, r_{CONT} %	Materials G93 (for conv steel) Emissions from primary production (kgCO2eq/kg produced)	Materials G94 (for conv steel) Emissions from secondary production (kgCO2eq/kg produced)	Materials G100 (for conv steel) Emissions from material finishing (kgCO2eq/kg produced)	Material Flows K97 Forming Manufacturing yield γ(%)
Conv Steel Flat carbon	0.05	1.87	0.40	0.49	0.55
Conv Steel Long&spec.	0.85	1.87	0.40	0.29	0.75
AHSS Flat carbon	0.05	1.87	0.40	0.49	0.55
AHSS Long & special	0.85	1.87	0.40	0.29	0.75
Hot Stamped Steel	0.05	1.87	0.40	0.49	0.55
Stainless Steel	0.05	1.87	0.40	0.49	0.55
Cast Iron	1.00	1.87	0.40	0.14	0.80
Aluminum Wrought	0.00	10.51	0.69	0.87	0.66
Aluminum Cast	0.85	10.51	0.69	0.62	0.80
Copper	0.00	3.74	0.00	0.00	1.00
Magnesium Cast	0.00	35.10	21.00	21.00	0.55
Mag Wrought	0.00	35.10	0.80	0.80	0.96
Glass	0.00	1.07	0.00	0.00	1.00
Plastic	0.00	3.62	0.00	0.00	0.90
CFRP	0.00	22.00	0.00	0.00	0.50
GFRP	0.00	8.00	0.00	0.00	0.50
Rubber	0.00	2.90	0.00	0.00	0.90
Battery (electric car)	0.00	18.60	0.00	0.00	1.00

Table of material production and shaping process GHG parameters for Part B136:G148

	Mat from secondary production, r_{CONT} %	Emissions from primary production (kgCO2eq/kg produced)	Emissions from secondary production (kgCO2eq /kg produced)	Emissions from material finishing (kgCO2eq /kg produced)	Forming Manufacturing yield γ(%)
Steel-Conventional	0.05	1.87	0.40	0.49	0.55
Steel-AHSS	0.05	1.87	0.40	0.49	0.55
Steel-Hot Stamped	0.05	1.87	0.40	0.49	0.55
Steel-Stainless	0.05	1.87	0.40	0.49	0.55
Cast Iron	1.00	1.87	0.40	0.14	0.80
Aluminum Wrought	0.00	10.51	0.69	0.87	0.66
Aluminum Cast	0.85	10.51	0.69	0.62	0.80
Mag Wrought	0.00	35.10	0.80	0.80	0.96
Magnesium Cast	0.00	35.10	21.00	21.00	0.55
CFRP	0.00	22.00	0.00	0.00	0.50
GFRP	0.00	8.00	0.00	0.00	0.50
SMC	0.00	8.00	0.00	0.00	0.50

LCA Material Sheet-continued

Table of Shaping Process GHG kg CO2/kg
I136:U148

	Steel Stamp	Steel Tailor Welded Blank Stamp	Steel Hot Stamp	Steel Open Roll Form	Steel Tubular Hydro forming	Steel Forging	Iron Casting	Non Ferrous Stamp	Non Ferrous Extru	Non Ferrous Die Casting	Non Ferrous Forging	Compo site Sheet MoldCo mp	Compo site Resin Trans
Steel-Conv	0.203	0.203		0.203	0.203	0.203							
Steel-AHSS	0.271	0.271		0.271	0.271	0.271							
Steel-Hot Stamp			0.675										
Steel-Stnless	0.271	0.271		0.271	0.271								
Cast Iron							0.797						
Alum Wrght								0.505	0.987		0.6766		
Alum Cast										0.835			
Mag Wrght								0.457	0.924		0.6766		
Mag Cast										0.823			
CFRP												0.28	0.28
GFRP												0.28	0.28
SMC												0.28	

