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Using a Simplified Willans Line Approach as a Means to evaluate the Savings Potential of CO_2 Reduction Measures in Heavy-duty Transport

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Abstract

In this study a simplified Willans line approach is used to model the CO_2 emissions of a long-haul tractor-semitrailer combination. The results are validated with PEMS measurements and show that high accuracy levels can be achieved, if the vehicle and cycle specific parameters are known. It is shown that the same approach can be used to calculate and predict the savings potential of a reduction measure and that the effectiveness strongly depends on the vehicle weight and the velocity profile. Based on the measured effects of vehicle and system measures from recent studies, the generic approach is used to determine the cumulative effect of a given package of fuel efficiency measures, including: energy carriers, vehicle technologies and operational improvements. The cumulative savings potential is determined for two use cases: a city distribution rigid truck and a long-haul tractor-semitrailer. The results show that large CO_2 savings can be achieved when using an integrated approach of vehicle and system measures together. For the city distribution rigid truck, large CO_2 reductions are achieved with electric drivetrains in combination with a clean well-to-tank electricity production whereas improved engine efficiency, reduced road load and logistic options are more promising solutions for the long-haul tractor-semitrailer.

Keywords: Heavy-Duty, CO_2-modelling, Willans line, integrated approach, fuel efficiency.

1 Introduction

The reduction of greenhouse gas emissions is one of the large societal challenges faced by mankind. At the annual Conference of Parties in Paris (CoP21), 190 countries have agreed on the significance of global warming and the need to globally reduce greenhouse gas emissions by 50% in 2050 with reference to 1990. According to EC (2011a), the EU is

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committed to reducing greenhouse gas emissions even further to 80-95% in the context of necessary reductions by developed countries as a group. In EC (2011b), the above mentioned goals are translated to a CO_2 reduction of at least 60% for the transport sector alone.

While CO_2 emissions for new cars and vans are already regulated under EU legislation, no specific targets have yet been defined for the heavy-duty sector including trucks, buses and coaches. A first step to curbing heavy-duty emissions has been made by introducing certification and monitoring of heavy-duty emissions. For this purpose the computer simulation tool VECTO has been developed to measure CO_2 emissions from new vehicles. With the support of this tool the Commission intends to propose a new legislation. One of the considered options is setting mandatory limits on average CO_2 emissions for newly-registered heavy-duty vehicles – comparable to the current light-duty legislation - and the stimulation of fuel efficiency measures. When comparing efficiency measures at the level of individual vehicles and engines, with specific calibration and optimization, the side-by-side comparison may fail. In detailed models much information is needed to be able to run a simulation. Such information is often not available. Moreover, detailed modelling requires detailed validation. The latter is often absent and the effects can be attributed to the wrong aspect in detailed modelling. A generic approach is needed to recover generic effects and their interaction in normal vehicle usage.

In this paper a more generic approach is presented by using Willans lines in combination with user-specific mission profiles. This approach groups effects in such a way that they can be validated with vehicle testing data and vehicle monitoring data, like PEMS data. Determining the overall savings potential of a group of reduction measures is difficult to determine from first principles and often requires highly detailed vehicle models, the relative saving potential however can be determined more easily. In the presented approach, the actual vehicles and the vehicle usage observed in monitoring programs will be used as the baseline to determine the saving effects. It is shown that the presented approach can be used to determine the cumulative savings potential of a range of reduction measures. The forthcoming results indicate that large CO_2 savings can be achieved when taking into account vehicle as well as system measures that cover the entire spectrum of the supply chain in the use of a vehicle. Specifically, these are: alternative energy carriers, powertrain and vehicle technologies, behavioral effects as well as optimized logistic operations and intelligent traffic systems.

2 The Willans line approach to modelling CO_2 emissions

The CO_2 emission of a vehicle is closely related to the vehicle's power demand. This relation can be derived for any specific vehicle from PEMS measurements and is visualized in Figure 1 for a heavy-duty tractor-semitrailer combination. The relationship between power demand and CO_2 is referred to as the Willans line, see TNO (2008). The relationship can be expressed by a linear function

$$CO_2\ [g/s] = \alpha\ [(g/s)\ /\ kW\ ]\ x\ P_{load}\ [kW] + \beta\ [g/s],$$

where α is a measure for the efficiency of the powertrain [η_{PT}] as well as the carbon content of the fuel [γ], P the power demand and β a measure of the internal losses in the powertrain.

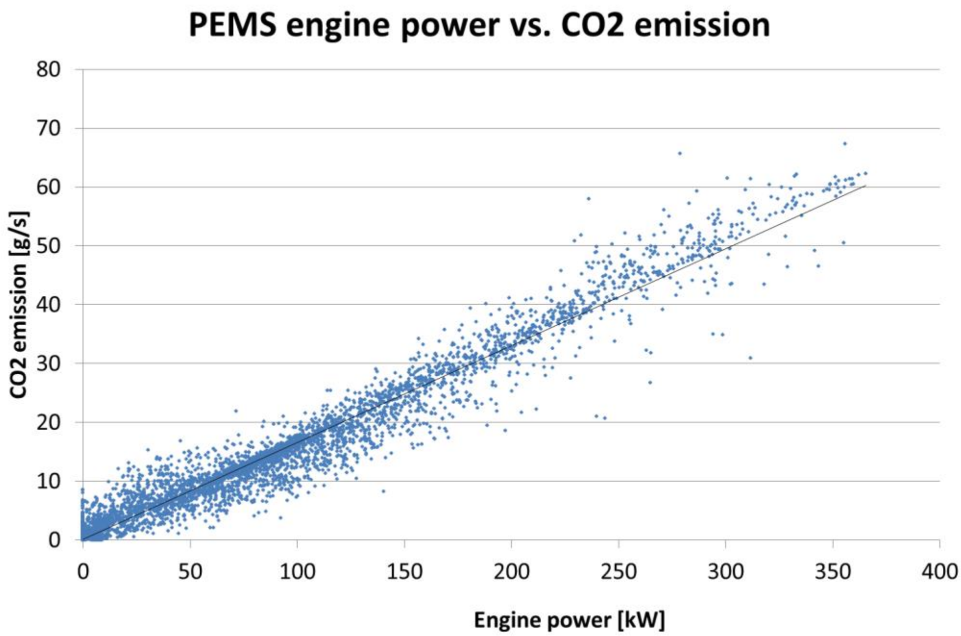


Figure 1: The Willans line for a tractor-semitrailer combination derived from PEMS measurement

