



The impact of material choice in vehicle design on life cycle greenhouse gas emissions

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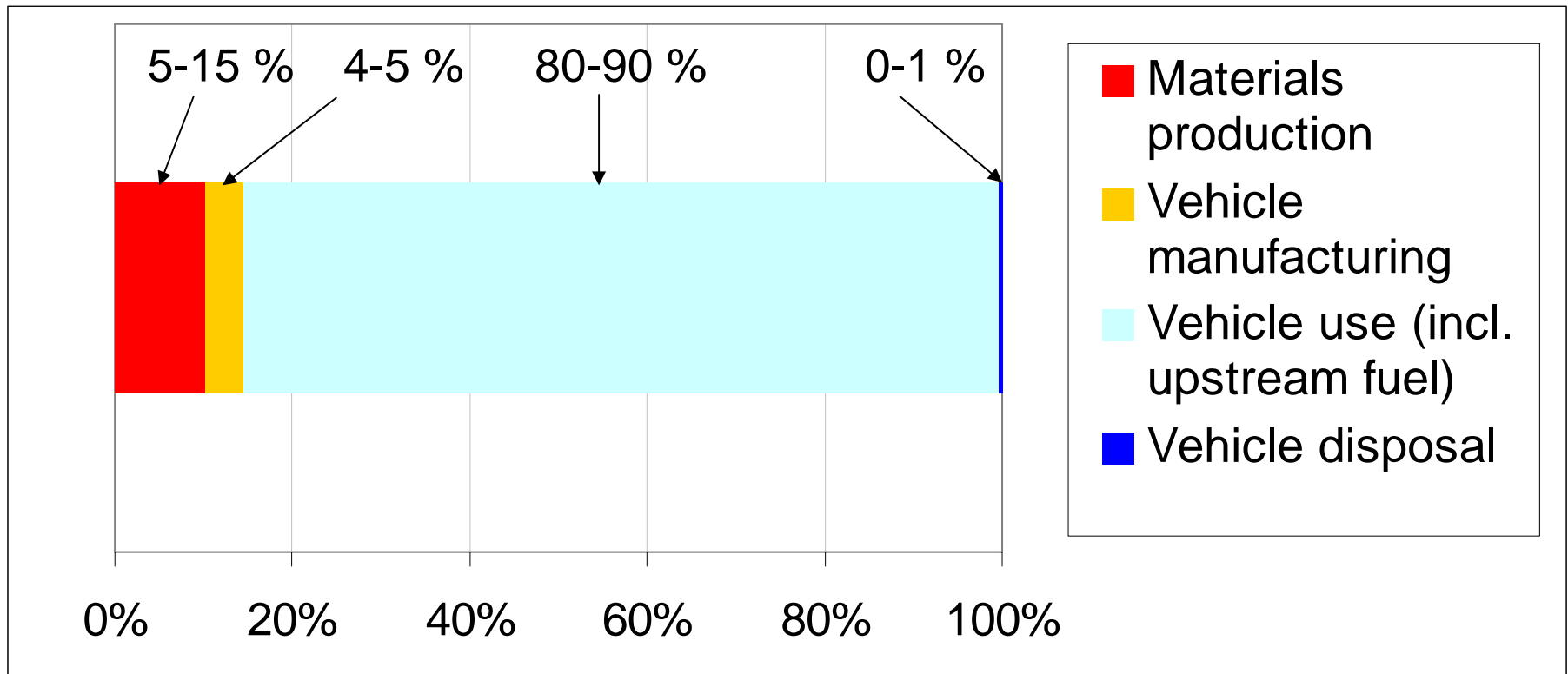


InLCA/LCM 2006, 4 - 6 October, Washington, DC

Typical life cycle greenhouse gas (GHG) emissions of a passenger car:

Total:

Compact	~ 50	tonnes of CO2 eq
Midsize	~ 60-70	tonnes of CO2 eq
SUV	~ 80+	tonnes of CO2 eq



Vehicle GHG reduction strategies focus on the use phase



Pressure to reduce greenhouse gas emissions from vehicles is increasing:

European Union

Goal: Average of 120 g CO₂ per km driven for passenger cars by 2010

- 1999/2000: Voluntary agreements with car manufacturers

California - Assembly Bill 1493

Goal: Average of 127 g CO₂eq per km driven for passenger cars by 2016

- 2002: AB 1493 passes Assembly and Senate
- 2004: AB 1493 is approved by Governor

