

Feasibility Study of a Heavy-duty Tractor - Motorized Semi-trailer Hybrid Electric Combination

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ABSTRACT

The objective of this study was to evaluate the concept of a heavy-duty tractor - motorized semi-trailer hybrid electric combination, which would have electric drive axles on the semi-trailer.

The scope of the project included an analysis of the general concept of a power-driven semi-trailer, the positioning of the concept of the heavy-duty tractor - motorized semi-trailer hybrid electric combination in the general context of the technology, and the evaluation of the applicability of the concept for different duty cycles.

Several transport activities were analyzed to determine specific duty cycles for heavy-duty vehicles: highway line haul and regional haul, construction haul, and off-highway hauling of raw materials, such as forestry transport with Class 8 and off-highway tractor-trailer combinations.

The concept of a heavy-duty tractor - motorized semi-trailer hybrid electric combination was compared with a corresponding conventional combination (conventional tractor and semi-trailer), and with a combination of a parallel hybrid electric tractor with a conventional semi-trailer. PSAT simulations were conducted to evaluate the fuel efficiency and the influence on traction and stability was evaluated for each representative duty-cycle.

The simulation results generally predict comparable fuel efficiencies for the heavy-duty tractor - motorized semi-trailer hybrid electric combination, and the correspondent parallel hybrid electric tractor with conventional semi-trailer combination. Depending on the duty-cycle, both hybrid versions would offer substantial fuel savings when compared to the conventional tractor-semi-trailer combination, such as up to 30% for off-highway hauling of raw materials.

The analysis of traction performances showed evident gains both in tractive force and gradeability for the motorized semi-trailer. Moreover, the use of motorized axles on the semi-trailer would improve the longitudinal stability of the vehicle combination by decreasing the potential for sliding, especially in off-highway conditions.

The evaluation of the impact on greenhouse gas emissions shows that the electric motorized semi-trailer concept would offer important annual reductions for all the analyzed transport activities, with generally attractive payback periods. Exemplifying for the off-highway hauling of raw materials using off-highway vehicles, GHG emissions reduction would be up to 108 tons/year per vehicle combination, with a payback period as low as 18 months, which is explained by very important quantitative fuel savings coupled with a relatively moderate increase in vehicle purchase costs. However, for highway and regional haul, the relative increase of the semi-trailer cost by a factor of three would make the concept unattractive.

The concept of a heavy-duty tractor - motorized semi-trailer hybrid electric combination would offer the best dynamic, environmental, and economical advantages when implemented for off-highway transport of raw materials, such as forestry or mining transport, for which the relative cost increases are acceptable and payback periods are relatively short.

INTRODUCTION

Hybrid vehicle technology is already a reality for urban applications where stop-and-go driving cycles offer many opportunities to recover and recycle braking energy, such as delivery, waste management and public transportation, for which minimum fuel savings of 15% have been proven. Hybrid vehicle technology is gradually finding specific applications in

the heavy-duty vehicle market, with several manufacturer already offering Class 8 hybrid vehicles.

Regenerative braking and hybrid technology could be interesting for forestry and mining applications, which are characterized by difficult terrain and climatic conditions. Operating a hybrid forestry truck would make it possible to recover braking energy when the vehicle travels on forest roads. The vehicle would use this energy during non-working time (for powering the loader, when waiting, for other idling, or for powering other auxiliary systems and devices), and during times when power needs are higher, by assisting the engine. The forestry truck can be equipped with a smaller, more economical engine and will use significantly less fuel.

Power-driven trailers have been tested and used in the last one hundred years for surmounting traction issues in low adherence conditions, such as those encountered in mining, forestry, agriculture or military applications. These power-driven trailers used or are using mechanical, hydraulic or electrical traction systems.

The concept of a heavy-duty tractor - motorized semi-trailer hybrid electric combination would have electric drive axles on the semi-trailer [1]. The scope of this project was to analyze the concept of a power-driven semitrailer and to evaluate the applicability of the concept for different transport sectors.

A literature research was conducted to analyse the history of the technology, the technical solutions and present applications, the advantages and disadvantages of the system, as well as the foreseen evolution. Despite the extensive research, not many actual application of the power-driven trailer concept were found. The mechanical traction systems, consisting of a combustion engine and a transmission installed on the trailer or on the dolly, are the most common, this technology being well developed and known within the mining industry, particularly in Australia. The hydrostatic systems are mainly used for military and forestry applications, designed for difficult terrain conditions but with limited loading capacity. Their main disadvantage is the low travel speed range, limiting their usefulness to applications that do not required high velocity, such as off-road forestry or agricultural machineries. The hydrostatic-mechanical systems, which use a combustion engine and a hydraulic motor, suffer from energy losses in both hydraulic and mechanical systems. The electric traction systems presents infinitely variable transmissions, high reliability and very effective braking capabilities. The disadvantages are related to the larger space and tare weight requirements, and to the accessibility to the electric energy (such as the limited autonomy of battery systems). There are several examples of electric traction systems for trailers and semi-trailers but, as far as we know, they have not gotten past the patent or prototype phases.

