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## Summary

### Background

Alternative drivelines and fuels are entering the Dutch car market and are part of prognoses to reduce transport emissions. In particular the number of vehicles with hybridization technology, i.e. hybrids and plug-in hybrids, is increasing. Also, the use of CNG and LNG, being considered as an alternative for diesel fuel, has been increasing over the last years.

### Goal

In order to keep the Dutch emission inventory up-to-date, it is important to account for major changes in the vehicle fleet. The calculation of emission factors for conventional vehicles is based on many emission measurements TNO has been performing over the years. For vehicles using alternative drivelines an equivalent measurement data set is not yet available. This report describes how TNO will calculate the emissions of hybrid vehicles and of alternative fuels and gives an overview of the emission factors that will be used for that.

### Approach

TNO will calculate the emission factors for this type of vehicle by estimating the differences between conventional vehicles and hybrids and subsequently applying these differences to the existing vehicle model that is used to calculate emission factors. This way, the emissions of hybrids are calculated relative to those of conventional vehicles. Table 1 shows the basis on which emissions are calculated for different alternative drivetrains.

Table 1 Overview of the reductions of emission factors per alternative driveline.

	Pollutant reduction	CO <sub>2</sub> reduction	Brake-wear reduction
<b>Petrol hybrid</b>	CO <sub>2</sub> -based	Braking + efficiency	95%
<b>Diesel hybrid</b>	None	Braking + efficiency	95%
<b>Petrol plug-in hybrid</b>	CO <sub>2</sub> -based + Electric	+Electric	95%
<b>Diesel plug-in hybrid</b>	Electric	+Electric	95%

### Emissions of vehicles using alternative drivetrains

Tailpipe emissions of CO<sub>2</sub> and pollutant emissions of hybrid cars using spark-ignited engines, i.e. running on petrol, LPG, Ethanol, or CNG, are reduced by means of two aspects: braking energy recuperation and engine efficiency. From the different driving cycles both effects are estimated, yielding reductions with respect to conventional technology as shown in Table 2.

Table 2 The emission reductions of hybrid technology in four separate service levels. The efficiency effect only applies to the driving, not the braking part, hence both effects cannot be added together in full.

Road type	Braking	Efficiency	Total
<b>Urban</b>	30%	50%	65%
<b>Rural</b>	15%	20%	30%
<b>Motorway</b>	3%	4%	7%
<b>Motorway congestion</b>	25%	50%	60%

So far, the not-to-exceed pollutant emission limits have only led to limited reduction of pollutant emissions in *diesel* light-duty vehicles. The gains are mainly traded off against lower fuel consumption, seeking the limits of pollutant emissions. Therefore, no gain is assumed for emissions of air pollutants from hybrid technology in diesel vehicles.

### **Emissions of vehicles running on alternative fuels**

Table 3 gives the overview for the emissions of alternative fuels, which is based on the corresponding values for petrol vehicles. All fuels represent a CO<sub>2</sub> reduction, but the air pollutants give a mixed view, with an overall increase.

Table 3 The change with respect to petrol emission factors (per vehicle kilometre), for alternative fuel vehicles.

	<b>CO</b>	<b>HC</b>	<b>NO<sub>x</sub>/NO<sub>2</sub></b>	<b>CO<sub>2</sub></b>
<b>Ethanol</b>	88%	137%	151%	97.3%
<b>LPG</b>	125%	85%	122%	89.6%
<b>CNG</b>	47%	127%	127%	76.6%

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# 1 Introduction

## 1.1 Background

Alternative drivelines and fuels are entering the Dutch car market and are part of prognoses to reduce transport emissions. In particular the number of vehicles with hybridization technology, i.e. hybrids and plug-in hybrids, is increasing. Also, the use of CNG and LNG, being considered as an alternative for diesel fuel, has been increasing over the last years.

In order to keep the Dutch emission inventory up-to-date, it is important to account for major changes in the vehicle fleet. Therefore, in 2014, TNO will perform an update of the emission model by expanding it with a software module capable of calculating emissions of vehicles with alternative drive trains or vehicles running on alternative fuels.

## 1.2 Aim

This report describes the emission model updates that will be performed to account for the effects of the introduction of hybrid drive trains and the use of alternative fuels. It provides the background on the adaption of the emission factors to incorporate the current and future changes in vehicle emissions due to alternative drivelines and technology.

## 1.3 Approach

The updates will be realized by designing a generic physical vehicle model for alternative drivelines and alternative fuels, that can be adopted based on the type of hybridization and/or the alternative energy carrier used.

The updated model will generate 'additional emission factors' that will be added to the emission factors for conventional driveline technologies and for conventional fuels, i.e. mainly petrol and diesel fuels. In other words, the model to be developed will function works as an add-on software module, expanding the existing model with a facility for calculating the effects of alternative drive trains and/or alternative fuels.

## 1.4 Scope

The model is capable of calculating emission factors for light-duty vehicles; heavy-duty vehicles do not form part of the emission factor model. With respect to alternative technologies, only OEM (Original Engine Manufacturer) technologies are incorporated in this study. Retrofit technology is not regarded here.

## 1.5 Structure of the report

The vehicle model used to calculate the emission factors is described in chapter 2. From it, the most important parameters that are to be adjusted to account for hybrid vehicles are derived.

Chapter 3 then details the several aspects that drive emissions of hybrid vehicles, after which chapter 4 gives insight into how emissions of alternative fuels compare to those of conventional fuels. Chapter 5 concludes in giving an overview of the emission factors for alternative drivetrains and alternative fuels.

## 2 Vehicle model for calculating emissions

The calculation of emission factors for conventional vehicles is based on many emission measurements TNO has been performing over the years. For vehicles using alternative drivelines, such as hybrid cars, an equivalent measurement data set is not yet available. Therefore, TNO will calculate the emission factors for this type of vehicle by estimating the differences between conventional vehicles and hybrids and subsequently applying these differences to the existing vehicle model that is used to calculate emission factors. This way, the emissions of hybrids are calculated relative to those of conventional vehicles. This chapter describes how the existing vehicle model will be made suitable for calculations on vehicles with alternative drivelines, with a focus on hybrid cars.

### 2.1 Introduction: the vehicle model

The combustion engine provides power for propulsion. It is used to overcome the driving resistance and the inertia forces. A vehicle model to associate the combustion engine with driving behaviour starts with the forces on the vehicle:

$$F[\text{N}] = F_{\text{inertia}} + F_{\text{rolling-resistance}} + F_{\text{air-drag}} = M a + g \text{RRC} M + \frac{1}{2} \rho c_D A v^2$$

Where “a” is the acceleration, “v” the velocity, “M” is the vehicle weight including passengers, payload, and rotational inertia of about 40 kg, “RRC” the rolling resistance coefficient [kg/ton], and “ $\frac{1}{2} \rho c_D A$ ” the air drag coefficient. With the exception of engine and drivetrain losses, this determines the forces on the vehicle.

Depending on the engine type, the CO<sub>2</sub> emission factor in g/km is directly linked to the forces:

$$\text{CO}_2[\text{g/km}] \sim Q F[\text{N}] + \text{losses}$$

Where Q has the value of 0.18 for a modern, larger diesel engine and the value of 0.22 for an older, smaller petrol engine, which spans the typical range. This is not the complete story. In particular at lower velocities, the engine losses are an important part of the total CO<sub>2</sub> emission. These losses can be characterized by two major contributions: friction losses and pumping losses, which are roughly related to the engine speed n [RPM]:

$$P_{\text{losses}}[\text{kW}] = R_{\text{friction}} n + R_{\text{pumping}} n^2$$

The engine losses at low engine speed, say idling, are about 3% of the rated power of the engine. At higher engine speeds, this can increase to a fourfold of this number. Consequently, engine losses are typically not related to the distance driven, but to the time of engine operation. An appropriate gear-shift strategy keeps the engine losses limited, except for high vehicle speeds in the highest gear, where the engine speeds are typically high.