New York State

- 2005: Official proposal to adopt California's regulation

Canada

- 2005: Voluntary agreements with car manufacturers

Unfortunately agreements / regulations do not use a full life cycle perspective

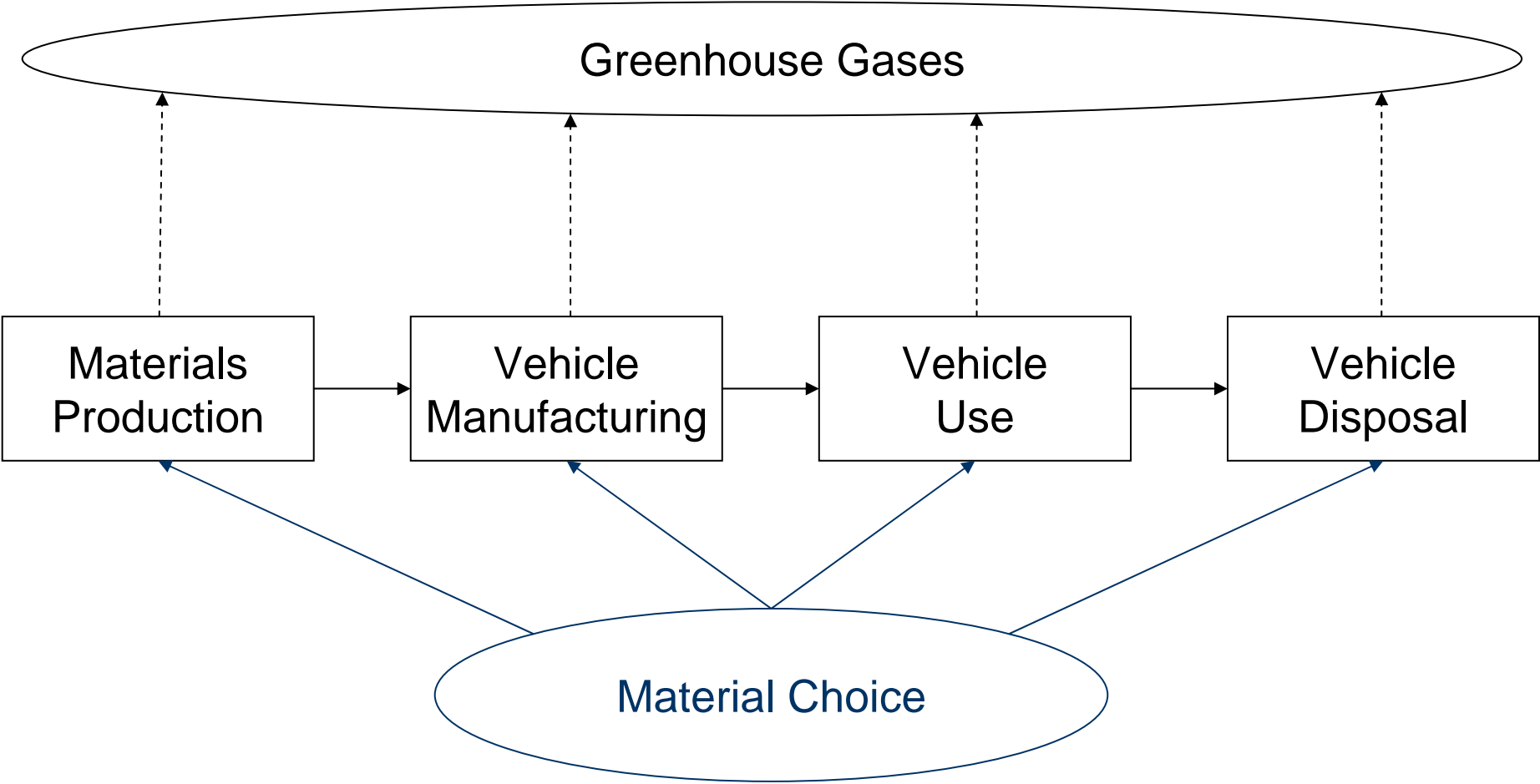


There are many ways to improve the fuel economy of vehicles:

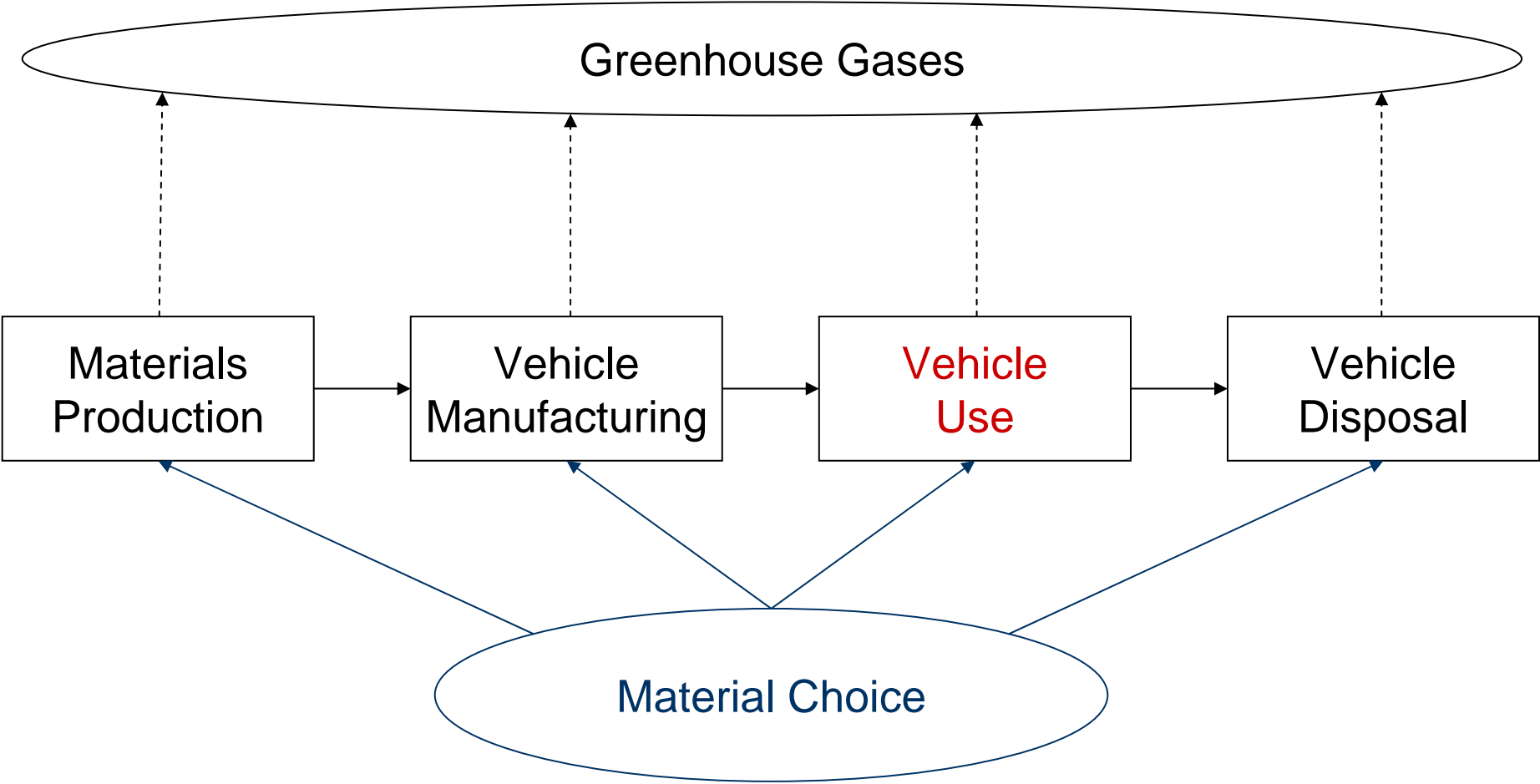
- **Power train modifications:**
HEV, BEV, FCV
- **Engine modifications:**
variable valve timing and lift, cylinder shut-off
- **Fuel combustion modifications:**
Turbocharger, variable compression rates, direct injection
- **Transmission modifications:**
Continuously variable transmission, shifting schedules
- **Alternative fuels:**
Diesel, biodiesel, ethanol, hydrogen
- **Reduction of aerodynamic drag and rolling resistance:**
Body shape, tires
- **Vehicle mass reduction:**
Smaller vehicles, better packaging, **light-weight materials**



Material choice can impact GHG emissions at all life cycle stages:



Impact of material choice on the vehicle use phase:



Calculation of GHG reductions during vehicle use phase:

$$\Delta E_{use} = \Delta FE \cdot E_{fuel} \cdot TM / 100$$

$$\Delta FE = FS \cdot (1 + s) \cdot (1 - k) \cdot \Delta M / 100$$

- ΔFE Fuel economy improvement (in l/100km)
- E_{fuel} GHG emissions from production, delivery and combustion (in CO₂eq/l)
- TM Total mileage during use phase (in km)
- FS Fuel savings (in l/100km and 100 kg mass reduction)
- s Secondary mass savings (in % of primary mass reduction)
- $1 - k$ Total mileage during use phase (in km)
- ΔM Replaced material (in kg)



There are a number of material options for vehicle mass reduction:

Material	Mass reduction potential (1-k) relative to mild steel
Advanced high strength steels (AHSS)	20 – 25%
Aluminum	40 – 50%
Magnesium	30 – 50%
Glass fiber reinforced plastics (GFRP)	30 – 35%
Carbon fiber reinforced plastics (CFRP)	50 – 60%

There exists large uncertainty regarding (1-k).
It summarizes a complex reality that depends on many factors.



