

Next Generation Engine Start/Stop Systems: “Free-Wheeling”

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ABSTRACT

Engine Start/Stop systems reduce CO₂ emissions by turning off the combustion engine at vehicle standstill. This avoids the injection of fuel that would otherwise be needed simply to overcome internal combustion engine losses. As a next development step, engine losses at higher vehicle speeds are to be addressed.

During deceleration, state-of-the-art engine technology turns off fuel injection as soon as the driver releases the gas pedal, thus the combustion engine is motored by the vehicle. The engine's drag torque could be desired by the driver, e.g. as a brake assist during downhill driving. However, quite frequently the driver wishes to coast at almost constant speed. Similar to Start/Stop operation, in such situations fuel is injected to simply overcome the combustion engine's drag torque. An operation mode referred to as “Free-Wheeling” reduces CO₂ emissions under such coasting conditions by disconnecting the combustion engine from the powertrain and by turning it off. Free-Wheeling can be considered as a next logical step of engine Start/Stop systems, with additional requirements for the vehicle system.

This paper quantifies the CO₂ potential of Free-Wheeling for various driving conditions and for common emission test cycles. Vehicle simulations as well as vehicle measurements have been carried out in order to derive fundamental requirements for the vehicle system, the engine, the starter system, auxiliaries, electric power net and transmission.

INTRODUCTION

Whereas only five percent of all new vehicles in Europe were equipped with a Start/Stop system in 2008, it is expected that in 2012 every second vehicle in Europe will be equipped with

this fuel-saving technology. This tremendous growth rate is due to a very favorable cost/benefit ratio: offering a fuel consumption benefit of up to 5% in the New European Driving Cycle (NEDC), Start/Stop systems generally use a number of new components that are compatible to existing ones. Therefore Start/Stop can be adapted quickly and in a cost-effective way for new engines and vehicles.

While initially Start/Stop technology was primarily introduced in vehicles with manual transmission, this technology has also been introduced in vehicles with automated transmissions. Today, Start/Stop systems are being implemented in all vehicle segments and markets, from entry level up to the luxury segment.

The basic principle behind Start/Stop is the elimination of engine drag torque at idling conditions, i.e. when no propulsion is requested by the driver. By turning off the combustion engine while decoupling it from the drivetrain, fuel is saved that would otherwise be injected simply to overcome the combustion engine's losses. A similar concept can be applied in order to reduce the combustion engine's drag torque and therefore fuel consumption at higher vehicle speeds.

State-of-the-art engine technology turns off fuel injection as soon as the driver releases the gas pedal. Turning off fuel injection is already a significant step forward in comparison to carburetor systems. However, when the combustion engine is motored by the vehicle, its friction and pump losses cause a significant loss of energy. Depending on the engine size, type and design, the motoring torque and therefore the resulting motoring power can be significant, see [Figure 1](#) and [2](#), respectively. The engine speed in a vehicle depends on vehicle speed and the gear/transmission ratio, but generally

speaking, a power loss of 5-10kW during coasting is quite typical.

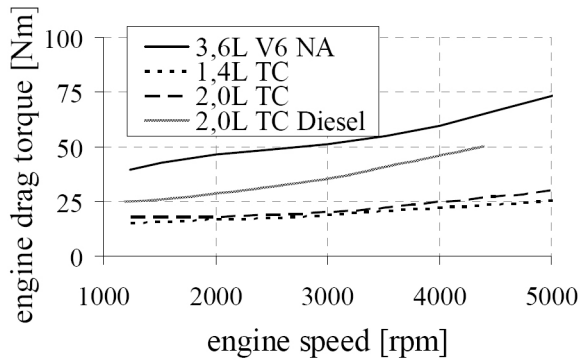


Figure 1. Motoring torque of various combustion engines as a function of engine speed

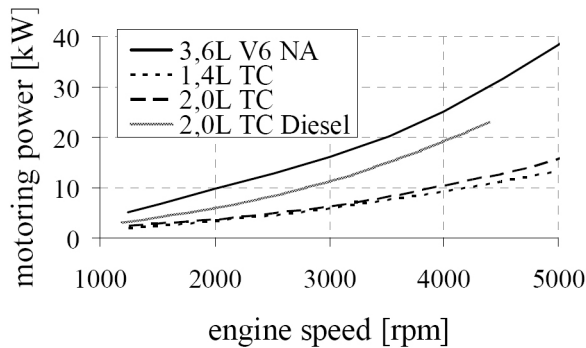


Figure 2. Motoring power of various combustion engines as a function of engine speed