With the knowledge of the Willans line coefficients α and β, modelling CO_2 for a specific vehicle is simply a matter of calculating the road load equation

$$P_{load} = P_{rrc} + P_{air} + P_{inertia} + P_{regen} + P_{gradient}$$
$$P_{load} = MC_{rr}\cos(\theta)v + \tfrac{1}{2}\rho C_d A v^3 + M_0 a^+ v + \eta_{regen} M a^- v + Mg\sin(\theta)v$$

and the following vehicle and cycle specific parameters:

- C_{rr} – coefficient of rolling resistance
- C_d – drag coefficient
- g – earth's acceleration
- ρ – air density
- A – frontal area of the vehicle
- η_{regen} – regenerative braking efficiency [only applicable for regenerative brakes]
- M – vehicle mass [empty weight + payload]
- θ – road gradient
- v – instantaneous velocity
- a+ – vehicle acceleration
- a^- – vehicle deceleration

The linear approach uses fixed values for all parameters, except for the road gradient, the velocity and the acceleration which are transient. This also reflects the limitations of the approach. The relation between power and CO2 emission is only linear by approximation. Some variation is to be expected, even though many aspects are already covered from the fit of emission data, including variations with engine speed. The lower the power, the larger the residual variation around the straight line approximation. This does not invalidate the approximation, as on average the fit provides the correct relation, and the typical variations are for a great part related to transients not covered by the Willans line. For example, the engine rotating inertia stores kinetic energy visible in the CO2 emission, but not in the power output. As a result, in acceleration from a stop to high velocity, with numerous gear shifts in between, the fuel rate, engine speed and engine power output vary rapidly, but not synchronously. At gear shift the power output and the fuel consumption are zero, and the engine is motoring. Gear shift therefore shows up as a large variation in the relation between CO2 rate and power output at low powers. Short periods of high fuel consumption are also used, apart for acceleration, to overcome engine losses at intermediate times when the clutch is engaged. Little energy is lost in this process as it is released at motoring. At longer time scales the buffering of energy in for example rotational engine inertia, cancels out and the linear relation is even more prominent that on a second-by-second basis.

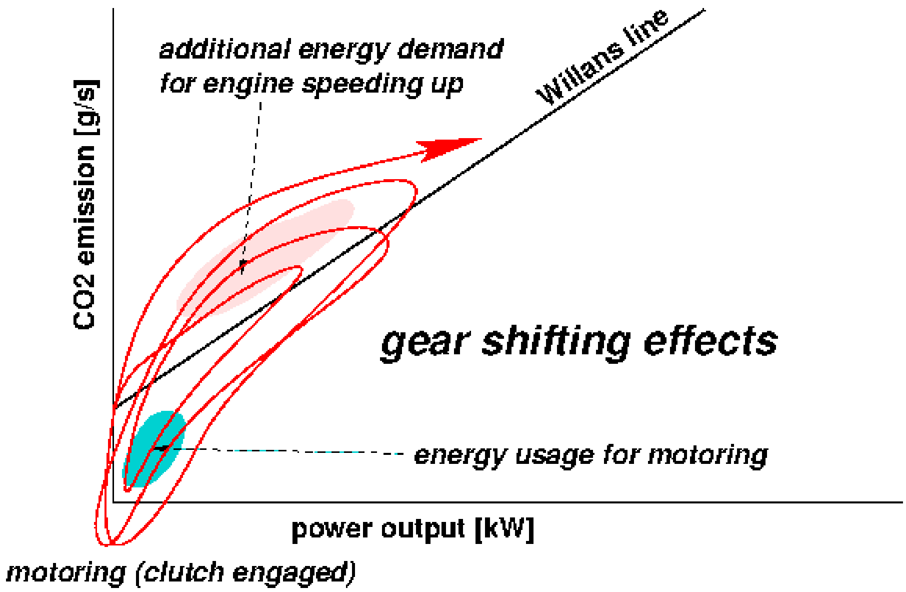


Figure 2: The spread of the data around the Willans line due to gear shifting. The additional energy to speed up the engine is released at intermediate motoring. The net effect is the Willans line, as no energy is lost.

With the given model, the savings potential of various CO_2 reduction measures can be determined. Each reduction measure interacts differently with the vehicle and therefore changes either the vehicle, the cycle specific parameters, or both. A schematic overview of how parameters are influencing the vehicle and cycle specific parameters is shown in Figure 3. The following reduction measures can be differentiated:

- Energy carriers like gas (LPG, CNG, LNG), electricity and hydrogen have an effect on the carbon content of the energy carrier, mostly in combination with a change in engine efficiency η_{PT}.
- Engine and driveline efficiencies, for example a hybrid transmission, control strategies, improved fittings and higher combustion pressures, have an effect on the powertrain efficiency η_{PT} and β, the internal losses.

- Vehicle measures effect the rolling resistance, the air drag and the vehicle weight (C_{rr}, C_d and M).
- High-over system measures, that influence the vehicles behavior, the traffic systems and the logistic supply chain have their main effect on the vehicle's velocity and its payload.

In the following sections, it is shown that the Willans line provides a relatively accurate modelling approach, given the knowledge of the vehicle and cycle specific parameters described above. For this purpose, the modelling accuracy of a Willans line is evaluated using PEMS measurement data of a tractor-semitrailer combination. Furthermore, it is shown that the Willans line is suited to model the savings potential of a CO_2 reduction measure without detailed knowledge of the engine map or the underlying control strategy. This is particularly useful, since in practice the control strategy of a specific make is often unknown. At last, the Willans line approach is used to evaluate the overall potential of two heavy-duty cases in order to demonstrate that the roadmap towards low emissions differ strongly per case.