FS - The relationship between mass savings and fuel savings:

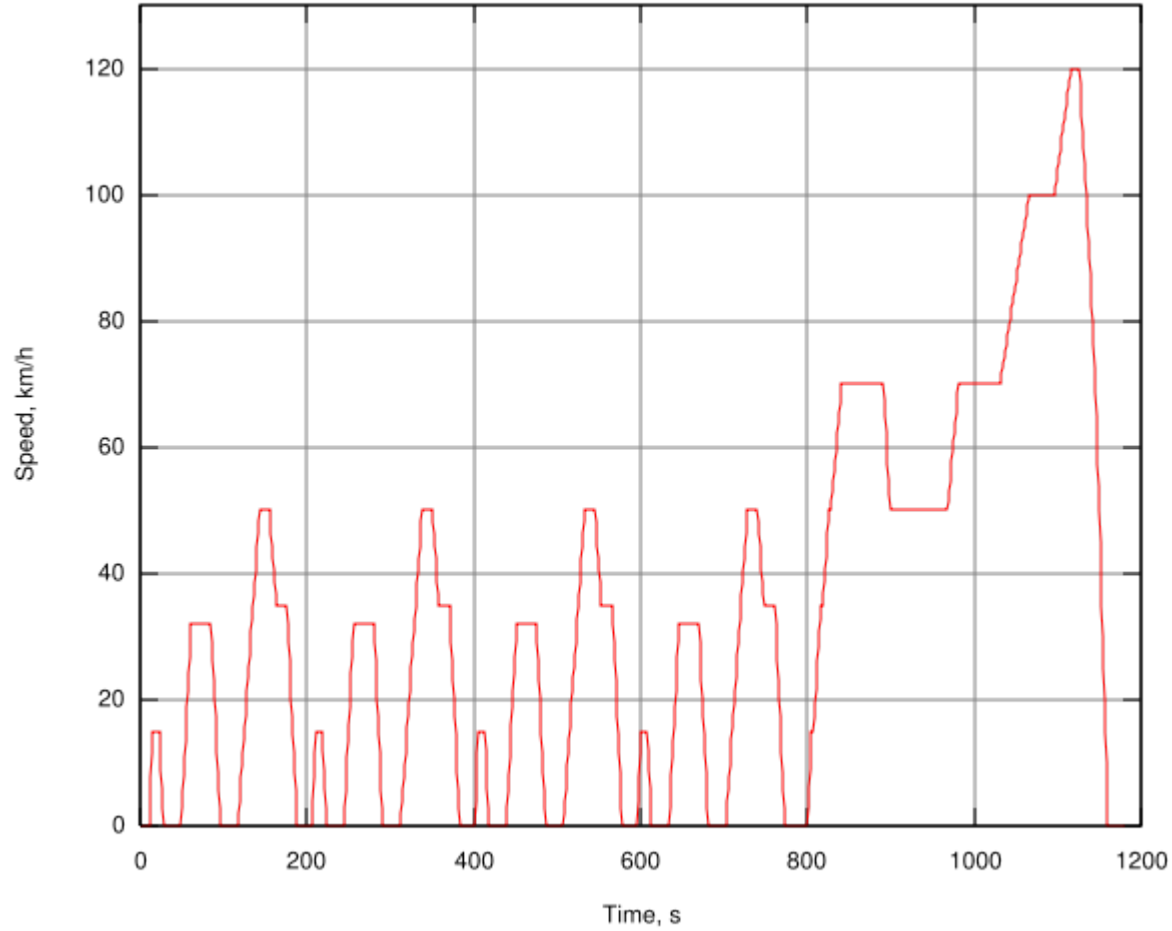
	ICEV (NEDC)	ICEV (Hyzem)	HEV (NEDC)	HEV (Hyzem)
FS in l/100km100kg without engine downsizing				
Compact	0.13	0.15	0.13	0.15
Midsized	0.11	0.16	0.22	0.18
SUV	0.15	0.16	0.11	0.16
FS in l/100km100kg with optimal engine downsizing				
Compact	0.33	0.28	0.20	0.23
Midsized	0.48	0.33	0.28	0.23
SUV	0.47	0.30	0.20	0.26

Source: FKA 2005

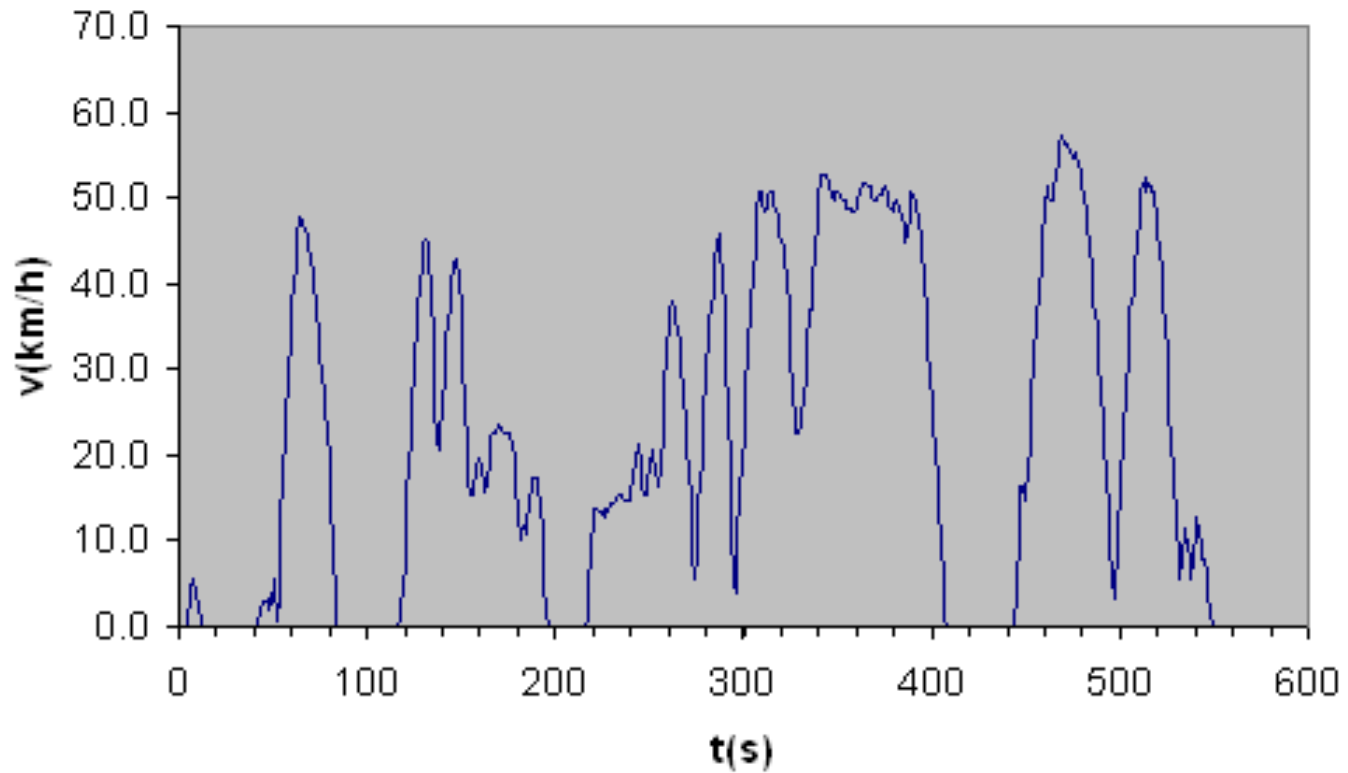
FS summarizes a complex reality that depends on many factors