In order to avoid the negative engine torque during coasting, a mechanical free-wheeling device could be built into the vehicle's transmission, allowing the transfer of positive torque only. Such free-wheeling mechanisms have been investigated in the past and have also been used for certain applications, see section "History". The drawback of mechanical free-wheeling devices is that typically they cannot be disabled during down-hill driving, when the combustion engine's motoring torque is actually beneficial. A free-wheeling type effect can be achieved if the combustion engine is decoupled from the drivetrain whenever the combustion engine's torque is negative. This decoupling can be achieved by opening a clutch or by shifting the transmission into neutral. Since this approach's effect has similarities to a mechanical free-wheeling function, it is referred to as "Free-Wheeling" in the following.

The driver can experience Free-Wheeling by an increased coasting distance, which is illustrated in Figure 3. Starting at a vehicle speed of 100km/h, the coasting distance, until a vehicle speed of 50km/h is reached, is more than doubled, in comparison to a vehicle coasting in 6th gear.

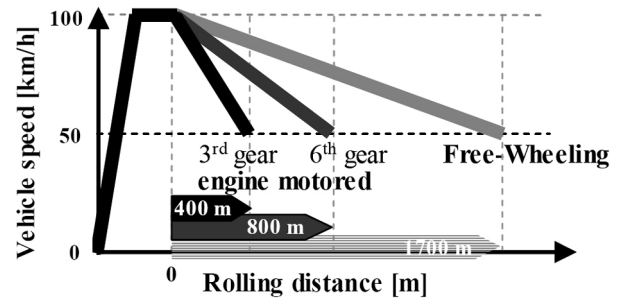


Figure 3. Increased coasting distance with Free-Wheeling, in comparison with coasting in 6th and 3rd gear (upper middle class vehicle, 1900kg, with 3,6L V6 NA Gasoline engine)

Opening the clutch under such coasting conditions gives the options of turning off the combustion engine or operating it at idle speed, in the following referred to as Free-Wheeling Engine-Off (FW-EO) and as Free-Wheeling Idling (FW-I), respectively. FW-I entails an idle speed fuel consumption, which can still be advantageous in comparison to a minimal fuel injection that only compensates drag losses, see Figure 4.

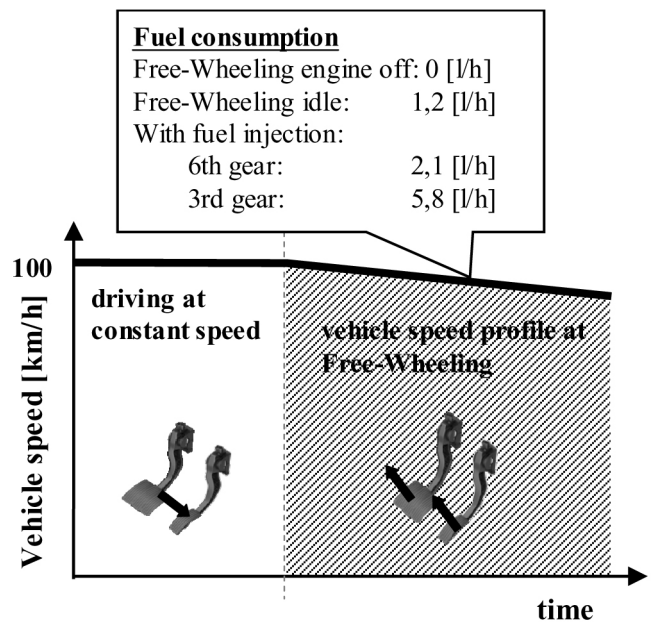


Figure 4. Fuel consumption comparison: a Free-Wheeling vehicle speed profile starting at 100km/h is tracked by a vehicle with gears engaged (6th and 3rd gear), i.e. with fuel injected (upper middle class vehicle, 1900kg, with 3,6L V6 NA Gasoline engine).

Notice that the fuel economy potential of Free-Wheeling depends strongly on the speed profile, i.e. driving cycle. For vehicle certification purpose, this speed profile is defined by legislation (like FTP75 or NEDC emission test cycles). Otherwise this speed profile is defined by the driver.

Significant fuel economy benefits can be obtained for the following driving conditions and speed profiles:

1. Economic drive style Free-Wheeling can provide a fuel economy benefit basically as soon as the driver releases the gas pedal and wishes to coast. In such conditions, the driver gets rewarded by a significantly increased rolling distance. However, a very sportive, dynamic or aggressive driver, who either accelerates or brakes, will hardly experience Free-Wheeling situations.

