Life Cycle Assessment of Steel vs. Aluminium Body Structures

This Life Cycle Assessment (LCA) follows up on the findings of the WorldAutoSteel study, *A New Paradigm for Automotive Mass Benchmarking*[1], which explored the current production vehicle data provided in the A2Mac1 teardown database, and using statistical benchmarking regression models, identified those components that were lighter than others of the same size and performance in the database, called the efficient designs. This LCA compares the efficient steel and aluminium body structure designs.

Life Cycle Assessment (LCA) is a methodology that considers a vehicle's entire life cycle, from the manufacturing stage (including material production and vehicle assembly) through the use stage (including production and combustion of fuel) to the end of life (EOL) stage (including end of life disposal and recycling).

Current automotive emissions regulations around the world are aimed at reducing Greenhouse Gas (GHG) emissions of automobiles, but focus only on tailpipe emissions, which are only a part of the actual life-cycle impact of an automobile (See Figure 1).

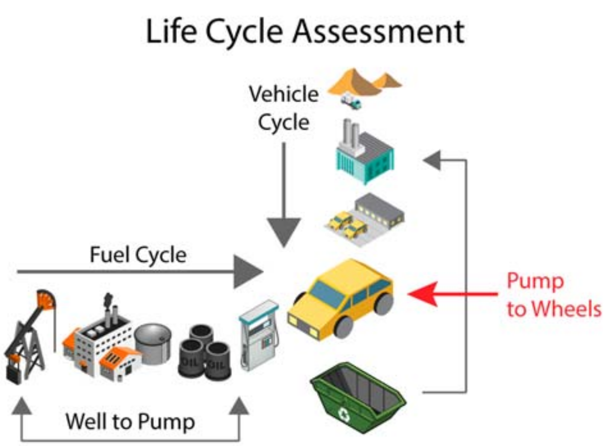


Figure 1 -Sources of GHG emissions in a vehicle's life cycle

Emphasis on the tailpipe alone may have the unintended consequence of increasing GHG emissions during the vehicle life. For example, many automakers, in order to comply with increasingly stringent tailpipe emissions regulations, are turning to low-density materials in an effort to reduce mass. By reducing the mass of a vehicle, it is possible to reduce the fuel consumption and, consequently, the tailpipe emissions. However, many of these materials can have impacts in the other life cycle stages that outweigh any advantage that may be gained in the use stage. This means that, contrary to the stated objective of reducing the GHG emissions of automobiles, tailpipe-only regulations may have the unintended consequence of actually *increasing* the GHG impact. This is why WorldAutoSteel is participating in the development of LCA tools and methodology and encouraging the use of LCA in the formulation and implementation of automotive emissions regulations.

Using data and mass estimation models from the WorldAutoSteel study, this case study will investigate the life cycle GHG impact of three principal categories of material usage in the Body Structure subsystems represented in the A2Mac1 data:

1. Average steel design – Using regression methodology, a power model was used to determine an estimated mass of each subsystem based on the influence of a primary mass driver. In the case of the body structure, the primary mass driver is gross vehicle weight (GVW).

2. Efficient steel design – The model developed for the average steel designs was iteratively manipulated until it was representative of the 17 most efficient steel designs.

3. Efficient aluminium design – A power model of the most efficient aluminium designs was developed in the same way as for the efficient steel designs.

These three categories were further compared with a fourth category, developed from body structure designs taken from the FutureSteelVehicle (FSV) program[2]. FSV is a clean-sheet vehicle architecture that offers mass-efficient, steel-intensive solutions to automotive lightweighting challenges.

The estimation of life cycle GHG emissions was conducted using the UCSB Automotive Materials GHG Comparison Model[3]. The UCSB Model was designed to quantify the energy and GHG impacts of automotive material substitution on a total vehicle life cycle basis, under a broad range of conditions and in a completely transparent fashion, and has been peer-reviewed.