**Example**

A 60 kW engine requires about 1.8 kW to overcome internal friction. At 18 km/h, this would correspond to an effective increase in the driving resistance of 360 Newton (i.e. two-third of the total force at low velocity), while at 108 km/h it is only 60 Newton (i.e. a 10% effect). A typical compact Dutch passenger car engine has a 60 kW engine. Hence the associated CO<sub>2</sub> emission at low engine speed is 0.32 g/s and at high engine speeds 1.3 g/s. With a velocity of 50 km/h in a high gear still 0.32 g/s times 3600 sec/50 km/h = 23 g/km of the CO<sub>2</sub> is associated with the engine losses. This is the result of the typical large engine power, which is common in modern vehicles. Given a 80 g/km CO<sub>2</sub> emission factor at 50 km/h for constant driving, the contribution of engine loss to the CO<sub>2</sub> emissions is substantial. This is related to the large passenger cars engine sizes, which have increased over the years, by popular demand.

Low engine speeds at low vehicle velocity can be achieved by eco-driving. At high vehicle velocity, in the highest gear, the higher engine speed is unavoidable. The increased engine losses at high velocity still have a limited effect as the running time of the engine is smaller for the same distance as at lower speed. For a compact car five gears are typically available. With eco-driving, the driver changes gear at 2000 RPM, however, in the fifth gear this engine speed is reached at 60-70 km/h. Above that velocity the engine speed increases, and so do the engine losses. A typical engine loss curve is 3% of rated power till 60 km/h and a linear rise with RPM above this velocity:

$$\text{CO}_{2,\text{loss}}[\text{g/km}] \sim P_{\text{rated}}[\text{kW}] (8.3/v + 8.3 \max(0, v-60)/(60 v))$$

Where v is the velocity in km/h.

## 2.2 Parameters influencing the fuel consumption

From the generic model for fuel consumption three parameters appear that are important for the variation of the fuel consumption for the different vehicles and market segments:

1. Vehicle weight M [kg];
2. Frontal area A [m<sup>2</sup>], or form factor x width x height: The frontal area is smaller than the rectangular size of width times height. The dimensionless form factor accounts for this difference. The frontal area is multiplied with the drag coefficient c<sub>D</sub> to yield the air drag of a specific vehicle shape;
3. Rated engine power P<sub>rated</sub> [kW].

**Example**

Frontal area (A) affects the fuel consumption. SUV models generally have a higher real-world fuel consumption compared to other cars with a similar weight and type-approval fuel consumption. This is caused by the fact that motorway driving and air-drag on the type approval test are underrepresented.

Apart from the vehicle characteristics described above, the way the vehicle is driven also influences the fuel consumption of a vehicle. More specifically, the following three aspects in driving are of significant impact on fuel consumption and thus the CO<sub>2</sub> emission:

1. Vehicle velocity;



2. Gear shift; and
3. Braking.

Braking seems out of place, but is not. Energy stored in the vehicle as kinetic energy is not a priori lost. If the foot is taken off the accelerator, the fuel injection stops and the vehicle coasts to a lower velocity. In this manner, distance is covered with the available kinetic energy. The energy is only lost if the vehicle brakes and energy is converted to heat in the brakes.

From a study [UNECE 2013], using data from several countries, the driving resistance of vehicles can be decomposed into the weight component (rolling resistance) and the vehicle's width and height (air drag). The total resistance is:

$$F[\text{N}] = 0.10 * (1 + 0.00002 * v^2) * M[\text{kg}] + 0.0121 * \text{width} * \text{height} * v^2 [\text{m}^2]$$

The rated power varies greatly between vehicle models, however. For European vehicles typical values range between 50 and 110 kW.

### 2.3 Definition of three vehicle classes

Rather than relying on specific vehicles for the comparison of alternative vehicle technologies with conventional technology, the comparison of generic compact, medium, and business vehicles is more appropriate for future vehicle fleets. Moreover, this allows for the tuning of aspects of this technology. For hybrid technology for instance, the balance between engine size, braking energy recuperation and additional weight is shifting, as high-end vehicles use the electric driveline as booster rather than as main propulsion.

In order to derive the vehicle classes described above, both the weight and the width x height were recovered from the Dutch 2011-2012 sales figures (source: RDW) for passenger cars in recent years. From the sales data the average values and the range, or standard deviation ( $\sigma$ ), were determined (see Figure 1 to Figure 3). These values were subsequently used to define three types of vehicles: compact, medium and business. The values for vehicle mass, frontal area and power are calculated by subtracting the standard deviation from the average value for compact cars ( $M = M - \sigma_M$ ,  $A = A - \sigma_A$  and  $P = P - \sigma_P$ ) and adding the standard deviation to the average value for business cars ( $M = M + \sigma_M$ ,  $A + \sigma_A$ ,  $P + \sigma_P$ ). For medium cars the average values apply. Table 4 shows the average values and standard deviations as derived from the sales data and states the vehicle mass, frontal area and power for the three defined vehicle classes.

Table 4 Vehicle mass, frontal area and power for the three vehicle classes.

parameter	symbol	unit	2012-2013 sales data		defined vehicle classes		
			average	$\sigma$	compact	medium	business
<b>Weight</b>	M	[kg]	1277.7	269.4	1008	1278	1547
<b>Frontal area</b>	A	[m <sup>2</sup> ]	2.65	0.27	2.39	2.65	2.92
<b>Power</b>	P	[kW]	78	30.9	47	78	109

This segmentation of the new passenger car fleet allows for the analysis of the effects of hybridization in different market segments.

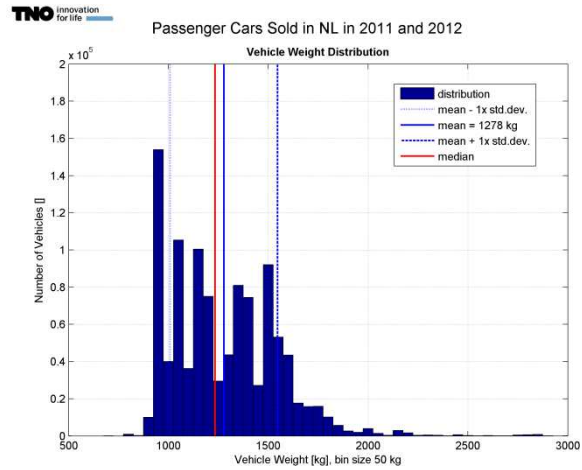


Figure 1 Vehicle weight distribution for all passenger cars sold in the Netherlands in 2011 and 2012.

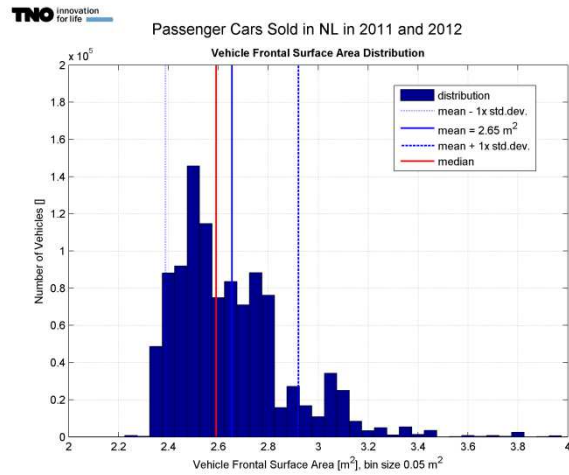


Figure 2 Vehicle frontal surface area (i.e. width x height) distribution for all passenger cars sold in the Netherlands in 2011 and 2012.