2. Flexibility in speed profile The speed profile during Free-Wheeling depends on the vehicle inertia, i.e. vehicle speed and weight, and on resistances from wind and wheels as well as road slope. Since these conditions vary, any pre-defined and rigid speed profile without speed tolerance represents a constraint that inherently chokes off most of the Free-Wheeling benefit. This fact will be discussed in more detail in section “CO₂ Potential”.

For the sake of simplicity, “Free-Wheeling” refers to “Free-Wheeling Engine-Off” in the following. Free-Wheeling Idling will be stated explicitly.

HISTORY

Free-Wheeling techniques have quite a long history. In 1958, the Trabant 500, “the car of East Germany”, was equipped with a mechanical free-wheeling function. Initially in all gears, this free-wheeling mechanism was implemented into the 4th gear only for later models.

In order to address the second oil crisis, Volkswagen developed the so called “Schwungnutzautomatik” (SNA) in the late 1970s. Based on a manual transmission, SNA combined an automated clutch with an engine Start/Stop system. This allowed to automatically decouple the engine and transmission during coasting conditions, to stop the combustion engine, and to restart it as soon as the accelerator pedal was depressed. Different techniques were considered: starting the combustion engine via starter motor (SNA-1) and also using a flywheel to restart the engine (SNA-2). This flywheel was positioned between the transmission clutch and a second clutch separating it from the engine. For this second technique, the starter motor was only needed for the initial start and for restarts after long stop-phases. In 1980 Volkswagen planned to implement the SNA-1 concept into the Golf I for the American market. However, the end of the oil crisis stopped this project due to a lack of demand.

In 1994 Volkswagen adopted the SNA-1 idea for the Golf III *Ecomatic*. This 1.9L SDI diesel car was equipped with an electro-pneumatically actuated automatic gearbox. There was a manual gearshift lever, but no clutch pedal, which made the handling of the car rather unique. As a result this vehicle was never really accepted by the market. To meet the increased technical requirements, an improved brake vacuum

monitoring system was implemented, including a larger vacuum storage with a mechanically operated vacuum pump. To avoid voltage drops induced by the starter motor, a larger battery and alternator as well as an additional small backup-battery for lights were added. Free-Wheeling could be turned off by an extra switch in the dashboard.

The next step was made in 1999 with the VW Lupo 3L TDI. An automated manual transmission was used, with hydraulically actuated clutch and gear selector. During Free-Wheeling conditions, the clutch would open and the engine would be operated at idle speed.

With the introduction of parallel Hybrid vehicles that use an additional clutch between the combustion engine and the drivetrain, Free-Wheeling Engine-Off has lately made its way into various series applications like the Porsche Cayenne Hybrid introduced in 2010. Non-hybrid vehicles like the 2010 VW Passat 1.4L TSI Bluemotion also apply this fuel-saving technique. For non-hybrid vehicles, the first development step of Free-Wheeling technology is with the combustion engine operated at idle speed in order to drive accessories that are nowadays still coupled to the engine. With more and more accessories being driven electrically, the next development step will be towards turning off the combustion engine during Free-Wheeling.

HMI INTERFACE

In the framework of this study, Free-Wheeling has been implemented into both vehicles with a manual transmission and a dual-clutch transmission (DCT). In the following section, possible operating concepts are discussed. This is apart from the fact that Free-Wheeling Engine-Off especially requires changes to the vehicle system and components.

Free-Wheeling Idling can already be activated by a driver today. For a vehicle with manual transmission, the driver could simply depress the clutch pedal, or shift into neutral gear. Shifting from “D” to “N” would do the same task in vehicle with automatic transmission.

Free-Wheeling Engine-Off could be implemented and operated in a similar manner like a Start/Stop function of a manual transmission vehicle. This means the engine would be stopped as soon as the driver shifts into neutral gear and releases the clutch pedal, regardless of vehicle speed. The engine would be started again as soon as the clutch pedal is depressed. This approach would be relatively simple to implement; however, it would be a considerable change of the operation concept in order to activate Free-Wheeling and the intelligence, when to activate Free-Wheeling, would be up to the driver.

Figure 5 explains, how the driver could be supported with the decision to activate Free-Wheeling. It has become quite



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common for manual transmission vehicles to indicate the optimal gear to the driver via a cockpit display. However, even when driving economically in the highest possible gear as indicated by the cockpit display, for small acceleration pedal angles, Free-Wheeling would be more economical. This is due to the fact that below an acceleration pedal angle of α_0 , the injected fuel does not produce any positive torque M_{CS} at the engine crank shaft and therefore does not contribute to any vehicle propulsion. It only compensates the engine drag torque M_{drag} . Free-Wheeling inherently would avoid any negative torque from the engine. In situations when the driver coasts at small acceleration pedal angles ($<\alpha_0$), a cockpit display could advise to shift into neutral gear instead. The same cockpit display could be used to indicate which gear to select when the driver wishes to accelerate after a Free-Wheeling phase.