A. Model Parameters

1. Body structure mass

Body structure masses from each of the four categories were applied to two vehicle classes as defined by the NHTSA[4] study:

- Passenger Car/Light (PC/L) – curb weight 907-1134 kg
- Passenger Car/Compact (PC/C) – curb weight 1134-1360 kg

Mass drivers for vehicles in the A2Mac1 data that fit these categories were averaged and used in the appropriate models to generate an estimated average body structure mass for each category and class. The FSV design masses were averaged into the two NHTSA classes as follows:

- FSV1 (2 A-B class designs) – PC/L
- FSV2 (2 C-D class designs) – PC/C

Table 1 provides the resulting body structure average masses:

Table 1: Average Mass of Body Structures in kg

NHTSA Class	# in A2Mac1	GVW (kg)	Average Steel	Efficient Steel	Efficient Aluminium	FSV
PC/L	11	1487	250.1	219.5	172.9	195.9
PC/C	16	1714	295.1	259.0	204.0	216.7

2. Bill of Materials (BOM) Calculations

The bill of materials (BOM) for each design was calculated using the average curb mass of each category and class (Table 2). The UCSB model contains default values for each material as a percentage of curb mass. These defaults include a distribution in the body structure of 90% flat/10% long for steel designs, and 70%flat/30% extruded for aluminium designs.

Table 2: Bill of Materials in kg

	Passenger Car/Light (PC/L)				Passenger Car/Compact (PC/C)			
	Average Steel	Efficient Steel	Efficient Alum	FSV1	Average Steel	Efficient Steel	Efficient Alum	FSV2
Flat carbon steel	373	148	148	148	464	198	198	198
Long steel	140	115	115	115	174	144	144	144
Cast iron	93	93	93	93	116	116	116	116
Flat AHSS	0	198	0	176	0	233	0	195
Long AHSS	0	22	0	20	0	26	0	22
Rolled aluminium	9	9	130	9	12	12	154	12
Extruded aluminium	9	9	61	9	12	12	73	12
Cast aluminium	47	47	47	47	58	58	58	58
Other	350	350	350	350	414	414	414	414
Plastic	112	112	112	112	139	139	139	139
Rubber	28	28	28	28	35	35	35	35
Glass	28	28	28	28	35	35	35	35
Copper	19	19	19	19	23	23	23	23
Other	75	75	75	75	93	93	93	93
Fluids	29	29	29	29	29	29	29	29
Tires	60	60	60	60	60	60	60	60
Vehicle mass	**1022**	**992**	**945**	**968**	**1249**	**1213**	**1158**	**1170**

Other key parameters include:

- **Recycling methodology** – in accordance with the Declaration by the Metals Industry on Recycling Principles[5], the avoided burden method, in which credit is given for producing material (scrap) that allows a downstream user to avoid production of primary material, was used.
- **Powertrain** – for purposes of determining the use phase impacts, a conventional gasoline powertrain has been assumed.
- **Lifetime Driving Distance (LTDD)** – A2Mac1 database includes cars from all OEMs, and because automotive GHG modeling is very sensitive to this parameter, results were calculated using both European (150,000 km) and North American (250,000 km) averages for LTDD.
- **Powertrain resizing** – because the model is also very sensitive to the decision whether or not to resize the powertrain to take full advantage of mass reduction, results have been calculated both with and without resizing.
- **Secondary mass change** – as the mass differences involved in this study are relatively small (in all cases <100 kg), no secondary mass effects have been considered.
- **Driving cycle** – the New European Driving Cycle (NEDC) was used.
- **Fuel Consumption** – the UCSB model relies on baseline fuel consumption and weight elasticity values (WEV) developed by Forschungsgesellschaft Kraftfahrwesen mbH Aachen (fka)[6]. For purposes of this case study, the baseline fuel consumption and WEV for the compact class (NEDC driving cycle) was used. This WEV equates to a fuel reduction value (FRV) of .102 l/100kg/100km when the powertrain is not resized, and .282 l/100kg/100km when the powertrain is resized. The compact class baseline fuel consumption given by fka is 5.56 l/100km.

B. Body Structure Results

1. Total Life Cycle GHG Emissions

The results (Table 3) show that, for all eight scenarios studied, the efficient steel design yields the lowest life cycle GHG emissions, with GHG savings over the baseline average steel designs of 193 to 798 kg CO_2e. The FSV designs show the potential for an additional 118 to 721 kg GHG reduction. The possibility for unintended consequences is apparent from the results of the aluminium designs. In all cases, except the two that combine the 250,000 km driving distance with optimum powertrain resizing, the aluminium design, while producing the lowest use phase emissions, shows a net *increase* in GHG emissions over the existing average steel design. Even in the two scenarios for which the aluminium design shows life cycle GHG emissions lower than the baseline, it is clear that in order to minimize emissions, an efficient steel design is the right choice.