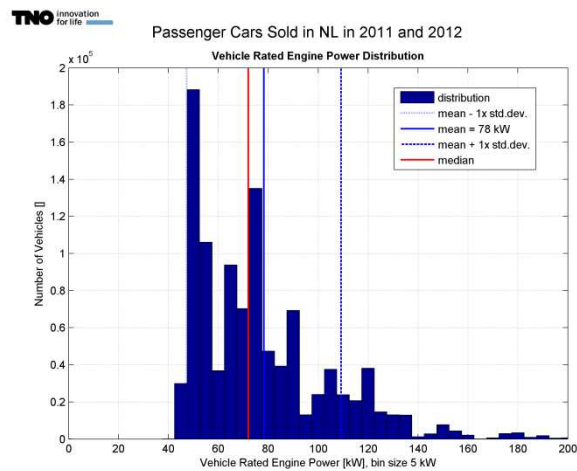


Figure 3 Vehicle rated engine power distribution for all passenger cars sold in the Netherlands in 2011 and 2012.

## 2.4 Calculating CO<sub>2</sub> emissions of hybrid cars

Using the vehicle model from section 2.1, the CO<sub>2</sub> emissions of hybrid vehicles at different constant speeds were calculated and subsequently compared to the CO<sub>2</sub> emissions of conventional vehicles. Figure 4 shows the approximate CO<sub>2</sub> emission factors for each vehicle class and the comparison between conventional and hybrid vehicles. From the figure, it can be clearly seen that the engine in a conventional vehicle is always running when the vehicle is in motion. For hybrid vehicles however the engine only runs during high-power demand: either at high velocity, or for battery charging. This explains the low CO<sub>2</sub> emissions at low speed for hybrid vehicles when compared to conventional vehicles.

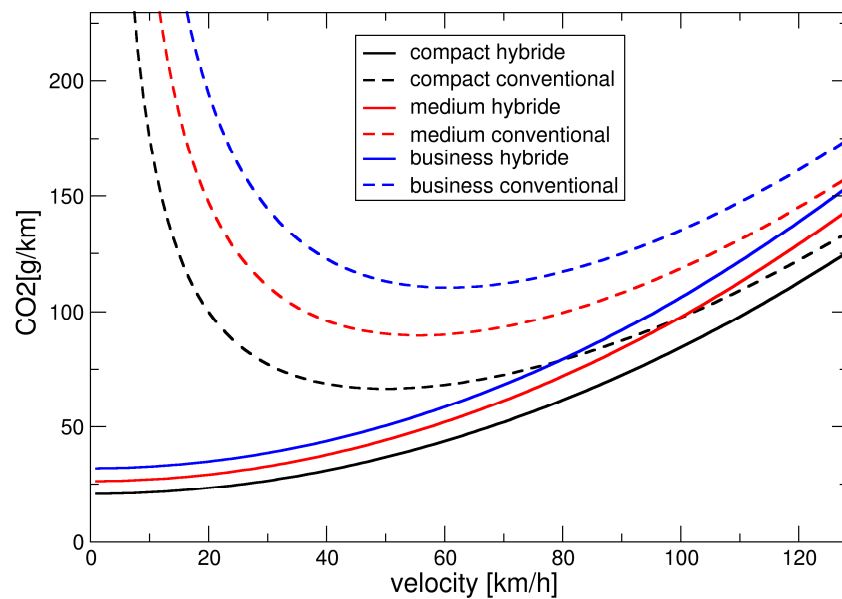


Figure 4 The CO<sub>2</sub> emission factors [g/km] for constant velocity based on the standard vehicles, with 0.2 g/km CO<sub>2</sub> for 1 Newton, and fixed 3% of rated power as engine loss. The differences lie in the fact that for the conventional vehicle the engine is always running, whereas for the hybrid vehicles the engine only runs during high-power demand: either at high velocity, or for battery charging.

This CO<sub>2</sub> data set can be used to determine emission factors for hybrid cars at different speeds. From that then also the pollutant emissions can be calculated, as they are linked to the CO<sub>2</sub> emissions, as will be explained in sections 3.6 and 5.1.1.

## 3 Emissions of vehicles with alternative drivelines

### 3.1 Introduction to hybrid technology

Hybrid technology covers several aspects of the vehicle fuel consumption in a better manner than conventional technology. There are different ways in which hybrid technology reduces the CO<sub>2</sub> emissions:

1. Engine operation at a higher engine load and moderate engine speeds and proportionally lower engine losses;
2. A smaller combustion engine is required, leading to lower engine losses compared to a larger engine (for full-hybrid at least one-third of the total power is electric);
3. Stationary operation of the engine leads to higher engine efficiency;
4. Recuperation of braking power leads to lower driving losses;
5. Engine off at low velocities and stationary position.

It sounds simple, but the control strategy of a hybrid vehicle and the layout of the driveline is not trivial. The analysis of full-hybrid vehicles shows two general strategies:

1. At higher velocities the combustion engine provides the energy to overcome the resistance. The electric driveline covers the power needed to accelerate. This power is recovered during braking. This strategy provides a State-of-Charge of the battery with limited variation, which is called charge-sustaining operation.
2. At low velocities, the battery is charged during braking and the vehicle will run partly on the electric engine alone, i.e. with the combustion engine switched off.

Higher market segment cars usually provide a lot of engine power. Hybrid variants of this kind of vehicles often use the electric power like 'boost power', and their normal operation will be less based on the electric power. There are three main parameters that affect the effectiveness of hybrid technology:

1. Rated power of the combustion engine;
2. The efficiency of braking energy recuperation;
3. The maximal power of the braking energy recuperation.

These three parameters interplay with the driving behaviour (section 2.2) to determine the actual reduction in emissions due to the use of hybrid technology.

The reduction potential of hybrid technology can be inferred from the elements above. Typically, the engine will operate in a favourable mode, limiting the losses, which are already smaller due to the smaller engine size. Hence the total work to overcome driving resistance is associated with less fuel consumption. The control strategy to accomplish this is not inferred in this study, but assumed to exist near optimal. The total driving resistance is a given fact, for a given velocity. The work to overcome this resistance cannot be avoided, by any technology. Even the variation of this work with velocity is limited for velocities below 100 km/h, i.e., before air-drag increases significantly. Hence this is the energy bill that must always be footed.

The driver can use the energy it needed for acceleration again by coasting, or by hybrid technology to recuperate during braking. The driving style, in other words, is a very important factor in determining the energy loss in braking and the amount of energy that can be recuperated. Claims of huge savings from energy storage, like batteries, super-capacitors or flywheels, are based on unrealistic expectations of driving behaviour.

In order to determine the appropriate effect of braking energy recuperation a large set of driving cycles together with the generic vehicle model introduced in chapter 2 was used in the analysis in section 3.3 below. This set of driving cycles determines the average and the bandwidth of the expected brake energy recuperation for different hybridizations, in different market segment vehicles, and on different roads.