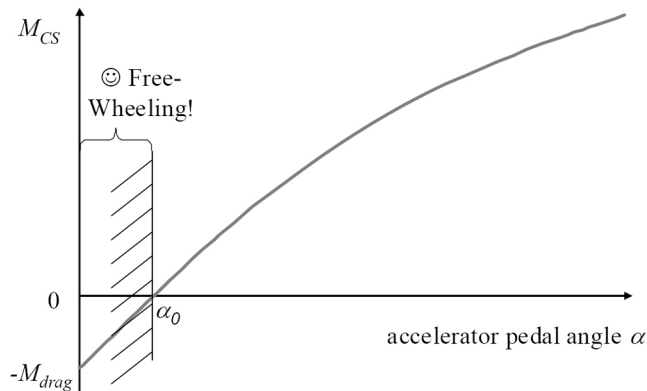


Figure 5. Engine torque at the crank shaft M_{CS} as a function of accelerator pedal angle α . For angles smaller than α_0 , the injected fuel only reduces engine drag torque M_{drag} , which means that Free-Wheeling would be more economical.

Even though the aforementioned operating concept would be relatively simple to implement into a manual transmission vehicle, this would be a new way of vehicle operation, requiring a significant change of driver behavior and possibly also some practical training. The introduction of a clutch-by-wire system could be a potential solution for manual transmission vehicles, avoiding any changes of vehicle operation: the clutch pedal would be used for driver initiated gear shifts, whereas a parallel clutch actuation could be initiated by a Free-Wheeling coordination function. With two instances actuating the clutch, a parallel hydraulic actuation principle could be used, or a clutch-by-wire system, coupling clutch and clutch pedal electronically.

Even though it is possible to implement Free-Wheeling Engine-Off into manual transmission vehicles, this functionality is more likely to be implemented into automated transmissions. In this case, the vehicle electronics control the

opening and closing of the clutch or drivetrain, as well as engine stop and restart.

Figure 6 shows a possible way how vehicle electronics could control Free-Wheeling mode in an automatic transmission vehicle. As soon as the driver releases the gas pedal, the clutch would open, entering Free-Wheeling. Recuperation technology is becoming state-of-the-art, which would be initiated as soon as the driver requests any deceleration, pressing the brake pedal. With belt driven alternators as they are currently being used, this would mean that the engine has to be coupled again to the drivetrain.

Below a certain vehicle speed (e.g. 10km/h) the vehicle would enter into Start/Stop operation, i.e. the combustion engine would be stopped with the drivetrain being open. This vehicle speed threshold could potentially be variable, e.g. as a function of road slope, brake pressure, battery condition or driver behavior.

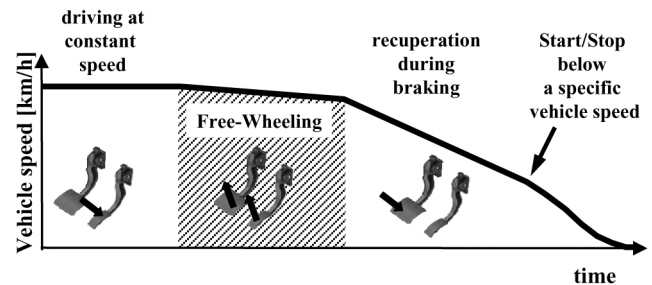


Figure 6. Free-Wheeling mode as transition between driving at constant speed and braking/recuperation. With current belt driven alternators, this recuperation would be done with the combustion engine motored.

CO₂ POTENTIAL

Theoretically, Free-Wheeling could be adopted even if the driver wishes to travel at constant vehicle speed: A cruise control function could toggle around a desired vehicle speed of e.g. 80km/h by switching between acceleration and Free-Wheeling. It is questionable, however, if such a function is realistic and if a driver may tolerate the changes of vehicle speed.

Nevertheless, such a function, creating a “saw tooth”-type vehicle speed profile, can give the impression of a theoretically achievable fuel economy benefit. Based on the simulation described in the following subsection “Pre-defined Test Cycles”, Table 1 compares the fuel consumption, driving at a constant speed of 80km/h and toggling between Free-Wheeling and acceleration at different acceleration rates.