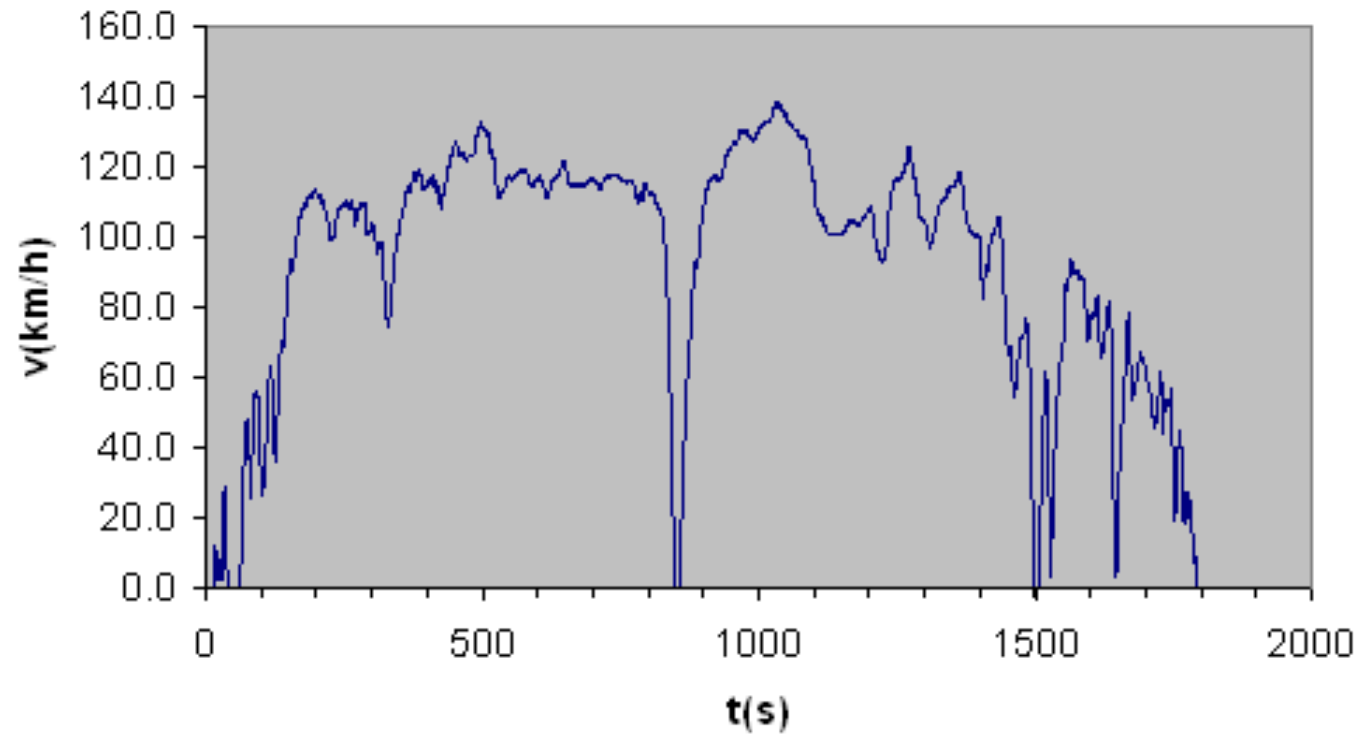
New European driving cycle (NEDC)



HYZEM Urban



HYZEM Highway



Extreme range of GHG savings during use phase:

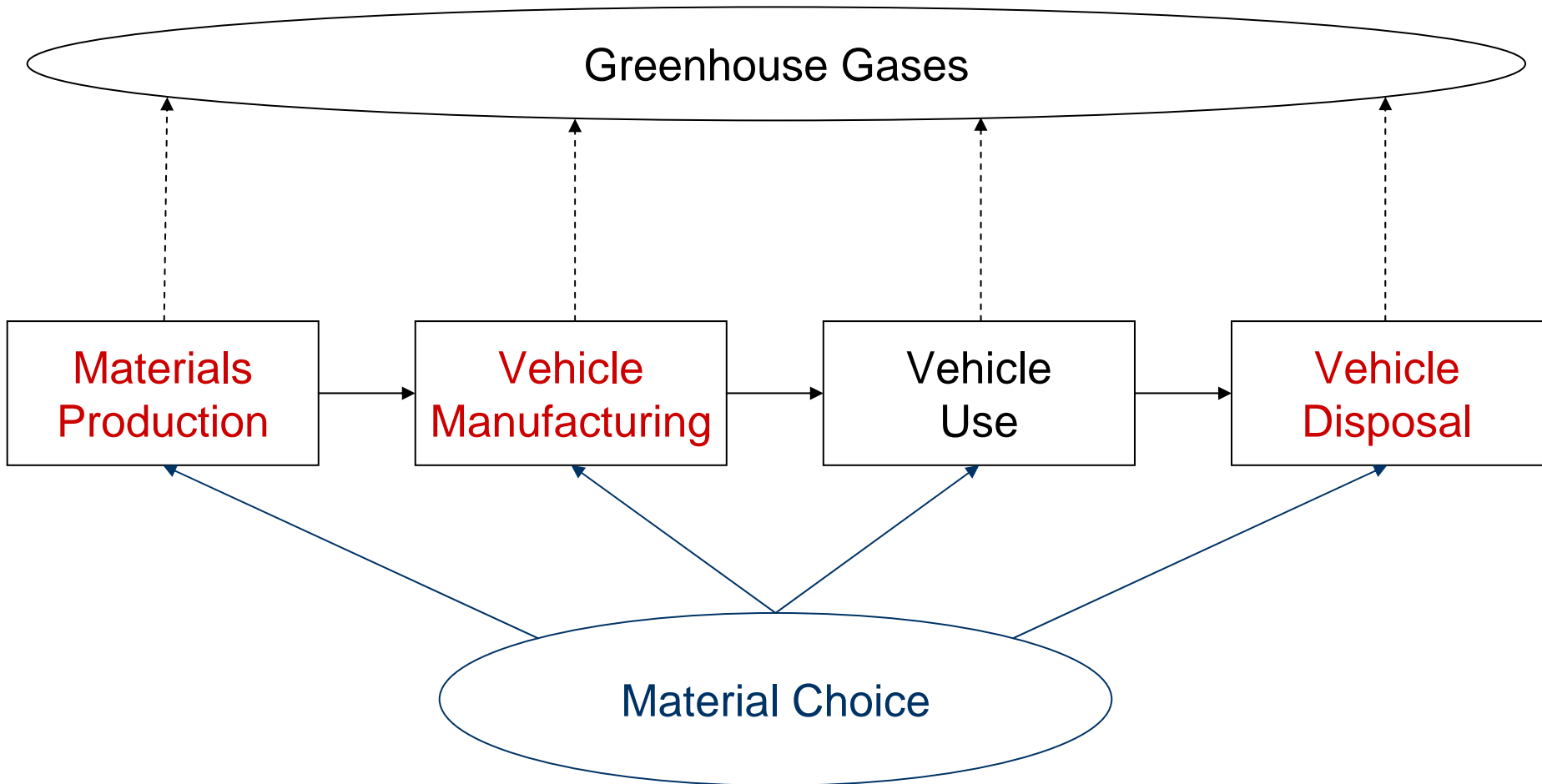
$$\Delta E_{use} = FS \cdot (1 + s) \cdot (1 - k) \cdot \Delta M \cdot E_{fuel} \cdot TM / 10,000$$