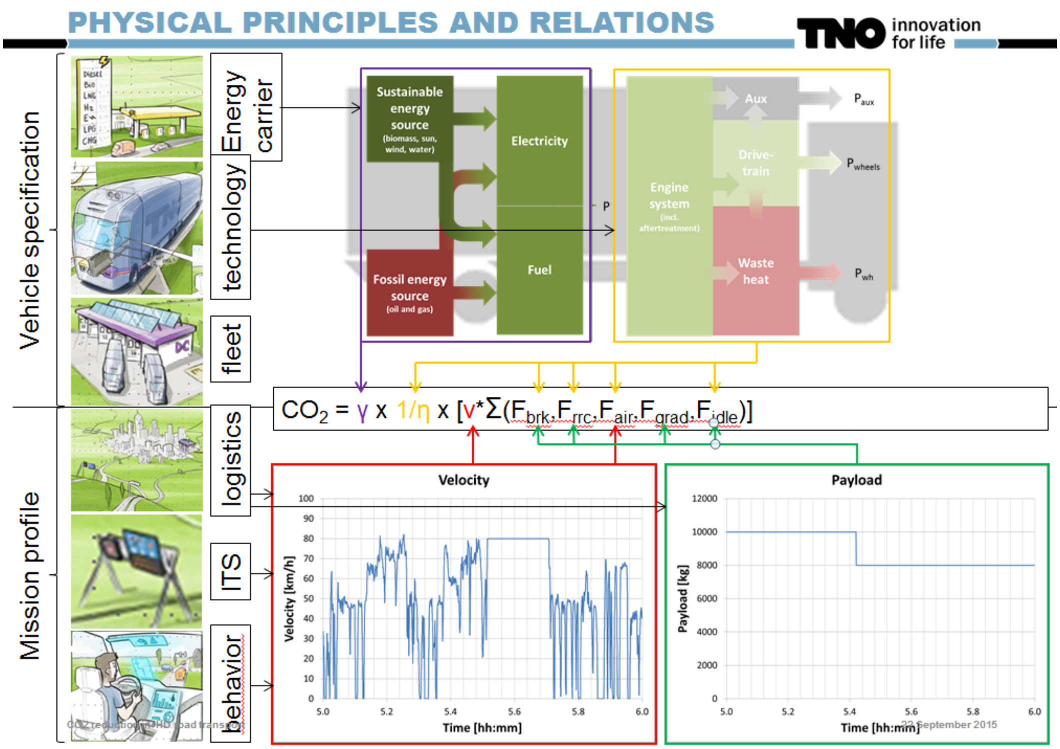


Figure 3: Schematic overview of the effects of reduction measures on the vehicle and cycle specific parameters and the CO_2 emissions in general

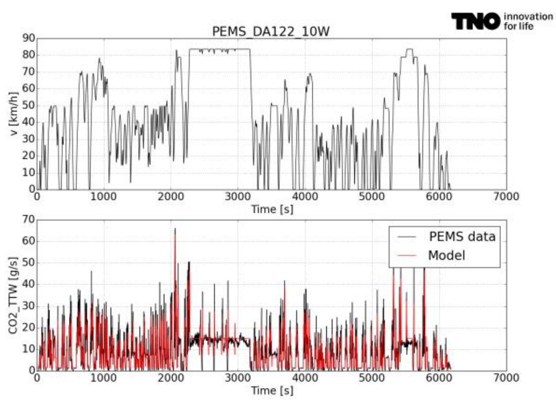
3 Validation of the Willans line approach with PEMS measurements

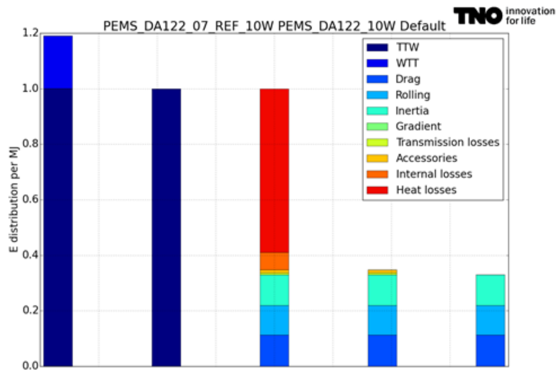
PEMS measurement data was used to validate the Willans line approach. For this purpose, three similar trips were logged with a tractor-semitrailer combination. For each trip, the payload was varied between 10% (3370 kg), 55% (17220 kg) and 100% (31120 kg) of the maximum load. The tailpipe CO_2 emission was measured and compared with the results from the model. The model specifications shown in Table 1 were determined from the vehicle subparts where possible. If this information was not available, an estimate was made based on values from literature such as UBA (2015), ICCT (2014) and ICCT (2015). Since internal losses depend on the engine load, with higher losses occurring at high loads, the internal losses have been assumed to be in the order of 2-4% of the rated power which corresponds to observed values from TNO in-house PEMS measurement results.

Table 1: Vehicle specific modelling parameters used for the PEMS validation

	Parameters	**Tractor-semitrailer**
Energy carrier	**γ [gCO_2WTW/MJ]**	89.7 (Diesel)
Powertrain	**Prated [W]**	340000
	η_{PT} [%]	40.0
	β [W]	6800 – 13600
Auxiliaries	**Paux [W]**	1360
Air drag	**CdA [m^2]**	6
Rolling resistance	**Crr [N/kN]**	6
Vehicle weight	**Empty weight [kg]**	15380

A comparison of the real-world PEMS measurements and the model is shown in Figure 4. The left figures provide a direct comparison of the CO_2 emissions between model (red) and measurements (black). The figures on the right show that the share of certain physical forces in the overall energy consumption of the trip.