### 3.2 Engine efficiency

The engine efficiency of the combustion engine as used in a hybrid vehicle is higher due to lower engine speed, higher engine load, smaller engine size and more stable engine operation. The reduction is relative to a similar vehicle with a conventional engine. Assuming an engine loss close to that of an idling engine would yield:

$$P_{\text{loss}} \sim 3\% P_{\text{rated}} \sim 0.3\text{-}0.5 \text{ [g/s] CO}_2$$

However, engine operation will be limited to the times when the actual power is needed, i.e. at high velocity and high acceleration, and the amount of time it takes to recharge the battery. Hence, engine loss is a fixed fraction of the amount of energy required, very much unlike the conventional engine. Hence, given the work to overcome the driving resistance,  $W$  [MJ], and the work lost in braking,  $B$  [MJ], the  $\text{CO}_2$  emission of a hybrid vehicle is comparable to that of a similar vehicle with conventional technology:

$$\text{CO}_2 \text{ [g]} = 190 * 1.03 * (W + (1-\eta)*B)$$

Where  $\eta$  is the efficiency of recuperating the braking energy, and 190 g  $\text{CO}_2$  for a 1 MJ is considered near-optimal for a smaller petrol engine. It corresponds to 684 g/kWh, and a maximal cycle efficiency of 38.6% of a small petrol engine running at optimal load and engine speed.

The actual benefits of braking energy recuperation very much depend on the driving behaviour and the road type. The bandwidth in this energy saving potential is derived from common driving cycles, combined with typical vehicle parameters.

### 3.3 Braking energy recuperation

The efficiency of recuperating braking energy, i.e., the amount of braking energy that can be used again for vehicle propulsion, is a combination of twice the drivetrain losses - once during acceleration when engine power is used to generate vehicle kinetic energy, and once during braking - combined with the losses of a charging cycle of the battery for the storage of braking energy. There is a large range in efficiency, however,  $\eta = 60\%$  is an appropriate average value.

A second aspect in braking energy recuperation is the maximal power that can be recuperated. The limitations may lie in the electric engine dimensions, but it is more likely to be limited by the maximal current the battery can absorb. It is increasing in recent years, but maximal recuperation power in the order of 20 kW is quite common nowadays.

Using the generic vehicle CO<sub>2</sub> emission model for passenger cars which was introduced in Chapter 2, together with a set of well known (i.e. CADC, NEDC, OSCAR and WLTC) and less well known (i.e., TNO FE & Ovs80) drive cycles for urban, rural and motorway (or a combination of these, i.e. 'mixed') type driving/roads, the relative brake energy saving potential was calculated for the previously introduced 'compact', 'medium' and 'business' type Dutch passenger cars.

For these calculations the efficiency of the brake energy recuperation system was taken as 60%, while an overall drivetrain efficiency of 85% was assumed. This means that 85% of the energy supplied by the engine is work at the wheels.

With these assumptions, the relative brake energy saving potential for each drive cycle (and for each passenger car type) was calculated as the total brake energy that would be saved using a brake recuperation system divided by the total engine energy needed without such a system multiplied by 100%.

The results of these calculations are first depicted per driving/road type in Figure 5 to Figure 8. From these graphs the following observations with respect to the brake energy saving potential are readily made.

1. The highest brake energy saving potentials occur for the urban cycles (Figure 5) with savings ranging from about 25% to 45%.
2. For the CADC rural cycle (Figure 6) the saving potential is already substantially lower at about 14%.
3. As one would expect the saving potential is lowest for the motorway cycles (Figure 7) with uncongested motorway cycles yielding savings ranging from 0% to 5%.
4. For motorway cycles with large and or frequent speed changes due to congestion (Figure 7), the saving potential is of course higher with values from about 10% to 25%.

Mixed driving cycles (

5. Figure 8) show an intermediate saving potential with values ranging from about 8% to 14%.
6. The brake energy saving potential increases with vehicle type from 'compact' to 'business' but compared to the effect of driving/road type this effected is much smaller.

Another way of looking at the available data is to plot the brake energy saving potential for all drive cycles considered as a function of drive cycle averaged vehicle speed characteristics.

This was done for the mean vehicle speed  $V_m$ , see Figure 10, and for the normalized standard deviation of the vehicle speed  $V_s/V_m$ , see Figure 9. Both ways of plotting give an instant and clear overall impression of the brake energy saving potential range and variation as well as of the dependencies on drive cycle type, on vehicle speed characteristic and on vehicle type.

A final analysis plot of the available data is given in Figure 11. This figure again shows the brake energy saving potential as a function of the mean vehicle speed  $V_m$  but this time only for the 'medium' type passenger car with a brake energy recuperation system with unlimited or limited (20 and 10 kW) recuperation power. As expected, limiting the recuperation power will reduce the brake energy saving potential but only for a rather strong limit of 10 kW the effect is substantial.

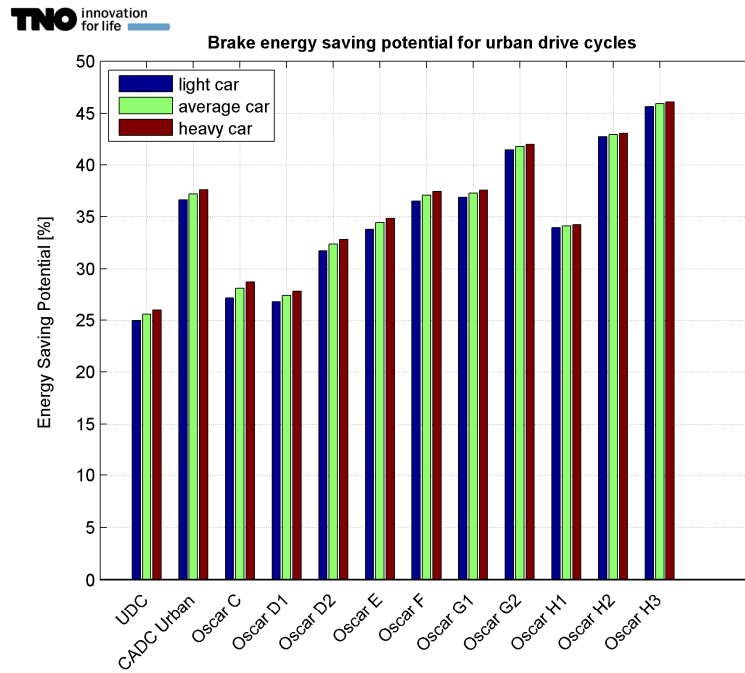


Figure 5 Brake energy saving potential for various urban drive cycles.

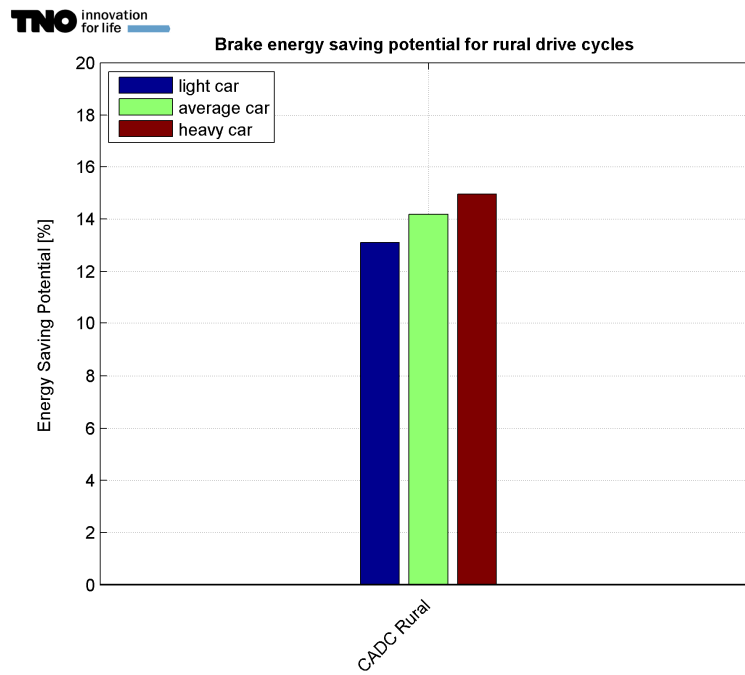


Figure 6 Brake energy saving potential for the only 'pure' rural drive cycle in the drive cycle set used, i.e. CADC Rural.