Consider the example of aluminum replacing 1 kg of automotive steel:

	Lower bound	Upper bound
E_{fuel} in kg CO ₂ eq	2.8	3.2
FS in l/100km100kg	0.11	0.48
$1 + s$ in % primary savings	1.0	1.5
$1 - k$ in % of replaced mass	0.2	0.5
TM in km	100,000	290,000
ΔM in kg	1	1
ΔE_{use} in kg CO ₂ eq	0.6	33.4



Impact of material choice on the rest of the vehicle life cycle:



GHG emissions from material production and recycling:

Cradle-to-gate GHG emissions in kg CO₂eq / kg semi-finished material product

	Primary production route	Secondary production route
Steel (incl. AHSS)	2 + (0.15 to 0.75)	0.4 + (0.15 to 0.75)
Aluminum	12.7 + (0.7 to 1.25)	0.6 + (0.7 to 1.25)
Magnesium	18 to 25	Recycled with aluminum
GFRP	2.5 to 8	-
CFRP	9.5 to 23	-

All lightweight materials apart from AHSS are GHG-intensive.

Secondary production routes offer significant GHG savings.



Calculation of GHG emissions from material production and recycling:

$$\Delta E_{mat} = \sum_i \frac{\Delta m_i}{\gamma_i} E_i^{att}$$

- Δm_i Change in mass of automotive material of type i (in kg)
- γ_i Manufacturing yield of material type i (in % of shipped material)
- E_i^{att} Cradle-to-gate GHG emissions attributable to material type i (in kg CO₂eq/kg)

Challenge: How to account for the environmental benefits of recycling?



Calculation of GHG emissions from material production and recycling:

Attributional LCA requires allocation or expansion of functional unit

Option 1: Avoided burden

$$E_i^{att} = E_i^p - \left((1 - \alpha) \cdot r_i^{cont} + \alpha \cdot r_i^{car} \right) (E_i^p - E_i^s)$$

$$r_i^{car} = (1 - \gamma_i) r_i^{prompt} + \gamma_i r_i^{eol}$$

- E_i^p C-t-g GHG emissions of material i (primary production route)
- E_i^s C-t-g GHG emissions of material i (secondary production route)
- r_i^{cont} % of automotive material from secondary production route
- r_i^{prompt} Prompt scrap recycling rate of automotive material i
- r_i^{eol} End-of-life scrap recycling rate of automotive material i
- $\alpha \in [0,1]$ Avoided burden factor



Calculation of GHG emissions from material production and recycling:

Option 2: Average burden over n recycling cycles

$$E_i^{att} = \frac{E_i^p + r_i^{car} \sum_{k=0}^{n-1} (r_i^{all})^k E_i^s}{1 + r_i^{car} \sum_{k=0}^{n-1} (r_i^{all})^k} = E_i^p - r_i^{av} (E_i^p - E_i^s)$$

$$r_i^{av} = \frac{r_i^{car} - r_i^{car} (r_i^{all})^n}{1 - r_i^{all} + r_i^{car} - r_i^{car} (r_i^{all})^n}$$

$$r_i^{car} = (1 - \gamma_i) r_i^{prompt} + \gamma_i r_i^{eol}$$

r_i^{car}

Overall automotive recycling rate (prompt and end-of-life)

r_i^{all}

Overall material recycling rate (automotive and all other applications)

r_i^{ave}

Average recycling rate after original use in automotive and n subsequent recycling cycles



Large range of GHG emissions attributable to materials:

Consider the example of aluminum and steel:

	Steel		Aluminum	
	Low	High	Low	High
r_i^{cont}	-	0 to 0.05	-	0 to 0.1
γ_i	0.65 to 0.8	-	0.6 to 0.8	-
r_i^{prompt}	0.95 to 0.98	-	0.92 to 0.95	-
r_i^{eol}	0.85 to 0.95	-	0.75 to 0.85	-
α	1	0	1	0
E_i^{att} (*)	0.6 to 0.5	2 to 1.9	2.8 to 2.2	12 to 11.5

(*) in kg CO2eq per kg slab or ingot



Extreme range of GHG emissions from materials production and recycling:

Consider the example of aluminum replacing 1 kg of automotive steel:

$$\Delta E_{mat} = \frac{k}{\gamma_a} E_a^{att} - \frac{1 + s(1 - k)}{\gamma_s} E_s^{att}$$

	Upper bound	Lower bound
s	0	0.5
k	0.2	0.5
γ_a	0.6	0.8
γ_s	0.65	0.8
E_a^{att} (*)	12	2.2
E_s^{att} (*)	2	0.5
ΔE_{mat} (*)	12.9	0.6

(*) in kg CO₂eq per kg slab or ingot



Conclusion: No conclusion

In the example of aluminum replacing 1 kg of automotive steel no general conclusion is possible due to

- Uncertainties in a variety of system parameters
- The large impact of allocation method

	Upper bound	Lower bound
ΔE_{use} (*)	0.6	33.4
ΔE_{mat} (*)	0.6	12.9

(*) in kg CO₂eq per kg slab or ingot

- Uncertainties can be reduced in principle.
- Ambiguity from allocation is fundamental to attributional LCA

Consequential methodology is required to assess the research question.