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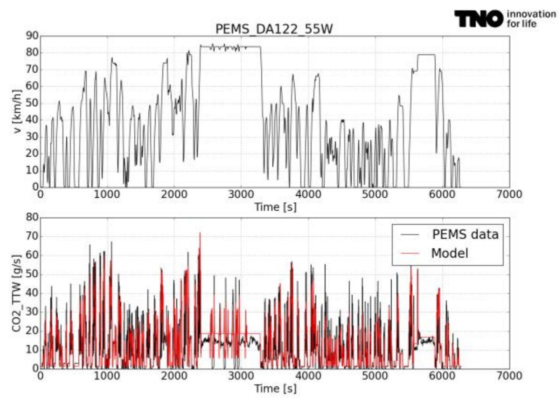
Heat losses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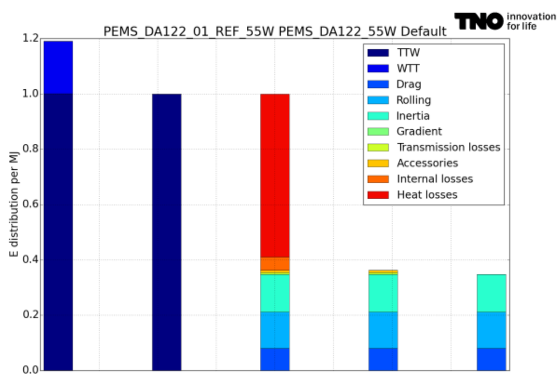
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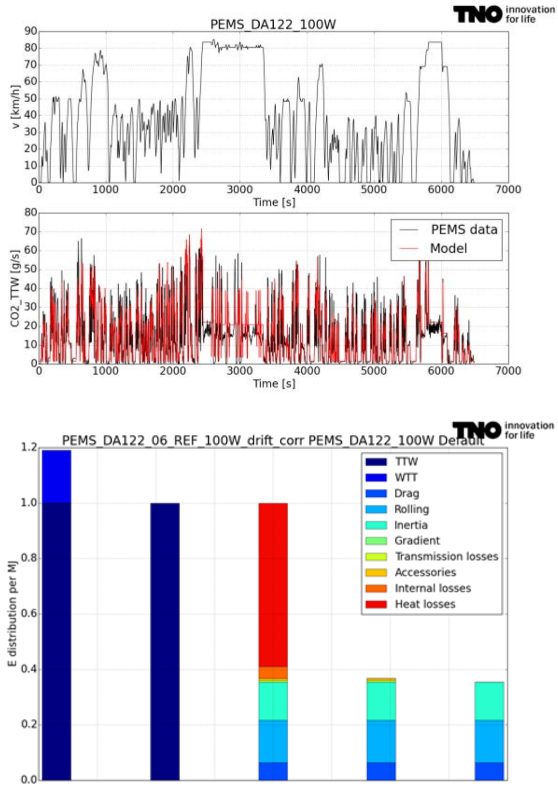

Figure 4: Validation results PEMS vs. model for three different load cycles (top to below: 10%, 55% and 100% loaded vehicle, left to right: CO_2 emissions and normalized share of energy consumption per trip

A number of observations are made:

- The modelled data clearly follows the same trend as the measurement data. The overall performance of each trip, both model and measurement, is shown in Table 2. From the results it can be concluded that the overall estimation accuracy is in the range of +/- 5%.
- Heat losses account for about half of the overall energy use. This is expected and is directly related to the thermal efficiency of the engine and the driveline efficiency. Although in practise exhaust and cooling losses of the engine system will differ depending on the load, in the model these losses remain constant over all three trips. This is due to the assumption that the powertrain efficiency η_{PT} is constant.
- The share of internal losses accounts for about 3% of the energy consumption and is higher at low loads (= low payload). This is to be expected, since the internal losses are assumed to be load-variant. The losses mimic the real-life performance of pumping and friction losses in the engine.
- As a result of the increased payload, the inertial forces and rolling resistance increase as well. This leads to overall higher CO_2 emissions of the vehicle, an increased shared of inertia and rolling resistance and a decreased share of air drag in the overall energy consumption.

- The trips were all performed in the Netherlands and hardly had any road gradients. In the Alps for example, the road gradient might have a significant share of the overall energy consumption.
- Transmission losses are small (1-2%) and are accounted for in the efficiency of the powertrain η_{PT}.

Table 2: CO_2 emissions model vs. PEMS

Payload	Model	PEMS	Ratio model/PEMS
Trip 1 – 10% payload	771 [g/km]	809 [g/km]	95.3 [%]
Trip 2 – 55% payload	1092 [g/km]	1057 [g/km]	103.3 [%]
Trip 3 – 100% payload	1322 [g/km]	1280 [g/km]	103.3 [%]

The results show that the Willans line approach is suitable way to determine the CO_2 emission of a vehicle with an accuracy of +/- 5%. It also illustrates that the savings potential of a reduction measure will vary strongly depending on the cycle, as the share on the different forces are amongst other influenced by the payload and the velocity profile. The large range of the effectiveness of reduction measures can best be demonstrated with two examples, low rolling resistance tyres and aerodynamic side skirts. According to the following sources: TNO (2014) and WABCO (2014),

- low rolling resistance tyres account for a reduction in rolling resistance of roughly 10%.
- aerodynamic side skirts can reduce the aerodynamic drag Cd of a Tractor-semitrailer by about 15%.

A 10% reduction in Crr is expected to reduce the CO_2 emissions by about 3-4% (10% reduction of Crr and 30-40% share of rolling resistance in the total road load). A drag reduction of 15% is expected to reduce CO_2 emissions by 3% (15% reduction of Cd and 30% share of air drag in the overall energy consumption). The exact savings potential depends on the payload and the velocity profile of the vehicle and is calculated using the Willans line approach. The results are summarized in the table below (Table 3) for two different vehicle payloads and two different mission profiles. The range of both savings potential are compared with the measurement results from the Future-Truck program in the Netherlands, TNO (2013a).

Table 3: CO_2 savings potential of low rolling resistance tyres and aerodynamic side skirts

	Vehicle type	Mission profile	Low rolling resistance tyres	Aerodynamic side skirts
Modelled	**Tractor-semitrailer (light)**	**city distribution**	1.9%	3.1%
	Tractor-semitrailer (heavy)	**city distribution**	2.3%	1.7%
	Tractor-semitrailer (light)	**long-haul**	2.9%	6.7%
	Tractor-semitrailer (heavy)	**long-haul**	4.1%	4.2%
Measured	**Tractor-semitrailer (mix)**	**mix**	2 - 4%	2.7 - 6%

The results show that the effectiveness of a reduction measure is not just a fixed number but a range that depends on the vehicle type and its use. The range of the savings potential for both, low rolling resistance tyres and aerodynamic side skirts, is large. While rolling resistance measures are most effective for heavy vehicles at high velocities, air drag measures are most effective for light vehicles at high velocities. It can be seen that the model results are well in-line with the measurement results. Small differences can be explained by the fact that the future truck program monitored a range of vehicles with marginally different payloads and velocity profiles than modelled.

4 Outlook 2020-2030

In the past years, large monitoring programs like the U.S. Super-Truck program or the Dutch Future-Truck program have shown that there are large CO_2 saving potentials to be harvested for heavy-duty transport, TNO (2013a) and ICCT (2014). However, these programs mainly focus on the technological feasibility of vehicle technologies, hereby excluding important aspects from system technologies like logistics, behaviour and intelligent traffic systems. The provided saving potentials therefore only represent a subset of the overall picture. This study aims at presenting a truly integrated approach which takes into account the overall savings potential of energy carriers, vehicle and system technologies.