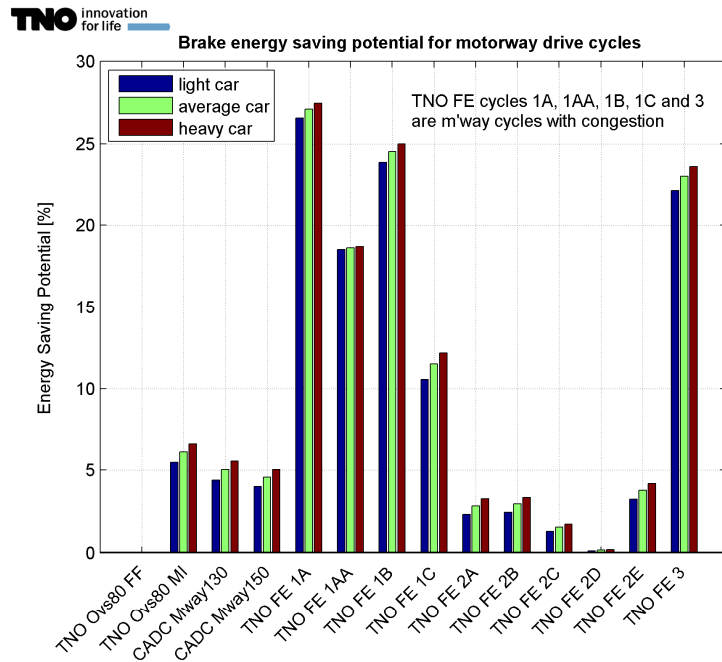


Figure 7 Brake energy saving potential for various motorway drive cycles.

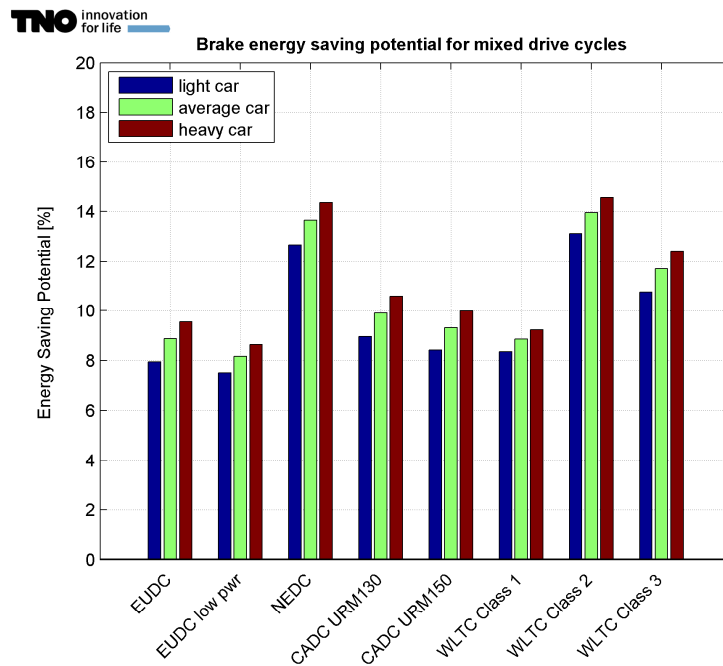


Figure 8 Brake energy saving potential for various 'mixed' drive cycles. Here 'mixed' refers to the fact that these drive cycles consist of various parts, e.g. an urban part combined with a rural or motorway part etc.

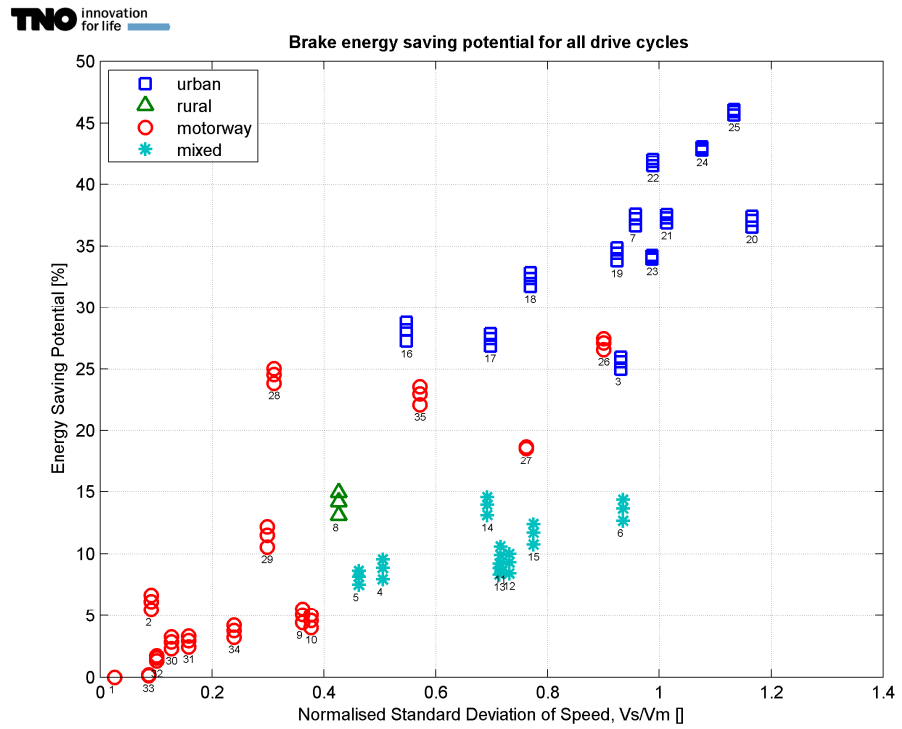


Figure 9 Brake energy saving potential for all drive cycles in the drive cycle set as a function of the normalized standard deviation of the vehicle speed (i.e.  $V_s/V_m$ ) during each drive cycle.