Table 3: Relative GHG Emissions in $kgCO_2e$ – Body Structure

		Passenger Car/Light (PC/L)				Passenger Car/Compact (PC/C)			
		Average Steel (baseline)	Efficient Steel	Efficient Alum	FSV1	Average Steel (baseline)	Efficient Steel	Efficient Alum	FSV2
No Resizing	150000	-	-190	623	-337	-	-224	736	-488
	250000	-	-277	403	-492	-	-327	476	-711
With Resizing	150000	-	-420	42	-745	-	-496	50	-1,078
	250000	-	-661	-565	-1,172	-	-779	-667	-1,695

2. Body Structure GHG Emissions by Life Cycle Phase

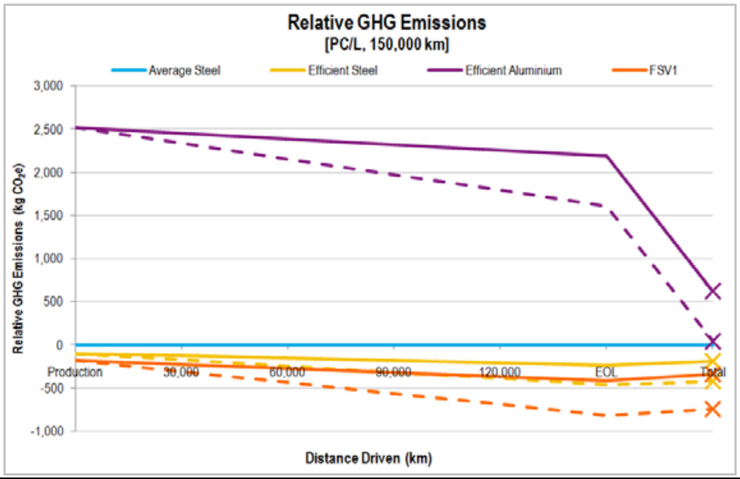
GHG emissions for each combination of class and driving distance are displayed by life cycle phase in Figures 2 through 5. For all eight cases studied, the efficient steel and FSV designs show a consistent pattern:

- Lower production phase emissions due to the reduced amount of material required.
- Lower use phase emissions due to reduced mass of the vehicle.
- Slightly higher EOL emissions due to smaller credit for recycling because less material goes into the vehicle, less EOL scrap is available for downstream recycling.

The effect of this pattern is, as outlined above, lower total emissions. The slightly higher EOL impact is outweighed by savings in the production and use phases. The two aluminium designs show a different, but still consistent, pattern:

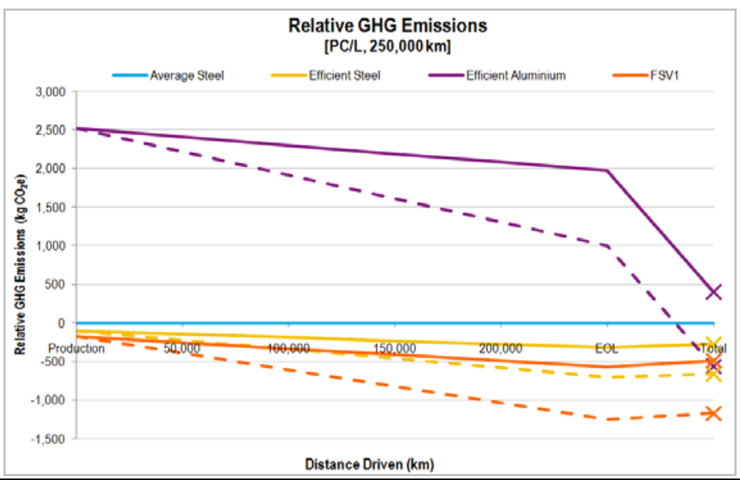
- Significantly higher production phase emissions due to energy-intensive aluminium production.
- Lower use phase emissions due to reduced mass of the vehicle.
- Significantly lower EOL emissions due to larger credit for recycling – recycling credit is based on the difference between primary and secondary material production, and for aluminium this difference is relatively high.

The effect of this pattern is higher overall emissions, except for the two cases that assume both the 250,000 km LTDD and optimal resizing of the powertrain (Figures 3 and 5). The lower use and EOL phase emissions are outweighed by the increase in the production phase.



