

CO₂ Emissions Reduction via 48V Active Engine-Off Coasting

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ABSTRACT

Global CO₂ reduction by 2021, according to some projections, will be comprised of multiple vehicle technologies with 7% represented by hybrid and electric vehicles (2% in 2014) [1]. Other low cost hybrid methods are necessary in order to achieve widespread CO₂ reduction. One such method is engine-off coasting and regenerative braking (or recuperation) using a conventional internal combustion engine (ICE).

This paper will show that a 48V power system, compared to a 12V system with energy storage module for vehicle segments B, D and E during WLTP and NEDC, is much more efficient at reducing CO₂. Passive engine-off coasting using 12V energy storage shows a CO₂ benefit for practical real world driving, but, during NEDC, multiple sources of friction slow the vehicle down to the extent that the maximum benefit is not achieved. By adding active engine-off coasting at the 48V level the CO₂ emissions for NEDC are improved by decreasing the rate of deceleration with a 48V electric motor for propulsion. Also important, which will be explored in more detail, are the necessary power dimensions for the major components for different electrical load profiles.

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INTRODUCTION

Passive Engine-Off Coasting/Sailing

The term Passive Engine-Off Coasting (or Sailing) refers to an operating mode of a moving hybrid vehicle which is entered whenever power from the vehicle propulsion system is not needed and the driver is not depressing the brake pedal. Passive engine-off coasting goes one step further than the traditional "decel fuel-cutoff" method of coasting by placing the transmission into "neutral - disengaged mode" and ceasing fuel injection. This eliminates engine drag resulting in a lower rate of deceleration and saves fuel. It provides energy savings (CO₂ reduction) potential, for example during the WLTP (Worldwide Harmonized Light Vehicles Test Procedure); especially during real-world driving scenarios not captured by WLTP or NEDC. Passive engine-off coasting can be realized using 12V or 48V power system architectures [2][3]. Passive engine-off coasting, by its nature, requires an additional electrical energy storage system to provide backup power when the engine is stopped (electrical power generation ceased) during the disengagement phase.

During the time when the powertrain is disengaged and switched-off, the vehicle speed may slow down more than anticipated due to wind drag, rolling and mechanical frictions. The external forces on the vehicle thereby reduce the maximum potential for energy savings due to premature application of the propulsion system in order to maintain a constant vehicle speed (e.g. cruise control or driver command). Ideally, the vehicle would not slow down during the coasting phase. Furthermore, during the NEDC, the coasting function is not well utilized due to the requirement to drive the vehicle with near constant speeds and often requires hard decelerations which may engage the regenerative braking feature (if implemented). Thus, the opportunity to apply the passive engine-off coasting feature is very minimal during the NEDC.

Active Engine-Off Coasting at 48V Level

The peak power of a 12V electrical alternator is generally limited to 3kW due to the maximum current carrying capacity of the largest reasonable diameter vehicle wiring and the internal design of the alternator itself to handle such large currents. If the 12V electrical system is replaced by 48V / 12V architecture with BSG (Belt driven

Starter Generator) (Figure 1) with up to peak power of 15kW, depending on vehicle size and weight; the coasting feature can be enhanced by applying recuperated energy to the BSG in order to keep the vehicle speed constant over a longer period of time by compensating for the vehicle drag torque; benefiting the NEDC in a very positive way. This additional feature is termed (active engine-off coasting/sailing) and is used for velocities up to an average minimum of 60km/hr, found through simulation of maximum fuel savings for all vehicle segments. Generally, 15kW is the minimum peak power level required to achieve the active engine-off coasting function up to 60km/hr depending on vehicle size and class. Propulsion electrical power of 15kW at the 12V level would require very large diameter cabling, extra weight, and cost to the vehicle, not to mention the additional high current interconnects and fusing.