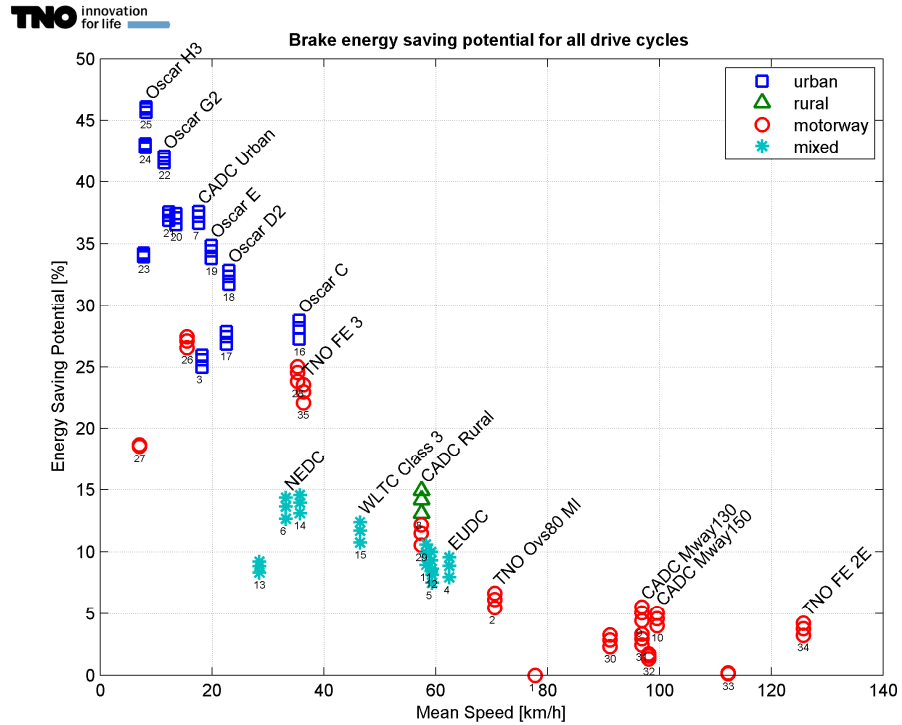


Figure 10 Brake energy saving potential for all drive cycles as a function of the mean vehicle speed. Of each symbol triple the highest one is for the 'business' type passenger car, while the middle and lower ones are for the 'medium' and 'compact' types respectively.

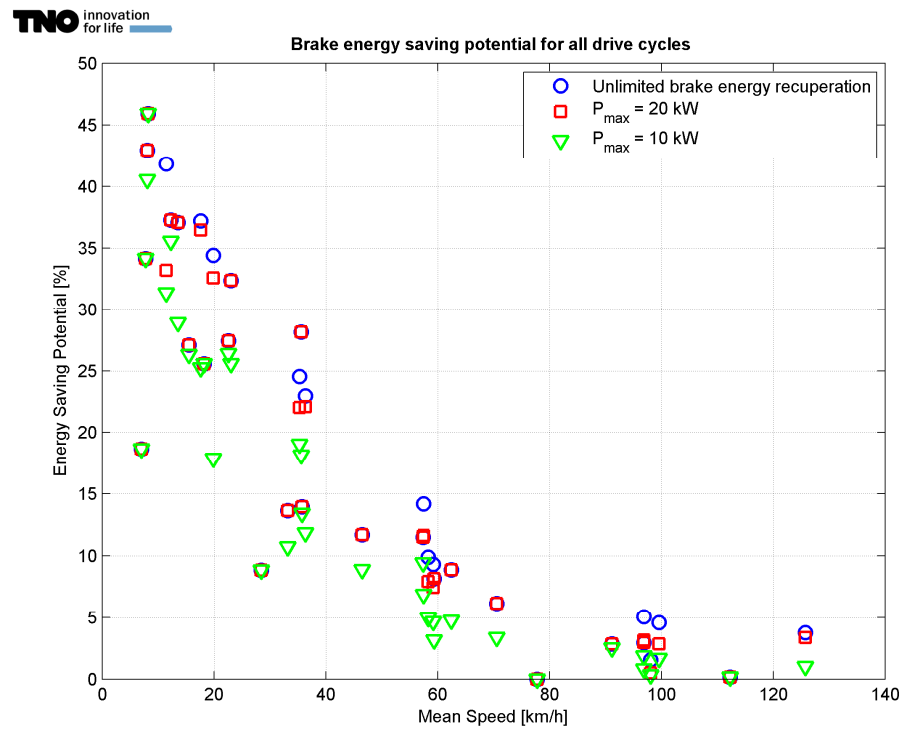


Figure 11 Brake energy saving potential for all drive cycles as a function of the mean vehicle speed for the 'medium' type passenger car having brake recuperation power: unlimited (blue circles); limited to maximally 20 kW (red squares); limited to maximally 10 kW (green triangles).

### 3.4 Accounting for hybrid technology in the vehicle model

After having introduced the basic principles of hybrid technology in section 3.1 and having discussed the engine efficiency and braking energy recuperation characteristics of hybrid vehicles in sections 3.2 and 3.3, hybrid technology and its generic effect on CO<sub>2</sub> emissions can be accounted for in the vehicle model. This is done under the following assumptions:

1. Engine efficiency is assumed near optimal for that type of combustion technology and engine size.
2. The typical combustion engine size in hybrid technology is assumed 60% of a comparable conventional engine size and the losses are proportionally smaller.
3. The engine will only run when needed, largely decoupled from power demand at the wheels, such that near optimal engine operation can be assumed. Furthermore, the energy demand at the wheels is matched with the energy provided by the combustion engine at optimal operation.
4. The braking energy is recuperated with an average efficiency of 65%, below a certain maximal recuperation power  $P_{\max}$ .

Applying these principles to standard driving cycles, the total work and the braking work can be determined for different car sizes.

### 3.5 Plug-in hybrid vehicles

Plug-in hybrid electric vehicles, or plug-ins, allow the battery to be charged from the electricity network. In that case not all energy is eventually derived from the combustion engine, as is the case with a standard hybrid. Plug-in hybrid vehicles, like hybrid vehicles, are typically available in the upper market segments, which is associated with a high annual mileage. Consequently, the amount of charging, and full-electric operation, is limited. The values are typically between 15% and 30% of the total distance travelled [Ligterink 2013, Ligterink 2014]. For emissions, full-electric operation is free of tailpipe emissions, and a 25% reduction of tailpipe emissions with respect to the same hybrid, without plug-in capability, is assumed for plug-in hybrids.

### 3.6 Pollutant emissions

Generally speaking, engine control in hybrid cars can be optimized more easily than in conventional cars, as engine speed is not coupled directly to the vehicle speed, and the accelerator not directly to the fuel injection. Although this should allow for reduced pollutant emissions, in practice this is not always the case.

The simplest assumption is a reduction of pollutant emissions that is proportional to the reduction of CO<sub>2</sub> emissions. In that case the combustion process and emission reduction technology are assumed to be robust against variations in the energy demand. This is more-or-less the case for spark ignition, e.g. petrol, vehicles. For diesel vehicles the trade-off between fuel consumption and pollutant emissions is more dynamic: the pollutant emissions and the change therein by hybridization are completely open. So far, the additional emission control has not lead to lower emissions, but rather to a shift in control towards lower fuel consumption with the same emissions.

For modern spark ignition engines, the robustness of the three-way catalyst ensures low emissions across the board. Unlike older technology, there are no longer specific excursions of high emission, e.g., at high acceleration or during motoring or coasting. Motoring is deceleration where the motion of the vehicle supplies the power to keep the engine running, while coasting is typically with the clutch disengaged, and the engine running idle. In that case hybrid technology, even automatic transmission leads to lower emissions, as it decouples the accelerator pedal from the engine operation somewhat. The engine speed and load variations are limited in the case of automatic transmission. Hence, the approximation that the pollutant emissions are reduced proportional with the CO<sub>2</sub> emissions are legitimate for the modern and future hybrid vehicles.

### 3.7 Brake, road, and tyre wear

Without any detailed information, the brake, road and tyre wear can be assumed to be proportional to the total energy transferred. Hence, as a first order estimate the road and tyre wear can be assumed proportional with the work at the wheels, which is again well-approximated by the fuel consumption.