This paper uses the Willans line approach to estimate the overall savings potential of fuel reduction measures in the 2020-2030 timeframe. In the approach, references from the knowledge domains of powertrains, logistics and smart mobility are used to form an overall picture. By using Willans lines, the physical relationships between the one domain and the other are taken into account, instead of oversimplifying the calculation by cumulating effects. To demonstrate the range of possibilities, two use cases were studied: a rigid truck with a city distribution cycle and a Tractor-semitrailer combination driving long-haul distances. EURO VI truck technology was taken as the baseline.

Baseline scenario – current state of the art

Vehicle and cycle specific modelling parameters as shown in Table 4 were derived from in-house PEMS measurements (see above) and compared with recent studies UBA (2015) and ICCT (2015). Average cycle payloads were taken from TNO (2013b) and assumed to be constant over time. When dealing with daily logistic operations this is obviously not the case as the payload typically changes between empty and full. The cycle and weight of loading and unloading however is very operations specific and does not provide a general insight, as provided in TNO (2013b) for Dutch average payloads.

Table 4: Baseline scenario - vehicle and cycle specific modelling parameters

		Parameters	Rigid truck	Tractor-semitrailer
Vehicle specific parameters	**Energy carrier**	**γ [gCO$_2$WTW/MJ]**	89.7 (Diesel)	89.7 (Diesel)
	Powertrain	**Prated [W]**	185000	310000
		η_{PT} [%]	40	41
		β [W]	3700 – 7400	6800 - 13600
	Auxiliaries	**Paux [W]**	750	1360
	Air drag	**CdA [m^2]**	4.4	5.85
	Rolling resistance	**Crr [N/kN]**	7	6
	Vehicle weight	**Empty weight [kg]**	8820	15380
Cycle specific parameters	**Payload [kg]**		2376	17220
	Velocity profile		see below	

The velocity profiles of a city distribution and long-haul cycle were taken from subsections of in-house PEMS measurements and are shown in Figure 5 and Figure 6, respectively. In both figures are shown from top to below the velocity profile, the histogram of velocities and acceleration as well as the relative shares of CO_2 emission at specified velocity bins.

In order to make cycles more representative for daily operation, several cycles were repeated to attain a realistic distance. From the histogram of velocities it can be seen that the long-haul cycle is dominated by motorway driving at 80 km/h, whereas in city distribution the velocity profile is more balanced between urban (<50 km/h) and motorway (70-80 km/h) driving. The acceleration profile for both cases is relatively similar, however for the long-haul case it is observed that on average the tractor-trailer combination decelerated harder than the rigid truck in city distribution. This is possibly due to the heavier tractor-trailer combination, but could also be effected by driving behavior. The relative shares in CO_2 emissions are split apart for heat losses, auxiliaries, internal and transmission losses as well as the road load. For combustion engines, heat losses account for the largest share of the energy consumption. It can be seen that internal losses have a high share in overall emissions at low velocities. At velocities between 10 and 50 km/h, inertia losses have the highest share in the emissions contributed to road load. At velocities above 50 km/h, rolling resistance and air drag contribute most, while air drag dominates the emissions at velocities higher than 70 km/h.

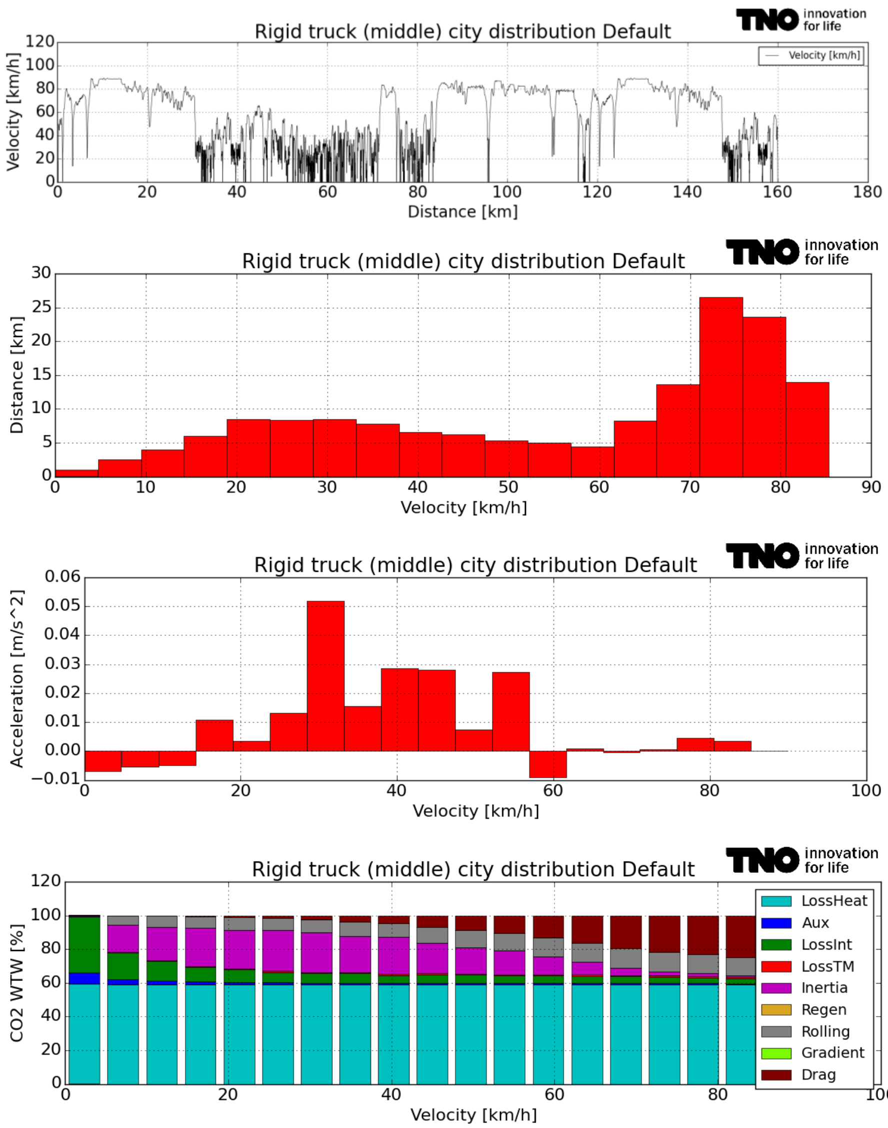

Figure 5: City distribution rigid truck – from top to bottom: velocity profile, histogram of velocities, histogram of acceleration and relative CO_2 emission at different velocity bins