Active engine-off coasting does not come without complications; since the 48V electrical machine is driven by a belt, the ICE cannot be decoupled from the transmission as in the passive engine-off coasting mode. This forces the BSG to use additional electrical energy to overcome the additional driveline torque (I.e. ICE drag torque, transmission losses, axle losses) associated with transferring the mechanical power of the BSG to the road. Because of this, the benefit provided with active engine-off coasting must be evaluated for each specific application in order to determine if the additional weight and cost of the BSG system is worth the effort. The 60km/hr speed limit, mentioned earlier, is based on the maximum power capability of the 15kW motor where it is no longer able to maintain the vehicle speed on a flat road. The specific value depends on mechanical implementation of the 48V starter/generator (integrated or belt driven) and the vehicle roll and air drag (vehicle mass, cw value, etc.). Another implementation of the 48V hybrid would be to integrate the 48V electrical machine into the transmission, known as an ISG (Integrated Starter Generator), thereby reducing or eliminating the engine drag torque during active engine-off coasting/sailing; however, this was not simulated in this paper and remains for another study.

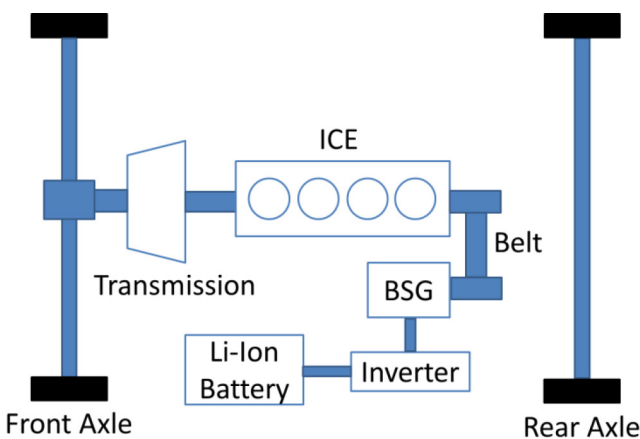


Figure 1. BSG (Belt Starter Alternator) hybrid powertrain

The 48V propulsion system capability is directly influenced by the quantity of electrical energy harvested during regenerative braking (recuperation). This varies widely depending on the driving cycle and

habits of the driver. If no energy is harvested then the positive features mentioned earlier cannot be obtained. This follows from the criteria to only use harvested energy (free energy that would have been lost) as opposed to indirectly using gasoline or diesel to produce electrical power for propulsion. The harvested energy can be applied to the BSG in order to help (boost) acceleration thereby reducing the fuel required to propel the vehicle; more closely mimicking a full hybrid. Also, efficiency improvements of the ICE (I.e. BSFC optimization and transmission schedule) should be evaluated side-by-side with the BSG active engine-off application before deciding to implement the 48V architecture. Figure 2 contrasts the difference in vehicle velocity between passive and active engine-off coasting for a simple set of maneuvers (e.g. acceleration → engine-off coasting → light braking (recuperation) → constant vehicle speed).

In summary:

- **Passive engine-off coasting:** During coasting/sailing, engine is turned off, transmission is placed into neutral and the 12V / 48V electrical system provides power to run the vehicle electrical system using stored energy in the 48V Li-Ion battery and/or the 12V battery.
- **Active engine-off coasting:** During coasting the BSG is powered by the 48V electrical system to provide torque to spin the engine with the transmission engaged in drive, providing up to 15kW of electrical propulsion power to maintain a constant vehicle velocity up to an average of 60km/hr depending on vehicle size and weight.
- **Driver feel and torque pleability:** The torque based driver comfort was not measured, benchmarked or taken into consideration during the design of the control algorithm used to engage the passive and active engine-off coasting features.

An additional feature of the 48V BSG is the ability to creep in stop-and-go traffic without restarting the ICE; thus providing the driver with more comfort and reducing wear and tear on the engine starter battery and traditional 12V cranking actuator.