The brake wear depends on the amount of braking, hence is limited mainly to urban and congested driving. Given a driving cycle there is a certain amount of deceleration at each velocity, where the brakes have to be applied. This curve depends less on vehicle size than the rolling resistance and air drag, which increases with the size of the vehicle. The force associated with deceleration increases with the weight of the vehicle, yielding a near constant coast-down line, for passenger cars:

$$a_{\text{coast-down}} = -0.10 * (1 + 0.00002*v^2) - 0.0121 * \text{width} * \text{height} * v^2/M$$

The size is related to the weight, although the frontal sizes vary less than the weight. However, a “universal coast-down line” can be derived using the average values for size and weight of the vehicle:

$$a_{\text{coast-down}} = -0.1 - 2.7 * 10^{-5} v^2[\text{km/h}]$$

Decelerations below this value are associated with braking and brake energy and power:

$$P_{\text{brake}} = (v/3.6) (a_{\text{coast-down}} - a)*M$$

The braking power already appeared in the braking energy recuperation of hybrid and electric vehicles. Furthermore, in 2009 the amount of braking energy per kilometer for average Dutch driving on urban, rural, and motorway were estimated for the national wear PM emissions on the basis of this energy. The results are presented in Table 5. The results in this report provide insufficient reason to adapt these values, as they are very similar to current findings.

Table 5 The average braking energy on Dutch roads to distribute the total brake wear emissions (proportional to braking energy), and the total road and tyre wear emissions (proportional to total absolute energy at the wheel) accordingly.

Road type	Braking energy	Total energy
Urban	0.250 MJ/km	0.700 MJ/km
Rural	0.075 MJ/km	0.450 MJ/km
Motorway	0.040 MJ/km	0.550 MJ/km

Unlike braking, the tyre and road wear are related to both the forward power, or propulsion, and the braking power. The power needed to accelerate, to overcome driving resistance, and lost in braking are added together. This total energy, in Table 5, is more than the energy needed from the engine. The energy to overcome rolling resistance and air drag is the total energy minus twice the braking energy. This corresponds to forces of 200 Newton urban, 300 Newton rural, and 470 Newton on the motorway, which is within the range of the current findings.

### 3.8 Type approval results of hybrid vehicles

The vehicle model bases emission factor calculations on type-approval values of current makes and models. Currently, there are several hybrid vehicle models available for sale in The Netherlands. The information of these vehicles can be compared to the findings above. The two parts of the type-approval tests: the UDC (Urban Driving Cycle) and the EUDC (Extra-Urban Driving Cycle) are stylized tame versions of urban and rural driving. Hence, it is to be expected that with braking energy recuperation, the urban fuel consumption is similar to the extra-urban fuel consumption. This is unlike the conventional technology, where braking losses and low engine efficiency yield an urban fuel consumption which is typically 30%-50% higher than the extra-urban fuel consumption. Indeed, the type-approval data of 2012-2013 vehicle models show the clustering of data along these two lines.

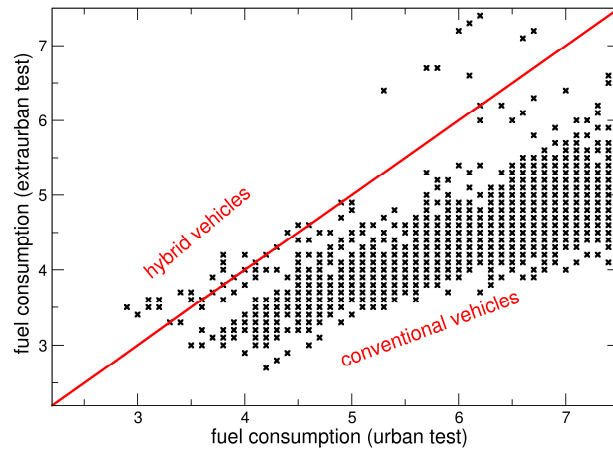


Figure 12 Hybrid vehicles show a typical one-to-one relation between urban and extra-urban fuel consumption on the type-approval test. For conventional vehicles the urban fuel consumption is about 50% higher. Mild forms of hybridization, like stop-start systems bridge the gap between the two clusters.

Due to the tame nature of the type-approval NEDC test, the braking energy recuperation potential is less than with normal urban driving. Hence the type-approval urban fuel consumption is on the high side, compared with real-world driving cycles. Furthermore, the type-approval fuel consumption is extra high in urban driving due to the cold-start (one per 4 kilometer) compared with real-world operation (estimated at one per 7 kilometer). The vehicle model developed here accounts for these effects. Unlike popular belief, the urban part of the NEDC provides quite a high fuel consumption estimate for normal urban driving.

### 3.9 Conclusions

On the basis of current hybrid technology one can conclude that:

- The energy consumption of hybrid cars is lower than that of conventional cars. This is realized by means of:
  - braking energy recuperation. The amount of energy recuperated is as follows: 30% urban, 14% rural, 4% free-flow motorway, and 20% congestion motorway (average velocity below 50 km/h).
  - increased engine efficiency in hybrid operation:
 
$$\text{CO}_2^{\text{hybrid}}[\text{g/km}] = \text{CO}_{2,\text{conventional}}[\text{g/km}] - 1100/v_{\text{average}}[\text{km/h}]$$
- The pollutant emissions are proportionally lower with the energy consumption and CO<sub>2</sub> emission for hybrids with spark-ignited engines; for diesel engines the favorable characteristics of hybrid technology are generally used to decrease CO<sub>2</sub> emissions while maintaining the same level of pollutant emissions.
- The brake wear emission is decimated, due to the energy recuperation instead of dissipation in brake pads when comparing hybrid vehicles to conventional vehicles; the tyre and road emission are the same as for conventional technology.

## 4 Emissions of vehicles running on alternative fuels

Alternative fuels are mainly used in spark ignition vehicles. For compression ignition, or diesel, engines it is altogether not possible to make claims on pollutant emissions, as the control strategy is the determining factor for these emissions.

The standard emission control of spark ignition engines is the three-way catalyst. It is a robust, yet complex aftertreatment system. The effectiveness for the reduction of emissions in real-world circumstances can be related to the effectiveness on the type-approval test. In the case of CNG vehicles, where mainly OEM technology is tested, the limited number of emission test results are similar to the relative effect in the type-approval tests. For LPG, the emission tests are mainly retrofit installation, which yield higher emissions than the OEM technology [Verbeek 2014].

Table 6 shows the average type-approval values over all vehicle models of pollutant emissions of all newly-sold spark ignition vehicles in the Netherlands during 2012-2013.

Table 6 The average type-approval values for 2012-2013 for spark-ignition engines.

[g/km]	CO	HC	NOx
<b>Petrol</b>	0.381	0.045	0.024
<b>LPG</b>	0.476	0.038	0.029
<b>CNG</b>	0.179	0.057	0.031
<b>Ethanol</b>	0.335	0.061	0.036

These numbers are a measure for the relative effectiveness of the three-way catalyst for different fuels. LPG vehicles have standard petrol technology, but the gaseous fuel makes the catalyst less effective than for petrol fuel. CNG and ethanol have different technology, with a reduced efficiency compared to petrol. Based on these results the scale factors for real-world NO<sub>x</sub>, CO and HC for alternative fuels are stated in Table 7.

Table 7 Increases and decreases of pollutant emissions for alternative fuels, relative to petrol, based on the relative type-approval values.

	CO	HC	NOx
<b>Ethanol</b>	88%	137%	151%
<b>LPG</b>	125%	85%	122%
<b>CNG</b>	47%	127%	127%

For CO<sub>2</sub> emissions on the other hand, it can be assumed that the engine efficiency of spark ignition engines is identical for the different fuels. Some minor effects can be distinguished, which are however engine specific. The amount of CO<sub>2</sub> per lower heating value yields a measure of the relative CO<sub>2</sub> emission. The results are shown in Table 8.