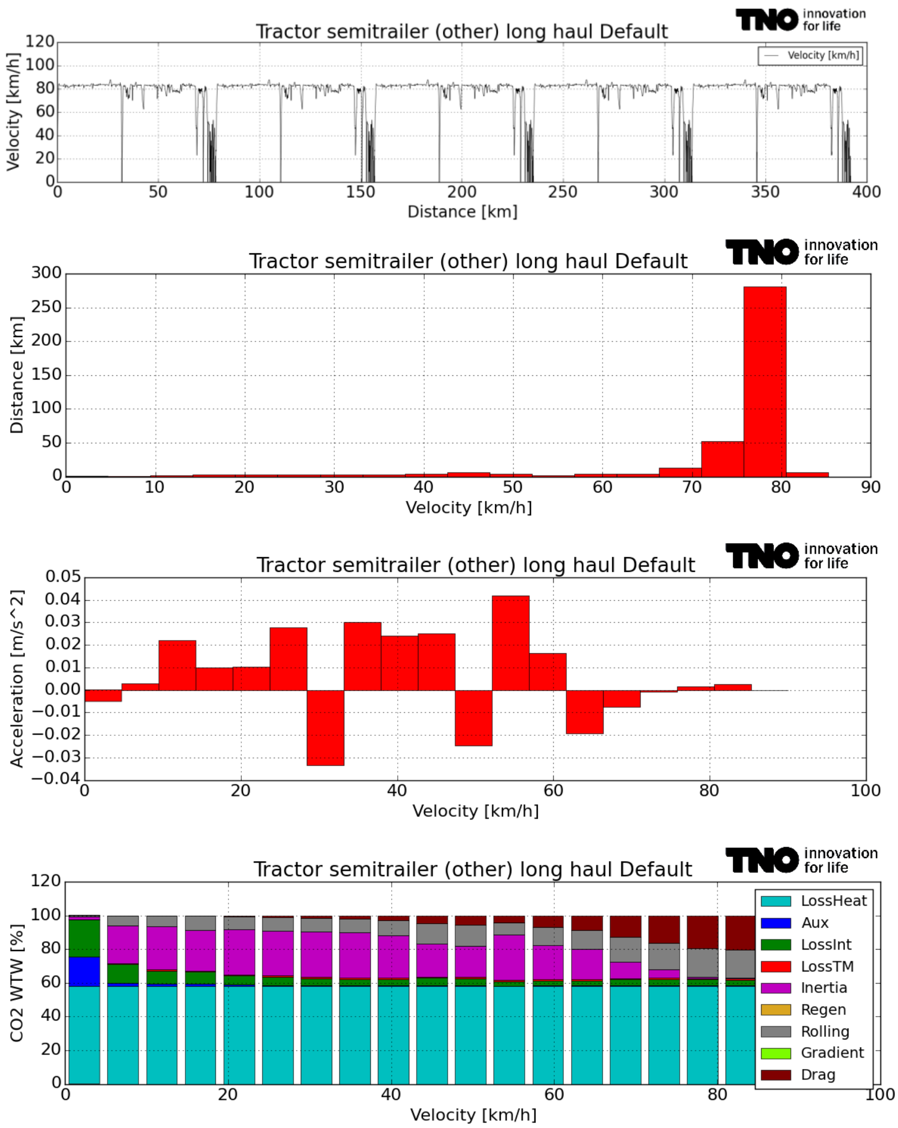

Figure 6: Long-haul tractor-trailer – from top to bottom: velocity profile, histogram of velocities, histogram of acceleration and relative CO_2 emission at different velocity bins

<u>Fuel efficient scenario – fuel efficiency technologies in 2020-2030</u>

The effectiveness of fuel efficiency technologies have been studied in previous publications, separately for vehicle technologies in ICCT (2015), logistics in TNO (2013c) and smart mobility solutions in RAEA (2015b). The following analysis aims at determining the overall effectiveness when combining the underlying assumptions of these three domains. For this purpose the baseline scenario is used as starting point to successively incorporate ready-to-market technologies in the timeline of 2020-2030 into the Willans line model. The results of all three domains are shown apart in Figure 7 and Figure 8, respectively for the city distribution rigid truck and the long-haul tractor-trailer combination. The underlying assumptions that lead to these results are detailed underneath.

The assumptions for the vehicle technology packages are shown in Table 5 and are based on

ICCT (2015), RAEA (2011), RAEA (2015b) and TIAX (2011).

Table 5: Vehicle measures and their effect on the vehicle specific modelling parameters

	Parameters	Rigid truck	Tractor-semitrailer
Energy carrier	**γ [gCO_2WTW/MJ]**	125 (Electricity $NL_{mix2015}$)	89.7 (Diesel)
Advanced powertrain solutions	**Prated [W]**	E-motor [150kW, 160kWh]	Advanced diesel engine [280 kW]
	η_{PT} [%]	80%	50% (+20%)
	η_{regen} [%]	50%	50%
	β [W]	n.a.	-10% downsized engine -20% downspeeding
Auxiliaries	**Paux [W]**	375 (-50%)	620 (-50%)
Reduced air drag	**CdA [m^2]**	3.06 (-30% CdA)	4.1 (-30% CdA)
Low rolling resistance	**Crr [N/kN]**	4.2 (-30% Crr)	4.2 (-30% Crr)
Lightweighting	**Empty weight [kg]**	7500 (-14% mass) + 1600 (mass E-motor) = 9100	13370 (-14% mass)

In ICCT (2015), a vision was formulated for the development path of diesel-powered heavy-duty vehicles up to the year 2030. This vision is largely based on the outcome of the U.S. Super-Truck program in which the commercial parties and RTOs Cummins, Daimler, Navistar and Volvo have demonstrated how to increase freight efficiency with 50% by applying cutting-edge vehicle technologies which are not yet ready-to-market but expected penetrate the market in the future. Based on these findings, different technology packages were defined, starting from moderate (2017), phase 1 (2020+), advanced (2020+ WHR) up to long term (2030+). In this study, the assumptions for 2020-2030 are largely based on the availability of the following technology packages.