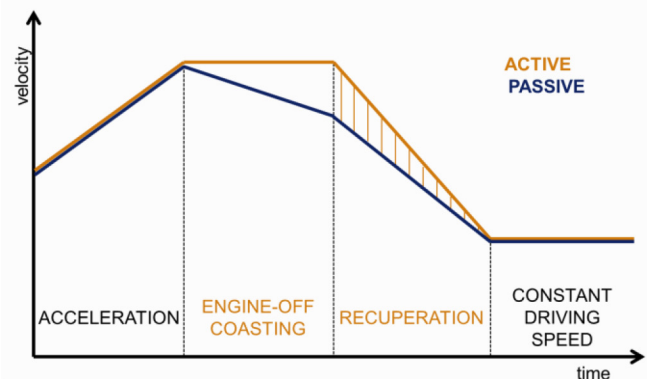


Figure 2. Passive vs. active engine-off coasting velocity example

SIMULATION

Hybrid Electrical Subsystem Topology

3 different vehicles representing segments B, D and E (see Appendix A for examples), were used in a simulation for the evaluation of different hybrid operating modes and their effect on CO₂ reduction. The simulation electrical topology (Figure 3) included:

- 48V (8kW to 15kW) BSG (Belt driven Start Generator)
- 48V lithium ion battery (5Ah to 20Ah)
- 48V/12V bidirectional DCDC (up to 3kW)
- 12V AGM lead acid battery with IBS sensor
- 48V / 12V loads (300W to 2500W) depending on environmental conditions

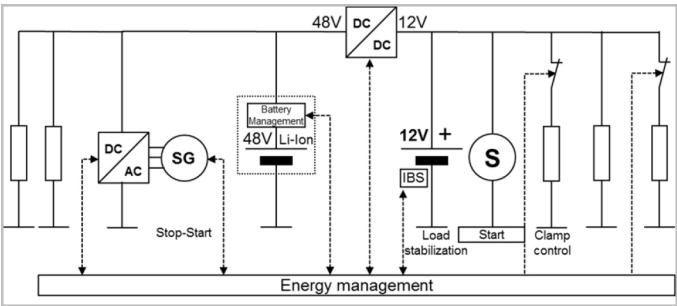


Figure 3. 48V / 12V Hybrid electrical subsystem topology

Energy management architectures and functions combined with their associated functions for all relevant vehicle classes and electrical subsystem topology layouts results in many possible powernet configurations [4]. This leads to new components such as DCDC-Converters, additional energy storage, power distribution centers with both mechanical and solid-state switches. A possible application of 48V architecture shown in Figure 4 is an example of a complete packaging of all the necessary components of a 48V hybrid vehicle. A key aspect is the dimensioning of the components in order to leverage the maximum fuel savings. The key safety components such as EPS (Electric Power Steering), ABS (Anti-lock Brakes) and (Brake Booster) must be powered by electricity from the 12V / 48V electrical system instead of mechanical power. This is because during passive engine-off coasting, the engine does not spin and thus it does not produce the required mechanical power to run those systems.

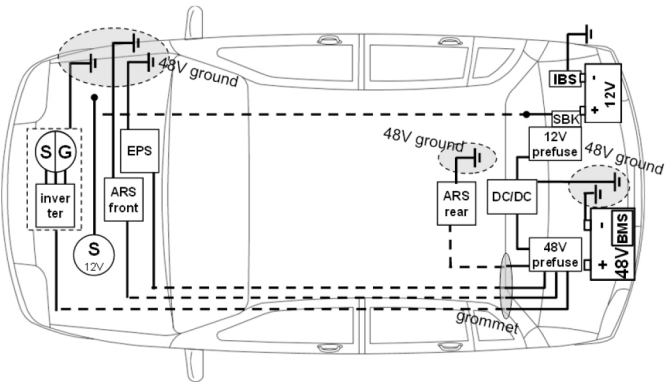


Figure 4. Possible 48V vehicle architecture for active and passive engine-off coasting + recuperation + boosting: source: [4]

Electrical Model

A model (Figure 5) was developed from the electrical system architecture to closely estimate the steady-state and transient behavior of the electrical subsystem to a high degree. Simulation models of each subsystem component were carefully constructed using physical and statistical time varying methodologies merited by a robust understanding of the important mechatronic principles governed by the nature of the application. The reader is encouraged to investigate, in more detail, the vehicle powertrain and electrical subsystem model used to generate the results of this paper in [4].