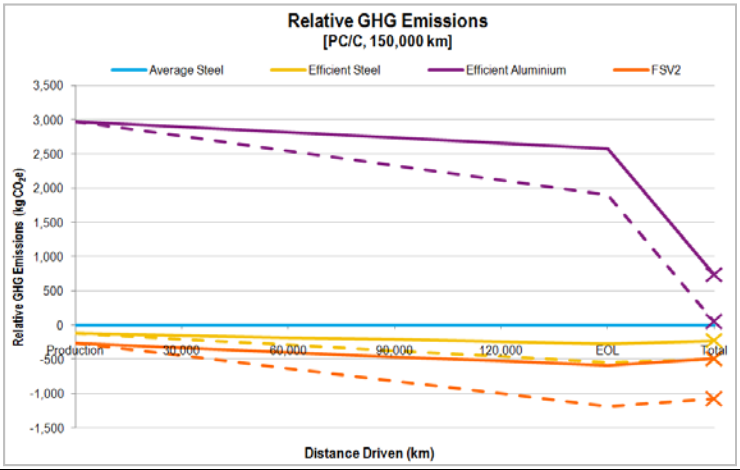
	Without Powertrain Resizing				With Powertrain Resizing			
	Average Steel (baseline)	Efficient Steel	Efficient Aluminium	FSV1	Average Steel (baseline)	Efficient Steel	Efficient Aluminium	FSV1
Production	0	-101	2519	-180	0	-101	2519	-180
Use	0	-131	-330	-232	0	-361	-911	-640
End of Life	0	42	-1566	74	0	42	-1566	74
Total	0	**-190**	**623**	**-337**	0	**-420**	**42**	**-745**

Figure 2: Relative GHG Emissions by driving distance- PC/L, 150,000 km



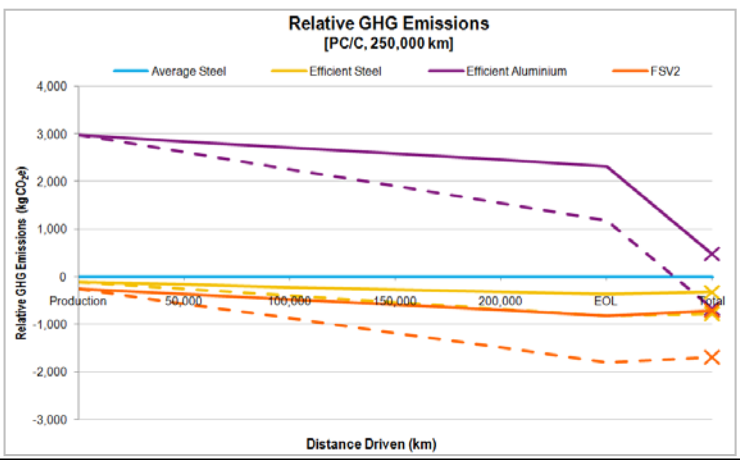
	Without Powertrain Resizing				With Powertrain Resizing			
	Average Steel (baseline)	Efficient Steel	Efficient Aluminium	FSV1	Average Steel (baseline)	Efficient Steel	Efficient Aluminium	FSV1
Production	0	-101	2519	-180	0	-101	2519	-180
Use	0	-218	-550	-386	0	-601	-1519	-1066
End of Life	0	42	-1566	74	0	42	-1566	74
Total	0	**-277**	**403**	**-492**	0	**-661**	**-565**	**-1172**

Figure 3: Relative GHG Emissions by driving distance - PC/L, 250,000 km



	Without Powertrain Resizing				With Powertrain Resizing			
	Average Steel (baseline)	Efficient Steel	Efficient Aluminium	FSV1	Average Steel (baseline)	Efficient Steel	Efficient Aluminium	FSV1
Production	0	-120	2973	-260	0	-120	2973	-260
Use	0	-154	-390	-335	0	-425	-1075	-925
End of Life	0	49	-1848	107	0	49	-1848	107
Total	0	**-224**	**736**	**-488**	0	**-496**	**50**	**-1078**

Figure 4: Relative GHG Emissions by driving distance- PC/C, 150,000 km



	Without Powertrain Resizing				With Powertrain Resizing			
	Average Steel (baseline)	Efficient Steel	Efficient Aluminium	FSV1	Average Steel (baseline)	Efficient Steel	Efficient Aluminium	FSV1
Production	0	-120	2973	-260	0	-120	2973	-260
Use	0	-257	-649	-559	0	-709	-1792	-1542
End of Life	0	49	-1848	107	0	49	-1848	107
Total	0	**-327**	**476**	**-711**	0	**-779**	**-667**	**-1695**

Figure 5: Relative GHG Emissions by driving distance - PC/C, 250,000 km

C. Other Systems

Six additional subsystems described in the A2Mac1 database were analyzed in the same manner: Front Bumper, Rear Bumper, Wheels (4 wheels), Hatchback, Hood, and Front Door (2 doors). Because of the relatively small mass of these subsystems, no powertrain resizing was considered. Only the three categories (average steel, efficient steel, efficient aluminium) from the A2Mac1 database were considered, since the comparison efficient steel vehicle, FSV, did not include designs for the other subsystems.