Table 8 Reductions in CO<sub>2</sub> emissions per km for alternative fuels, based on JRC/Concawe [JRC 2014].

LPG	Ethanol	CNG
-10.4%	-2.7%	-23.4%

Based on type-approval data for CO<sub>2</sub> emissions of LPG and petrol vehicles, a slightly different and larger reduction ( $\text{CO}_2^{\text{petrol}} [\text{g/km}] = 9 + 1.06 \text{CO}_2^{\text{LPG}} [\text{g/km}]$ ) is recovered for LPG. Likewise, for CNG:  $\text{CO}_2^{\text{petrol}} [\text{g/km}] = 15 + 1.18 \text{CO}_2^{\text{CNG}} [\text{g/km}]$ , and ethanol:  $\text{CO}_2^{\text{petrol}} [\text{g/km}] = -6 + 1.06 \text{CO}_2^{\text{Ethanol}} [\text{g/km}]$ . The spread in this relation is the largest for LPG and the smallest for ethanol. This is very likely due to the variation in composition of the gaseous hydrocarbon fuels.

For particulate matter (PM) emissions, it is expected - with the exception of direct injection - that the emissions are mainly due to the lubricant and they are the same for all fuels. The pollutant emissions of spark ignition vehicles are low compared to diesel vehicles. In particular, most PM emissions are produced at the cold start when the three-way catalyst is still cold, which is well represented in the NEDC type-approval test. The real-world emissions for spark ignition technology are lower than the type-approval values, as the number of cold start per kilometer is larger on the test than in real world.

It should be noted that the hydrocarbon (HC) emission of CNG is mainly methane emission. Methane is 30 times as effective as greenhouse gas (GHG) as CO<sub>2</sub>, which will yield about 1 to 2 gram/km additional GHG emission in CO<sub>2</sub>-equivalent emissions. This reduces the GHG benefits of CNG only slightly.

## 5 Conclusions: the emission factors

In the previous sections the emissions of alternative drivelines and alternative fuels are analyzed. The subsequent translation to emission factors is discussed below.

### 5.1 Emission factors for alternative drivelines

Alternative drivelines, i.e., different forms and degrees of hybridization, are characterized by three main aspects: the braking energy recuperation efficiency, the maximal recuperation braking power, and the engine efficiency in a hybrid driveline. The effects of these main characteristics were studied for three different vehicle segments: compact, medium and business, and a variety of road types and congestion levels.

The differences between these vehicle segments are limited. The vehicle velocity and the road type, i.e. the driving conditions, are dominant in the improved efficiency and lower fuel consumption of hybrid cars. In urban circumstances the benefits of hybrid technology are the largest, as under these conditions low engine load benefits are reaped and a significant amount of braking energy can be recuperated. On the motorway only a minor effect remains: engine speeds are reduced somewhat and so are the engine losses.

Table 9 Overview of the reductions of emission factors per alternative driveline.

	Pollutant reduction	CO <sub>2</sub> reduction	Brake-wear reduction
<b>Petrol hybrid</b>	CO <sub>2</sub> -based	Braking + efficiency	95%
<b>Diesel hybrid</b>	None	Braking + efficiency	95%
<b>Petrol plug-in hybrid</b>	CO <sub>2</sub> -based + Electric	+Electric	95%
<b>Diesel plug-in hybrid</b>	Electric	+Electric	95%

#### 5.1.1 Tailpipe emissions of hybrid technology

Tailpipe emissions of CO<sub>2</sub> and pollutant emissions of hybrid cars using spark-ignited engines, i.e. running on petrol, LPG, Ethanol, or CNG, are reduced by means of two aspects: braking energy recuperation and engine efficiency. From the different driving cycles both effects are estimated, yielding reductions with respect to conventional technology as shown in Table 10. For spark ignition the effect is assumed the same for all emissions.

Table 10 The emission reductions of hybrid technology in four separate service levels. The efficiency effect only applies to the driving, not the braking part, hence both effects cannot be added together in full.

Road type	Braking	Efficiency	Total
<b>Urban</b>	30%	50%	65%
<b>Rural</b>	15%	20%	30%
<b>Motorway</b>	3%	4%	7%
<b>Motorway congestion</b>	25%	50%	60%

So far, the not-to-exceed pollutant emission limits have only led to limited reduction of pollutant emissions in diesel light-duty vehicles.

The gains are mainly traded off against lower fuel consumption, seeking the limits of pollutant emissions. Therefore, no gain is assumed for emissions of air pollutants from hybrid technology in diesel vehicles. The gain for fuel consumption is somewhat smaller than for petrol vehicles, due to the higher efficiency of the conventional diesel engine. However, given the absence of pollutant reductions the numbers in Table 10 for petrol CO<sub>2</sub> and tailpipe pollutant are a good approximation for diesel hybrid technology as well.

#### 5.1.2 *Brake-wear emissions of hybrid technology*

Brake-wear emissions, unlike tyre-wear and road-wear emissions, are reduced by the application of hybrid technology. From the analysis, it is clear that different absolute reductions are achieved during urban, rural, and motorway driving. However, in relative numbers the reductions can be assumed to show the same large effect. From the analysis it is clear that most of the braking - more-or-less except for emergency braking - can be used to recuperate energy. Hence, an assumption of 95% reduction of brake-wear emissions for all road types is appropriate.

#### 5.1.3 *Plug-in hybrid vehicles*

So far 25% electric driving is a rule-of-thumb for current plug-in vehicles, like the Opel Ampera, Chevrolet Volt, Toyota Prius, Mitsubishi Outlander and the diesel-hybrid Volvo V60. This is based on the limited electric driving range, and the high annual mileages of these mostly business-category vehicles. Only the BMW i3 seems to make it less appropriate to use the combustion engine for normal driving, and forces the motorist to seek full usage of its charging capabilities. Hence, this vehicle may generate a different trend from the current usage. The market share of BMW is as yet small.

In the emission factor calculations, plug-in hybrid vehicles are assumed to have a further reduction of 25% on top of the reduced emissions of vehicles equipped with a standard hybrid driveline.

## 5.2 **Emissions factors for alternative fuels**

For alternative fuels, ethanol, LPG, and CNG, spark ignition is the dominant engine technology. Hence, the CO<sub>2</sub> and pollutant emissions are related to the carbon content per lower heating value of the fuel and the efficiency of the three-way catalyst respectively. The former is well-known; the latter can be deduced from the type-approval values and the cold-start strategy. LPG, Ethanol, and CNG all yield a reduced efficiency of the three-way catalyst on NO<sub>x</sub>. On the other hand the CO<sub>2</sub> emissions are reduced with respect to petrol-driven vehicles.

Table 11 gives the overview for the emissions of alternative fuels, which is based on the corresponding values for petrol vehicles. All fuels represent a CO<sub>2</sub> reduction, but the air pollutants give a mixed view, with an overall increase.

Table 11 The change with respect to petrol emission factors (per vehicle kilometre), for alternative fuel vehicles.

	<b>CO</b>	<b>HC</b>	<b>NO<sub>x</sub>/NO<sub>2</sub></b>	<b>CO<sub>2</sub></b>
<b>Ethanol</b>	88%	137%	151%	97.3%
<b>LPG</b>	125%	85%	122%	89.6%
<b>CNG</b>	47%	127%	127%	76.6%

## 6 Literature

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