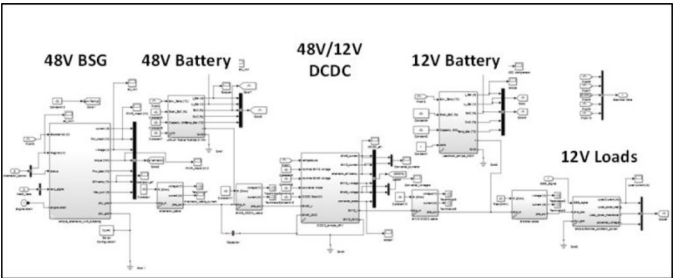


Figure 5. Top level electrical subsystem of vehicle simulation model for B, D and E class cars

Model Parameters

Table 1 summarizes the input parameters to the simulation model for the vehicle segment profiles.

Table 1. Car segment model parameters

Segment	Engine	Mass (Kg)	48V BSG (kW)	Vehicle Configuration	Base Electrical System Consumption (W)
B	1.2l gas	1200	8	5-speed transmission, 60Ah 12V AGM lead acid battery	300 to 750
D	1.7l gas / 2.0l diesel	1500	10	7-speed transmission, 60Ah 12V AGM lead acid battery	450 to 1125
E	2.0l gas / 2.2l diesel	1800	15	7-speed transmission, 60 Ah 12V AGM lead acid battery	1000 to 2500

For B segment, a generic 1200kg vehicle with 1.2l gasoline engine, 5-speed transmission, 8kW 48V BSG and 60Ah 12V lead acid battery was used.

The D segment model used a 1500kg vehicle, 1.7l gasoline or 2.0l diesel, 7-speed transmission, 10kW 48V BSG, and 60Ah 12V starter battery.

For E segment, an 1800kg vehicle with 2.0l gasoline or 2.2l diesel, 7-speed transmission, 15kW 48V BSG, and 60Ah 12V starter battery was used.

The impact of varying 48V Lithium ion battery capacities was simulated using capacities of 5Ah, 10Ah, 15Ah and 20Ah for all vehicle segments.

The normal environmental electrical consumption of the power systems was defined to be 300W for B segment, 450W for D segment and 1000W for E segment. The base electrical power consumption was increased by 2.5 times for winter or cold driving environments.

Hybrid Operating Modes

The following (see Table 2) operational modes were simulated and evaluated for their CO₂ saving potential with 48V recuperation active in all modes:

Table 2. Hybrid operating modes (1-7)

Mode	Coasting		Boosting	48V Recuperation
	Active	Passive		
Mode 1				X
Mode 2	X			X
Mode 3	X		X	X
Mode 4			X	X
Mode 5		X		X
Mode 6		X	X	X
Mode 7	X	X		X

**All modes above were compared against a stop/start micro-hybrid outfitted with only standard 12V AGM lead acid starter battery.*

Passive engine-off coasting, active engine-off coasting and boosting rely on a sufficient amount of harvested electrical energy during braking. For all experiments, the capacity of recuperation was determined for 48V systems in [2].

Mode 2

Active Engine-Off Coasting

Figure 6 shows the calculated recuperation energy from simulation for all operating modes while driving the NEDC and WLTP for a D-segment 2.0l diesel with medium level base electrical loads.

NOTE: Because passive engine-off coasting phases are not possible within NEDC, the operational Modes 5 through 7 were not assessed for the NEDC.

Looking closely at Figure 6, for the 48V lithium ion energy storage sizes of 5Ah, 10Ah, 15Ah and 20Ah; the 5Ah lithium Ion battery was too small to achieve the full recuperation potential. A capacity of 10Ah offered the best compromise while the 15Ah and 20Ah capacities only showed slight or minimal improvement beyond the 10Ah capacity.

Looking again at Figure 6 during WLTP, Mode 2 (active coasting + recuperation) recuperated more energy as compared to Mode 1 (recuperation). This is because active engine-off coasting uses electrical energy to maintain vehicle speed thus discharging the 48V battery to a lower SOC; allowing more recuperation later on in the WLTP.