1. Subsystem Masses

Table 4: Subsystem Masses (kg)

	Passenger Car/Light (PC/L)			Passenger Car/Compact (PC/C)		
	Average Steel (baseline)	Efficient Steel	Efficient Aluminium	Average Steel (baseline)	Efficient Steel	Efficient Aluminium
Front Bumper	4.5	2.4	2.1	5.4	2.9	2.5
Rear Bumper	4.4	1.9	1.5	5.3	2.3	1.8
Wheels	35.1	27.5	24.2	41.7	32.7	28.8
Hatchback	11.4	8.7	7.6	12.2	9.2	8.1
Hood	8.8	6.8	4.5	11.3	8.8	5.8
Front Door	30.9	24.6	19.2	32.6	25.9	20.3

D. LCA Results

The LCA results in Table 5 show a trend similar to that of the body structure analysis. In 14 of the 24 scenarios studied, the efficient aluminium design shows the unintended consequence of *higher* life cycle emissions than the baseline design. And, in *all* scenarios, the efficient aluminium design shows *higher* life cycle emissions than the efficient steel design. As in the case of the body structure, the most efficient steel design shows the lowest life cycle emissions in all cases.

Table 5: Relative Difference in Total Life Cycle GHG Emissions in kg CO_2e - Subsystems

		Passenger Car/Light (PC/L)			Passenger Car/Compact (PC/C)		
		Avg Steel (baseline)	Efficient Steel	Efficient Aluminium	Avg Steel (baseline)	Efficient Steel	Efficient Aluminium
Front Bumper	150000	0	-13	0	0	-16	0
	250000	0	-19	-7	0	-23	-8
Rear Bumper	150000	0	-16	-8	0	-19	-9
	250000	0	-23	-16	0	-27	-19
Wheels	150000	0	-48	101	0	-57	121
	250000	0	-69	71	0	-82	84
Hatchback	150000	0	-17	29	0	-19	31
	250000	0	-25	18	0	-27	19
Hood	150000	0	-13	4	0	-16	6
	250000	0	-18	-8	0	-24	-10
Front Door	150000	0	-40	61	0	-42	64
	250000	0	-58	27	0	-61	29

E. Conclusions

From a total life cycle perspective, the mass savings achieved by aluminium in current production vehicles is not resulting in a smaller vehicle emissions footprint overall. For all cases studied, the efficient steel designs show a consistent pattern of lower emissions in production, use and EOL, which results in lower total cycle emissions. The aluminium designs showed higher production phase emissions due to the energy-intensive manufacturing process, which is offset neither by the reduced use phase emissions nor the significantly lower EOL due to the larger recycling credit.

Regulations based on tailpipe emissions drive the use of low density materials, such as aluminium, to achieve fleet average fuel consumption targets. However, as these challenges are faced during the vehicle design process, the value of the lightweighting technology must be properly weighed against cost and life cycle emissions.

Annotations

[1] A New Paradigm in Automotive Mass Benchmarking (September 2015), available at http://www.worldautosteel.org/projects/auto-mass-benchmark/

[2] FutureSteelVehicle (May 2011, May 2013), available at http://www.worldautosteel.org/projects/future-steel-vehicle/

[3] Geyer, Roland: The Example of Mild Steel, Advanced High Strength Steel and Aluminium in Body in White Applications Methodology Report (December 2007). The Methodology Report and a free download of the UCSB Automotive Greenhouse Gas Materials Comparison Model are available at http://www.worldautosteel.org/projects/vehicle-lca-study/assessments-of-automotive-material/

[4] Singh, Harry, *Mass Reduction for Light-Duty Vehicle Models Years 2017 – 2025 Final Report,* NHTSA Report DOT HS 811666 (http://www.nhtsa.gov), (August 2012,).

[5] AISI, et al., *Declaration by the Metals Industry on Recycling Principles*, International Journal of Life Cycle Assessment, 2006

[6] 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.