- Energy carrier: According to EMOSS (2015), a 12 ton rigid truck with 80% payload, comparable to the rigid truck in the use case, achieves an energy consumption of about 0.8 kWh/km. With the Willans line approach, an energy consumption of 0.85 kWh/km is determined when taking into account the improved motor efficiency of 80% (vs. 40% of the Diesel engine), 50% regenerative braking efficiency and when accounting for the additional weight of the battery pack of roughly 1600 tons (10 kg/kWh times 160 kWh). In comparison to EMOSS, the estimated energy consumption is probably even a conservative estimate. Since the diesel powertrain is completely replaced with an electric one, no further powertrain improvements are expected for the rigid truck. Carbon content levels of the current electricity mix in the Netherlands is assumed. This is a conservative estimate, since the renewable share of the electricity mix in Europe is planned to be 20% in 2020 and even higher beyond.
- Improved engine efficiency of 52% BTE_{peak}. This is achieved by reducing the friction losses in the engine, using on-demand accessories, optimized combustion control and waste heat recovery: In the Willans line approach, this translates to a increased powertrain efficiency of 50% including transmission losses and a reduction of the energy demand of all accessories (e.g. the steering pump, AC, compressor, etc.). Based on RAEA (2011), a maximum reduction of accessory energy demand of up to 50% is assumed. Hybrid powertrains could reduce energy consumption further by making use of regenerative brakes. A regenerative braking efficiency of 50% is assumed based on TNO (2012).

- 20% engine downspeeding is achieved by use of a dual clutch transmission. Furthermore, a 10% engine downsizing is assumed feasible. Both measures are reflected in the internal losses of the Willans line approach.
- The road load is expected to be reduced by 30% less air drag, 30% less rolling resistance and 14% less weight. Although not explicitly stated in ICCT (2015), it is assumed that the rigid truck can achieve the same road load reductions. According to FAT (2013), large air drag reductions can be achieved with side skirts and boat tails, both for rigid and tractor-trailer combinations. It is also clear that low rolling resistance tyres, TNO (2014), and TPMS technology, TNO (2013c), can improve rolling resistance. However, it must be stated that a reduction of 30% in air drag and rolling resistance are very ambitious targets. Weight reductions in the range of roughly 2000 kg (14%) can only be achieved when taking into account innovations like an aluminium chassis [DAF (2015)], cabin size reduction and further material innovations mentioned in RAEA (2015).

The assumptions for the system technology packages are shown in Table 5. System measures typically influence the cycle specific modelling parameters like the velocity and acceleration profile as well as the vehicle payload. According to RAEA (2011) driver training can result in fuel economy reductions of 5 to 10%. Truck platooning technologies are also expected to result in fuel savings of up to 10%, see TNO (2015a). Driver education can be expressed in a reduced amount of inertial forces, while all other road load forces remain the same. Ideally the driver learns to coast for longer distances, instead of braking abruptly, and also reduces speeding. In the Willans line approach, this translates to a reduction in acceleration and deceleration levels. Truck platooning reduces the aerodynamic drag of both the leading and the following vehicle and thus yield a reduced fuel consumption. In the following analysis it is assumed that driver training will be most effective in dynamic driving conditions like city distribution, whereas truck platooning is effective on the motorway at long-haul cycles. For both use cases a fuel consumption reduction of 10% is assumed due to these technologies.
Longer Heavier Vehicles (LHVs) have a large CO_2 savings potential which is directly related to the increased freight efficiency. According to Daimler (2015), two LHVs can replace three standard tractor-semitrailers, hereby reducing the fuel consumption by 15-20%. It will be assumed that this is only applicable for the tractor-semitrailer. When dimensioning an electric rigid truck, the weight of the battery packages will be trade with payload in daily operation. Therefore, it is assumed that no further logistic optimization can be realized for the rigid truck.

Table 5: System measures and their effect on the cycle specific modelling parameters

	Parameters	**Rigid truck**	**Tractor-semitrailer**
Behaviour and ITS	**Acceleration [m/s^2]**	-10% fuel consumption	-10% fuel consumption
Logistic solutions	**Payload [kg]**	n.a.	+8t (additional trailer) +30% payload
	Distance [km]	n.a.	-30%

The results in Figure 7 show that even with the current electricity mix in the Netherlands, electric rigid trucks can achieve a great WTW CO_2 reduction of more than 30%. Obviously, when this mix is 100% renewable, WTW emissions will even reduce to zero. Apart from

this, large savings of nearly 20% can still be achieved with road load reductions and behavioral measures. Even if the above described measures only achieve 80% of their target value and when excluding further renewable energy sources in the electricity mix, the cumulative savings potential for a rigid truck with a city distribution cycle is still 40%.
According to ICCT (2015), the development potential of a diesel engine is not yet saturated. This is reflected in the results below (see Figure 8). Without alternative powertrains and energy carriers, a long-haul tractor-trailer combination also achieves savings of at least 40% CO_2 WTW. The savings potential associated to the powertrain is roughly half as large as in the electric case above, however larger savings can be achieved with a reduction of road loads, ITS solutions like truck platooning and LHVs. Using HVO from waste cooking oil instead of Diesel can reduce CO_2 savings even up to 90% (carbon content of 8.1 MJ/l instead of 89.9 MJ/l), but just as with other biofuels the availability of sufficient resources remains uncertain. HVO from waste cooking oil is only mentioned in this analysis to illustrate the maximum range of the savings potential. With biofuels the origin of the energy source as well as the chemical composition of the fuel is always crucial, see TNO (2015b). A counter example is given with FAME from rape seed where in the best case no saving is achieved and even if using FAME from a different energy source, it is only intended as drop-in fuel up to 30% which reduces its savings potential drastically.