Table 1. Theoretically achievable fuel economy benefit of Free-Wheeling at 80km/h, when toggling in a “saw tooth manner” between acceleration and Free-Wheeling (vehicle #1, see table 3, in 5th gear)

Speed profile	Acceleration [km/(h·s)]	Fuel consumption [L/100km]/fuel economy benefit of FW-EO [%]
80km/h constant	0	7.2 L/100km
80±10 km/h “saw tooth”, toggling between acceleration and FW-EO	1	- 47.4 %

Through light acceleration and a subsequent Free-Wheeling phase, the fuel consumption can be reduced by almost 50%. With a higher acceleration rate, the combustion engine is operated at a more efficient load point and also for a shorter period of time, which amplifies the benefit of Free-Wheeling even more.

The fuel economy benefit does not only depend on acceleration rates, but also on the selected transmission gear, i.e. engine speed. [Table 2](#) compares the fuel consumption at a vehicle speed of 70km/h and 60km/h, both in fourth gear.

Table 2. Theoretically achievable fuel economy benefit of Free-Wheeling at 70km/h and at 60km/h, when toggling in a “saw tooth manner” between acceleration and Free-Wheeling (vehicle #1, see table 3, in 4th gear)

Speed profile	Acceleration [km/(h·s)]	Fuel consumption [L/100km]/fuel economy benefit of FW-EO [%]
70km/h constant	0	8.4 L/100km
70±10 km/h “saw tooth”, toggling between acceleration and FW-EO	1	- 49.2 %
60km/h constant	0	8.1 L/100km
60±10 km/h “saw tooth”, toggling between acceleration and FW-EO	1	- 57.8 %

The shown fuel economy potential is a result of both a shift of the engine load point to a more efficient one, and the increased vehicle rolling distance at zero fuel consumption during Free-Wheeling. It will not be discussed here in which way this theoretical fuel economy potential might be at least partially achievable by a smart cruise control functionality, if the speed variance could be made small enough so that the driver can hardly feel it, or if such a speed variance could be imbedded and covered by altitude changes and inherent

changes of vehicle speed or engine load. Still, such a vehicle speed profile can give the impression of a theoretically achievable fuel economy benefit.

Apart from this theoretical assessment, the CO₂ reduction potential of Free-Wheeling depends on driving behavior and the driving cycle. Since the vehicle speed profile during Free-Wheeling operation depends on many vehicle parameters, e.g. tires, aerodynamics of car body, vehicle mass and geographical factors like road slope, any predefined speed profile with a limited speed tolerance band inherently limits the benefit of Free-Wheeling. This explains why a major fuel economy benefit cannot be seen in current emission test cycles but rather in real world driving. The CO₂ reduction benefit of Free-Wheeling in current emission test cycles as well as in real world driving is explained and quantified in the following two sub-sections.

1. PRE-DEFINED TEST CYCLES

A feed-forward vehicle simulation model as shown in [Figure 7](#) has been developed in MATLAB/Simulink® in order to study the fuel economy benefit of different Start/Stop and Free-Wheeling strategies. As opposed to backward vehicle simulation approaches, where the required engine load is calculated backwards from the vehicle speed profile, feed-forward simulation models contain a driver model to control accelerator and brake pedals, as well as clutch pedal for a manual transmission vehicle, based on the desired speed profile and the current vehicle speed. The driver model also captures the cognition of a real driver, allowing him to release the gas pedal and start coasting when the situation allows and suggests this.

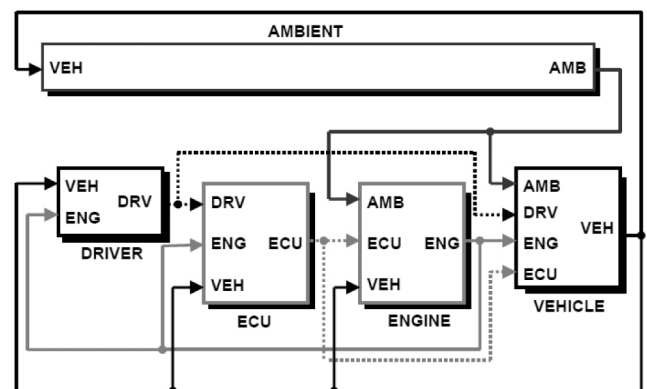


Figure 7. Feed-forward vehicle simulation in MATLAB/Simulink®

The simulation model was configured and validated with measurement data for three middle class vehicles. Some of their properties are shown in [Table 3](#) whereas the motoring torque of these engines was shown in [Figure 1](#).