LCA-Use Sheet

Table of fuel properties
C83:J97

	Fuel production	Fuel production	Fuel combustion	Combustion	fuel cost
	Fuel E30 (for Gas) Energy demand	Fuel G30 (for Gas) GHG	Fuel G73 (for Gas) GHG	Fuel D92 (for Gas) Energy	
				liquid MJ/liter	
	MJ/MJ	(gm CO2eq/MJ)	(gm CO2eq/MJ)		$/L,$/kwhr
Gasoline	0.21	17.97	71.90	31.88	0.97
Diesel	0.14	12.10	76.30	35.95	1.04
E85-corn	0.65	64.57	15.13	22.72	0.95
BioDiesel-soybeans	0.27	49.00	0.00	32.64	1.00
Hydrogen	0.77	132.00	0.00	31.88	
Electricity-USA	2.64	208.50	0.00	1.00	0.10
Electricity-Europe	2.26	144.53	0.00	1.00	0.20
Electricity-China	2.86	270.28	0.00	1.00	0.15
Electricity-Japan	2.40	165.75	0.00	1.00	0.25
Electricity-India	2.85	256.39	0.00	1.00	0.10
Electricity-Coal	3.26	333.69	0.00	1.00	0.09

Table of fuel source by powertrain type
C113:G122

	Energy source for various powertrains		Data Input J126 percent driving mix-elect/fuel
	Liquid fuel	electricity	
Internal Combustion-gasoline	1	0	
Internal Combustion-diesel	1	0	
Parallel hybrid-gasoline	1	0	
Fuel Cell	1	0	
Plug in Hybrid-20 mile range	0.5	0.167	0.5 elect
Plug in Hybrid-40 mile range	0.5	0.167	0.5 elect
Battery Electric- 140 mile range	0	1	

LCA-Use Sheet-continued

Table of fuel consumption reduction for ***liquid fuels same powertrain displacement***
I62:N71 (NEW ED-ES D18) Note: DA uses the same Fuel Consumption Reduction acrross all vehicle msss.

(MJ/100kg)	same powertrain displacement (inc perf)				
Powertrain from 'Set Nominal Vehicle' sheet list	HYZEM	NEDC	US Comb	US Highway	US City
Internal Combustion-gasoline	4.069	3.441	3.324	2.251932	4.849324
Internal Combustion-diesel	3.639	4.485	3.186	2.24369	4.567041
Parallel hybrid-gasoline	3.397	2.796	3.083	2.123464	3.859896
Fuel Cell	2.893	2.279	2.111	1.634325	2.537657
Plug in Hybrid-20 mile range	4.188	3.100	3.697		
Plug in Hybrid-40 mile range	3.886	4.437	4.306		
Battery Electric- 140 mile range	0.000	0.000	0.000		

Table of fuel consumption reduction for ***liquid fuels powertrain displacement resized***
P62:T71 (NEW ED-ES D30)

(MJ/100kg)	HYZEM	NEDC	US Com	US Hiway	US City
Internal Combustion-gasoline	8.860	11.515	9.247	6.610483	12.97713
Internal Combustion-diesel	7.237	9.652	7.422	5.275385	10.40687
Parallel hybrid-gasoline	5.939	5.140	5.910	5.205484	6.480586
Fuel Cell	2.355	2.810	2.651	1.987078	3.241993
Plug in Hybrid-20 mile range	5.070	4.006	4.148		
Plug in Hybrid-40 mile range	5.291	5.376	5.106		
Battery Electric- 140 mile range	0.000	0.000	0.000		

Table of fuel consumption reduction for ***electricity same powertrain displacement***
V62:Z71 (NEW ED-ES K18)

(MJ/100kg)	HYZEM	NEDC	US comb	US Hiway	US City
Internal Combustion-gasoline	0	0	0	0	0
Internal Combustion-diesel	0	0	0	0	0
Parallel hybrid-gasoline	0	0	0	0	0
Fuel Cell	0	0	0	0	0
Plug in Hybrid-20 mile range	1.42604	1.257063	1.35838	2.851586	4.96742
Plug in Hybrid-40 mile range	1.434639	1.269371	1.424193	2.517869	5.319639
Battery Electric- 140 mile range	1.41596	1.264472	1.448176	0.931794	1.704994