Case Study to illustrate conclusions:

Baseline vehicle: Compact Car (1260kg, 6.4 l/100km, ICEV)

Mass reduction: Body-in-weight (BIW) 360 kg of mild steel

(a) replaced by AHSS-intensive BIW (270 kg)

(b) replaced by aluminum-intensive BIW (216 kg)

Assumptions:

$$E_{fuel} = 2.82 \text{ kgCO}_2 / \text{l}$$

$$FS = 0.281 / 100\text{km} \cdot 100\text{kg}$$

$$k_a = 0.6 \text{ relative to mild steel}$$

$$k_s = 0.75 \text{ relative to mild steel}$$

$$s = 0.3$$

$$TM = 193080 \text{ km}$$

Allocation: Avoided burden $\alpha = 0.9$

$$\gamma_s = 0.65$$

$$\gamma_a = 0.60$$

$$r_s^{prompt} = 0.97$$

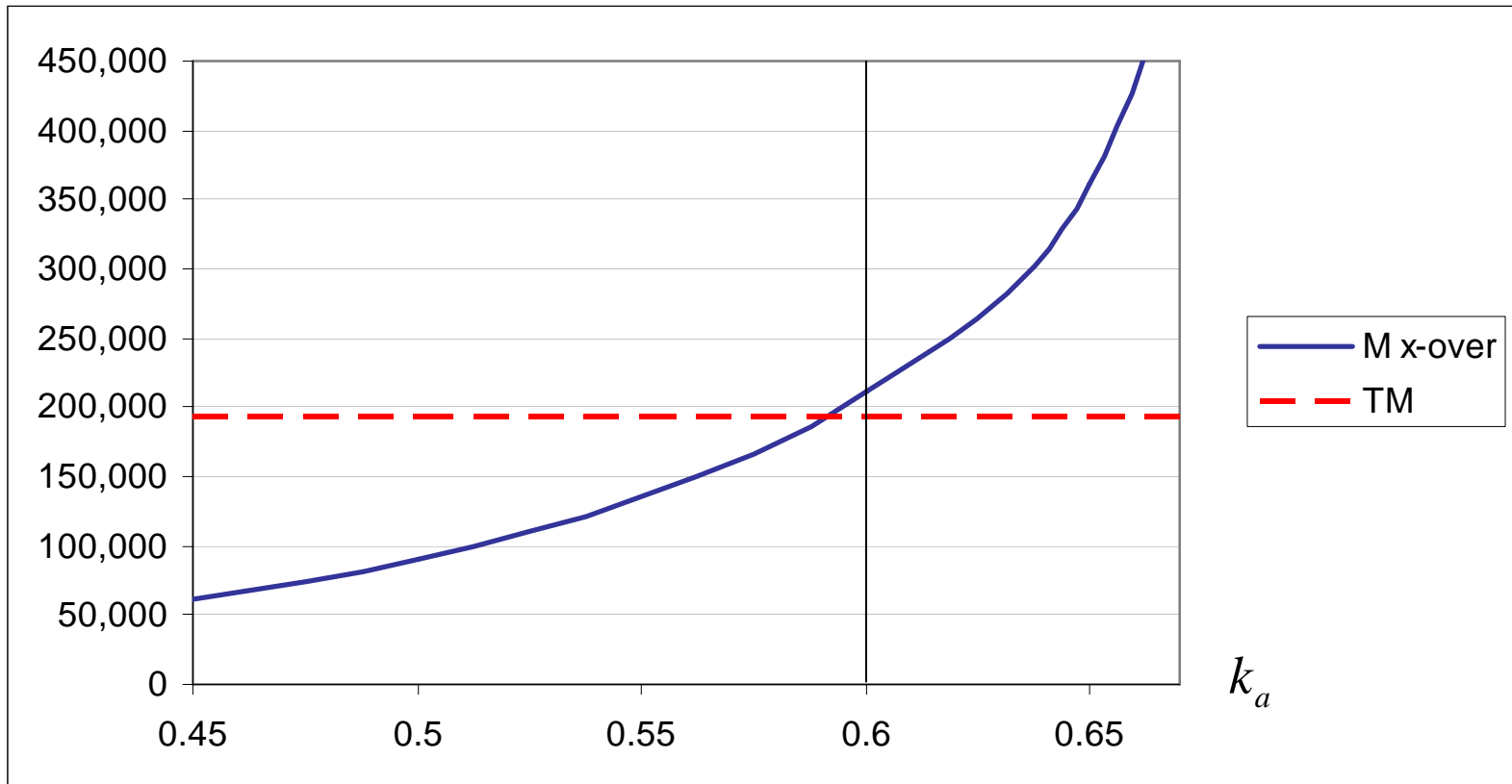
$$r_a^{prompt} = 0.92$$

$$r_s^{eol} = 0.90$$

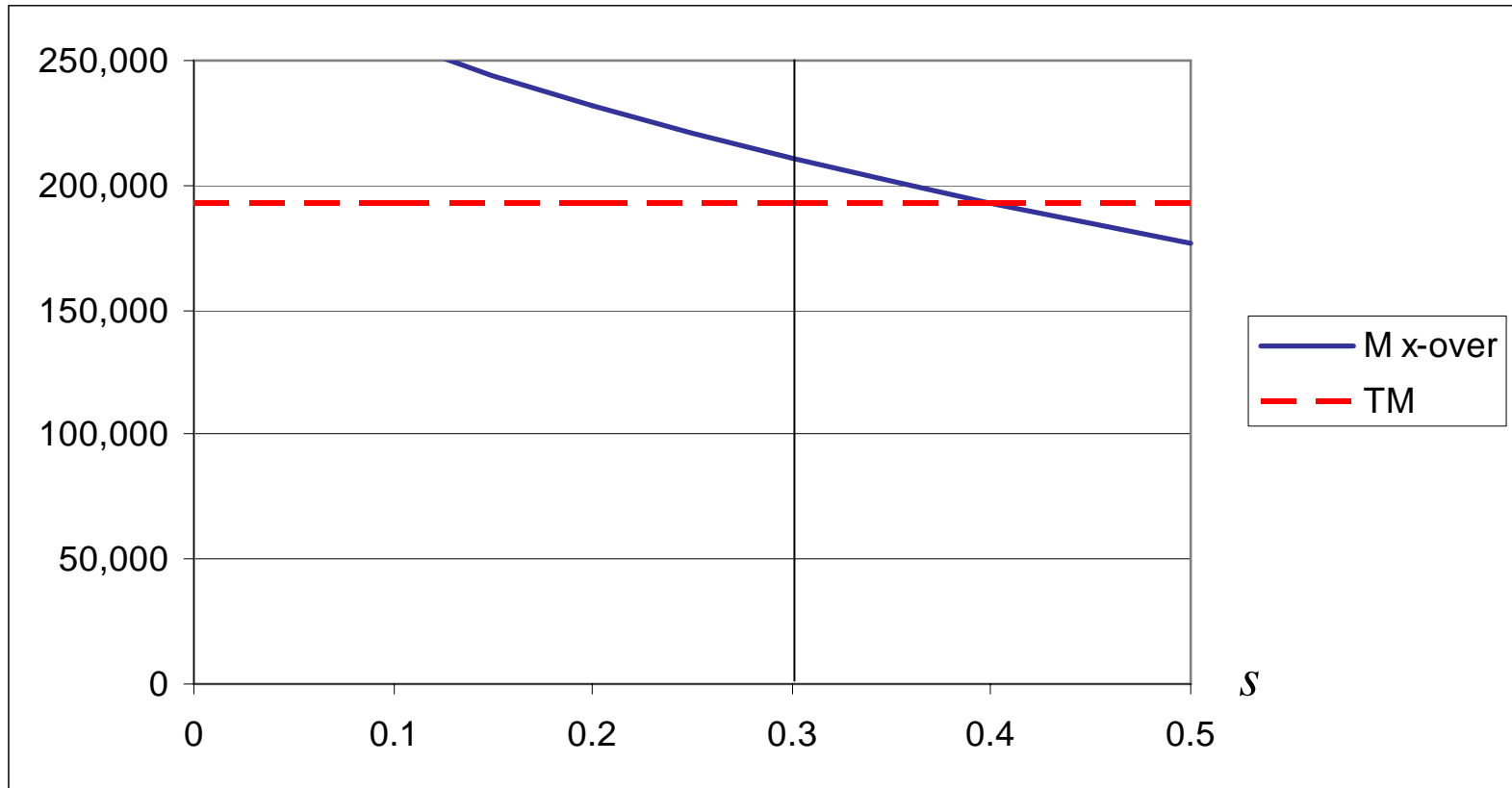
$$r_a^{eol} = 0.74$$



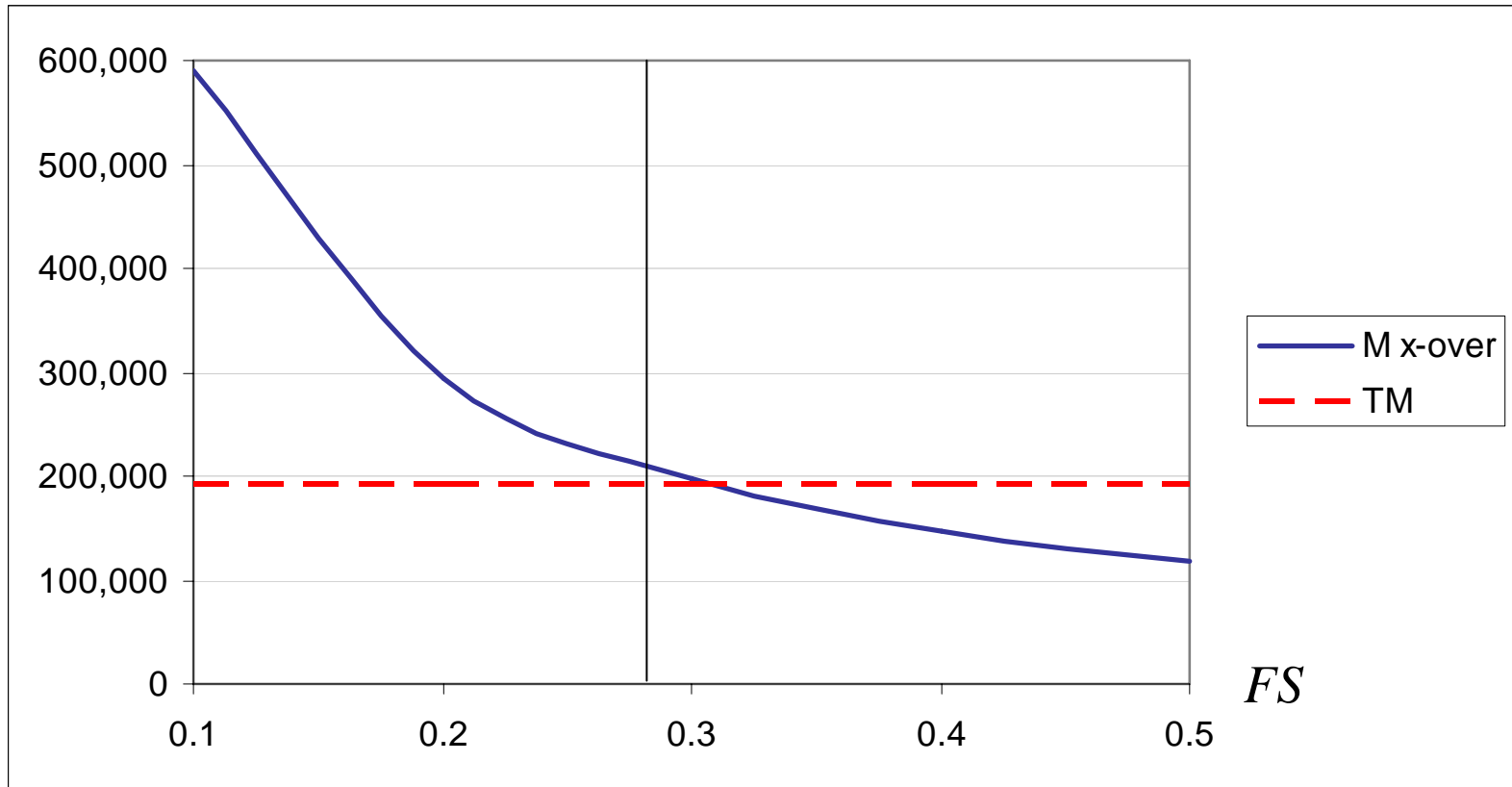
Crossover distance M x-over (AHSS vs. aluminum) in km as a function of the material replacement coefficient for the aluminum-intensive design k_a