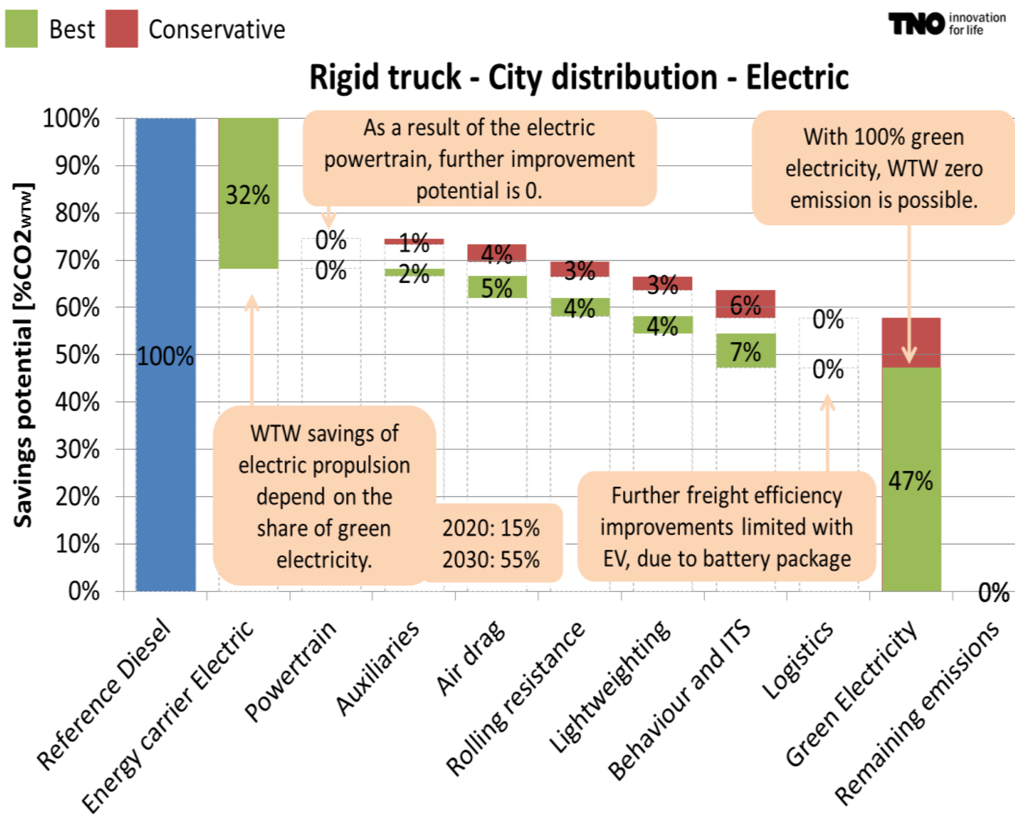

Figure 7: Savings potential for a city distribution rigid truck– route EV

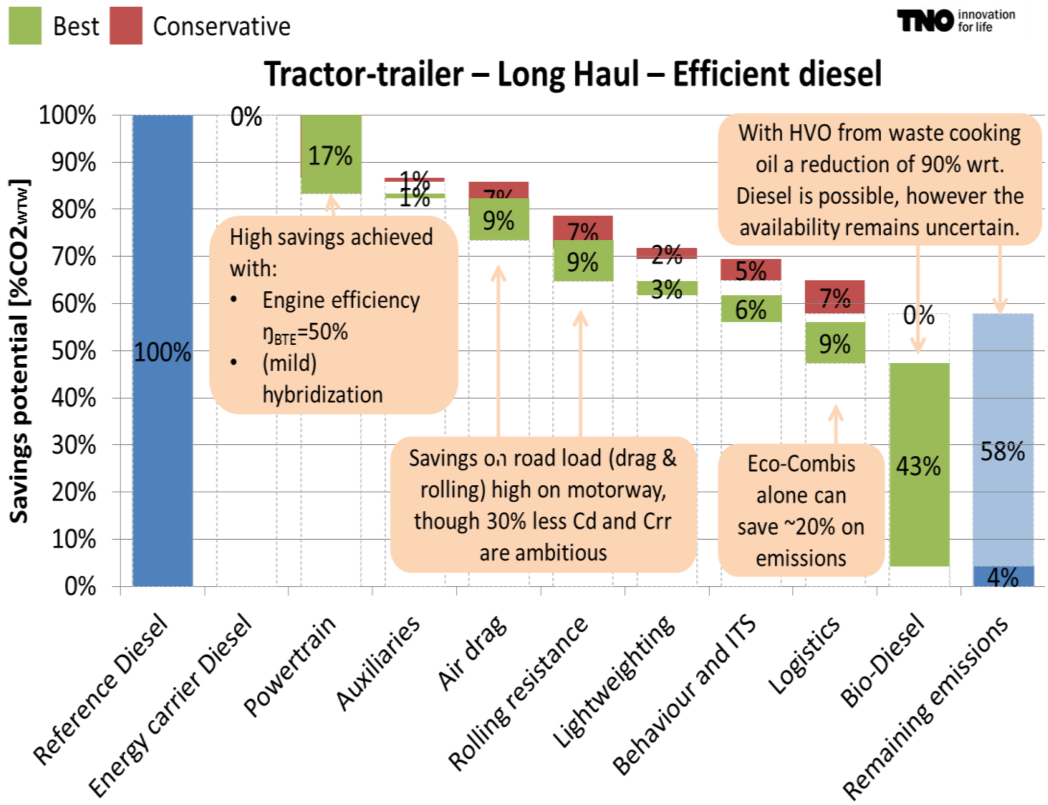

Figure 8: Savings potential for a long-haul tractor-semitrailer – route efficient diesel

5 Discussion and Conclusion

In this paper, a simplified Willans line approach was presented as an alternative tool to calculate the savings potential of heavy-duty reduction measures. For this purpose, PEMS measurements were used to derive vehicle specific modelling parameters and validate the modelling approach. By tuning the parameters according to suggested values from recent studies, the cumulative savings potential of two use cases was determined.

The results show that the heavy-duty transport sector can yet achieve large CO_2 reductions when considering vehicle as well as system measures. Depending on the vehicle and its daily operational cycle, the route towards low emission levels will differ and thus needs to be determined for different use cases and logistic sectors apart. The two cases illustrate that the choice of an energy carrier also lays out the path for further reductions. Obviously, choosing for an electric energy carrier eliminates the options of diesel engine measures which are applicable and optimized for diesel engines only. The same applies for logistic options which aim at higher truck loads, since in many cases the use of an electric truck is a trade-off between payload, designated battery package and the required loading infrastructure. The room for further logistic optimization in electric trucks remains something to be further explored for different logistic operations. Disregarding the choice of the energy carrier, road load reductions by means of reduced air drag, rolling resistance and weight provide large cumulative potentials. However, it is highlighted that the here assumed reductions mentioned in the 'advanced package' of ICCT (2015) are very ambitious and will require much research and development efforts. The road load can be even further reduced by behavioral and ITS measures which influence the inertial forces of the vehicle. The range of saving potentials for renewable energy carriers is large and always depends on the energy source and its chemical composition.

A good strategy to reach low emission targets could be to first improve the freight efficiency further, before relying on the availability of sustainable energy carriers.

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