Table of fuel consumption reduction for ***electricity powertrain displacement resized***
AB62:AF71 (NEW ED-ES K30)

(MJ/100kg)	HYZEM	NEDC	US Comb	US Hiway	US City
Internal Combustion-gasoline	0	0	0	0	0
Internal Combustion-diesel	0	0	0	0	0
Parallel hybrid-gasoline	0	0	0	0	0
Fuel Cell	0	0	0	0	0
Plug in Hybrid-20 mile range	1.615881	1.3808	1.460205	3.498146	5.286579
Plug in Hybrid-40 mile range	1.627076	1.386149	1.546266	3.549518	5.66624
Battery Electric-140 mi range	1.596435	1.293654	1.450687	1.122712	1.763017

LCA-Recycle Sheet

Table of parameters for GHG credit for materials in the vehicle Bill of Materials
D101:K119

	Material Flows K97 Forming Yield γ from LCA-Material sheet	Material Flows R97 Recycling rate matl in vehicle r_{EOL} %	Materials G95 (for conv steel) Emission credit (kgCO2eq/kg recycled)	Material Flows N97 prompt scrap recycle rate R_M %	Material Flows C97 Mat from secondary production, r_{CONT} %	Material Flows D97 NOT USED S_P=scrap input to primary production	Data Input E135 alpha
Conv Steel Flat carbon	0.55	0.903	1.471	0.97	0.05	0.106	0.1
Conv Steel Long&spec.	0.75	0.903	1.471	0.97	0.85	0.106	0.1
AHSS Flat carbon	0.55	0.903	1.471	0.97	0.05	0.106	0.1
AHSS Long & special	0.75	0.903	1.471	0.97	0.85	0.106	0.1
Hot Stamped Steel	0.55	0.903	1.471	0.97	0.05	0.106	0.1
Stainless Steel	0.55	0.903	1.471	0.97	0.05	0.106	0.1
Cast Iron	0.80	0.903	1.471	0.97	1	0	0.1
Aluminum Wrought	0.66	0.786	9.82	0.921	0	0	0.1
Aluminum Cast	0.80	0.786	9.82	0.921	0.85	0	0.1
Copper	1.00	0.9	1	0	0	0	0.1
Magnesium Cast	0.55	0.786	31.5	0.921	0	0	0.1
Magnesium Wrought	0.96	0.786	31.5	0.921	0	0	0.1
Glass	1.00	0	0	0	0	0	0.1
Plastic	0.90	0.7	1	1	0	0	0.1
CFRP	0.50	0	22	0	0	0	0.1
GFRP	0.50	0	8	0	0	0	0.1
Rubber	0.90	0	0	0	0	0	0.1
Battery (electric car)	1.00	0	4.82	0	0	0	0.1

Table of parameters for GHG credit for materials in the part
D123:I135

	Forming Yield γ %	Recycling rate matl in vehicle reol %	Emission credit kg CO2 /kg	prompt scrap recycle rate R_M %	Mat from secondary production, r_{CONT} %
Steel-Conventional	0.55	0.90	1.47	0.97	0.05
Steel-AHSS	0.55	0.90	1.47	0.97	0.05
Steel-Hot Stamped	0.55	0.90	1.47	0.97	0.05
Steel-Stainless	0.55	0.90	1.47	0.97	0.05
Cast Iron	0.80	0.90	1.47	0.97	1.00
Alum Wrought	0.66	0.79	9.82	0.92	0.00
Aluminum Cast	0.80	0.79	9.82	0.92	0.85
Mag Wrought	0.96	0.79	31.50	0.92	0.00
Magnesium Cast	0.55	0.79	31.50	0.92	0.00
CFRP	0.50	0.00	22.00		0.00
GFRP	0.50	0.00	8.00		0.00
SMC	0.50	0.00	8.00		0.00