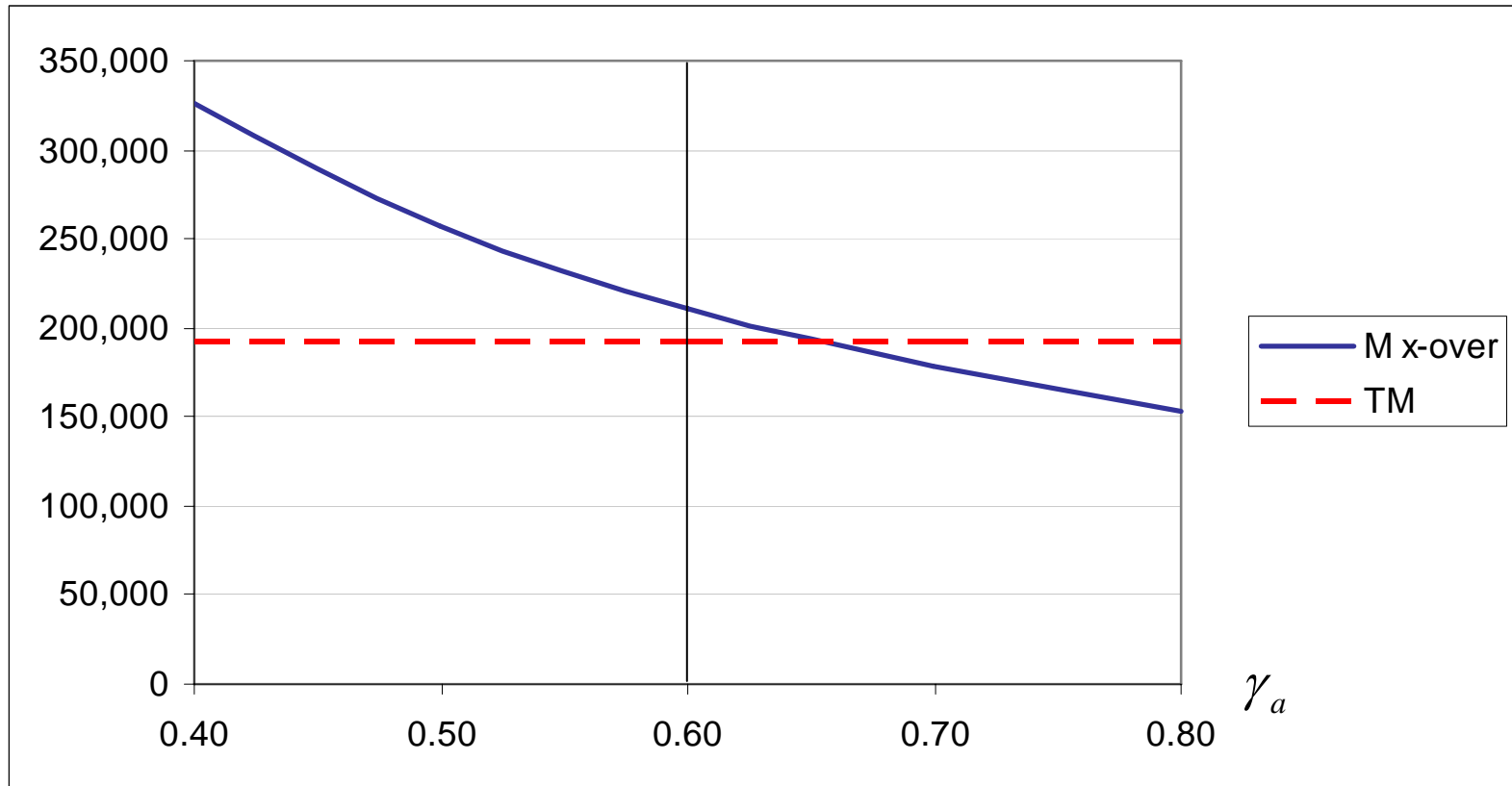
Crossover distance M x-over (AHSS vs. aluminum) in km as a function of the secondary mass savings coefficient s



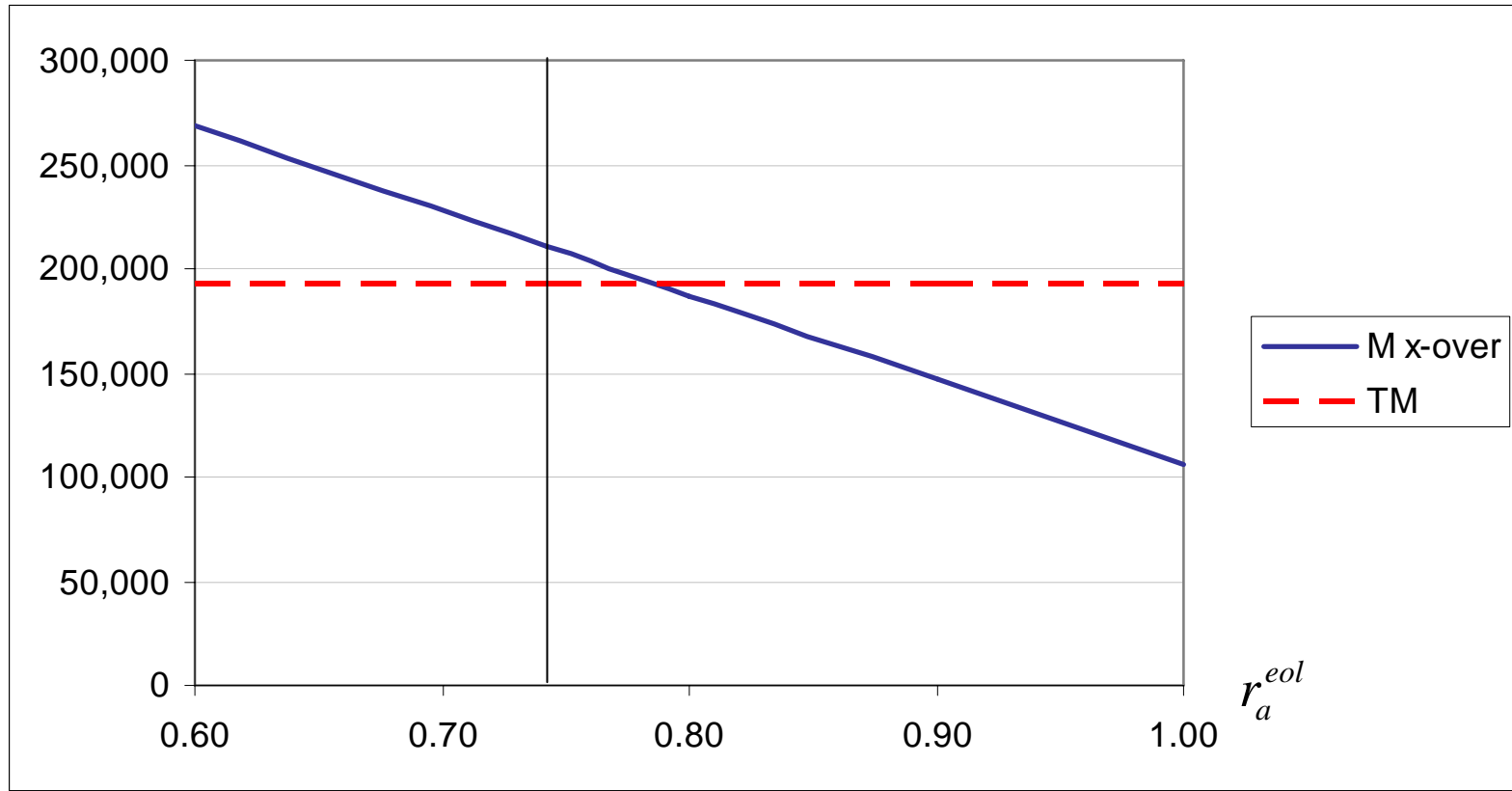
Crossover distance M x-over (AHSS vs. aluminum) in km as a function of fuel savings per mass savings FS (in liter / 100km & 100kg)



Crossover distance M x-over (AHSS vs. aluminum) in km as a function of the manufacturing yield for rolled aluminum



Crossover distance M x-over (AHSS vs. aluminum) in km as a function of the end-of-life recycling rate for automotive aluminum



Crossover distance M x-over (AHSS vs. aluminum) in km as a function of the avoided burden factor