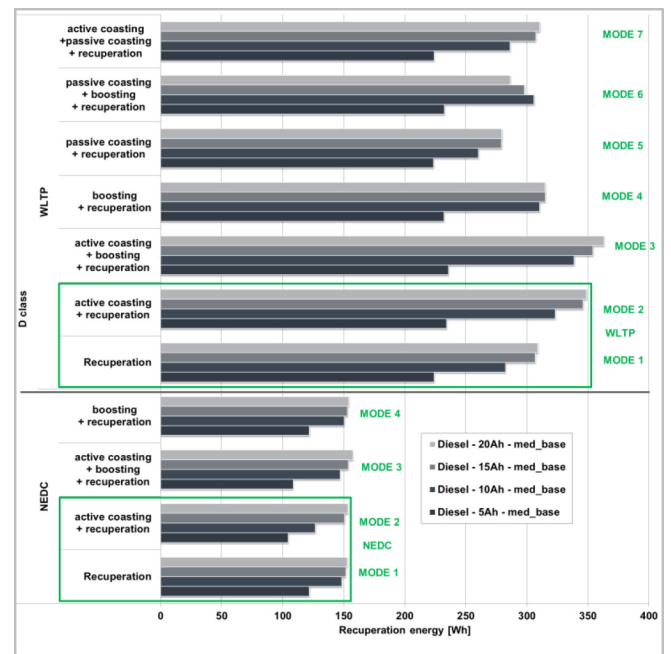


Figure 6. Energy recuperated during NEDC and WLTP using hybrid operating modes (1-7) for a standard D-segment diesel car with 48V battery capacities of: 5Ah, 10Ah, 15Ah and 20Ah

Applying Mode 2 during NEDC does not increase the amount of recuperated energy compared to Mode 1 due to a lack of coasting opportunities. NEDC has less dynamics with shorter durations as compared to WLTP.

By contrast, the average recuperated energy per km for NEDC and WLTP is nearly the same (see Figure 7); because the duration of NEDC is 1800sec as compared to 1200sec for WLTP. The NEDC also yields a higher average speed of 46km/h versus 34km/h for WLTP; which leads to the vehicle travelling farther (23km vs. 11km) so that the integral of available recuperation power (energy) ends up being nearly the same for both driving cycles.

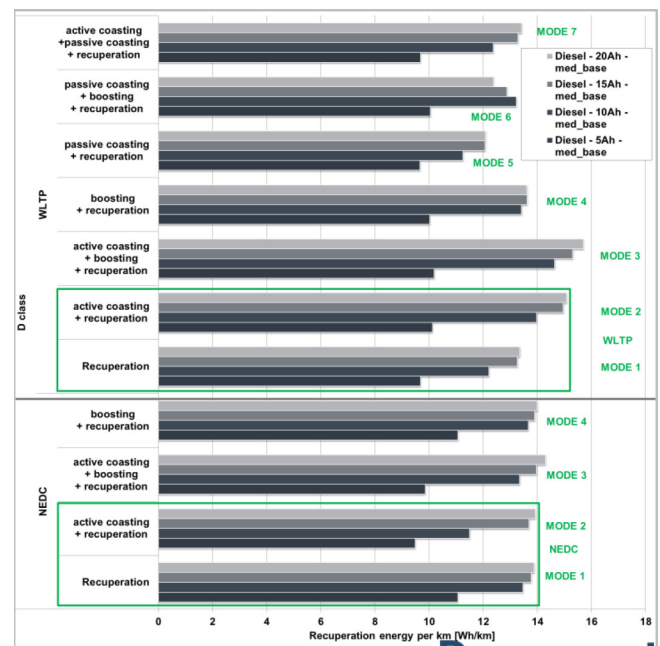


Figure 7. Average energy recuperated per kilometer during NEDC and WLTP using hybrid operating modes (1-7) for a standard D-segment diesel car with 48V battery capacities of: 5Ah, 10Ah, 15Ah and 20Ah