The project included the following stages: determining specific duty cycles for different types of heavy-duty hauling, evaluation of dynamic demands for each cycle, analyzing the concept of a heavy-duty tractor - motorized semi-trailer hybrid electric combination, assessing the fuel efficiency and dynamic performances of the concept, and evaluating the commercial potential of the concept.

SPECIFIC DUTY CYCLES FOR HEAVY-DUTY VEHICLES

Several transport activities were analyzed to determine specific duty cycles for heavy-duty vehicles: highway line haul and regional haul, construction haul, and off-highway hauling of raw materials, such as forestry transport with Class 8 and off-highway tractor-trailer combinations.

ON-HIGHWAY HAULING

Two types of operations were considered: highway line haul and regional haul.

Highway line haul operations are characterized by high average speeds, long trips, more constant engine operation, and overnight rest stops, which sometimes involve long idling. The typical combination is a Class 8 three-axle tractor with a two-axle semi-trailer, with a tare weight of 15,000 kg or more. The semi-trailer could be a dry van-box, a reefer-van, a tanker, a flat bed, a curtain trailer, a trans-container, or other [2]. Several vehicles have been monitored and a representative trip was chosen. The corresponding duty cycle was determined by simulation, using Otto 2000 software, which simulates the performance of haul vehicles and estimates fuel consumption, average travel speeds and trip times. Performance modeling for haul operations is based on mathematical models and the development of equations for the three factors that control performance: the vehicle, the driving technique and the road [3]. The duty cycle is shown in Figure 1. The vehicles models correspond to the tractor and two-axle or four-axle semi-trailers presented in Table 1.

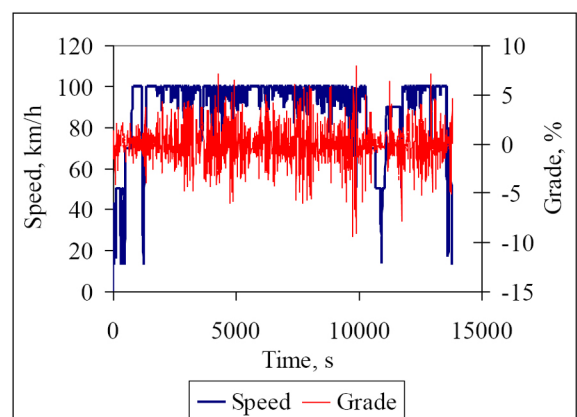


Figure 1. Duty cycle for highway line haul.

The regional haul is similar to highway line haul, but the trip lengths are shorter, the haul includes some suburban-type operation, and has none, or fewer, overnight stays. The average speeds are lower, and they are relatively more frequent traffic congestion situations. Two representative vehicles were followed in operation for three months. The vehicles were equipped with onboard computers and GPS systems. Based on the analysis of these trips, a representative route was built using the GPS profiles. The corresponding duty cycle was determined by simulation, using the Otto 2000 software (Figure 2), and the vehicles models also correspond to the tractor and two-axle or four-axle semi-trailers presented in Table 1.

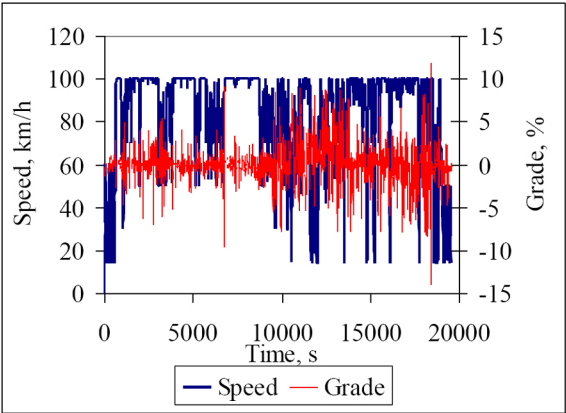


Figure 2. Duty cycle for regional haul.

Table 1. Vehicles type specifications for highway line haul and regional haul

Road type		Asphalt	
Tractor			
	Number of axles	3	
	Rated power, kW (HP)/rpm	324 (435) / 2100	
	Peak torque Nm (lb-ft)	2101 (1550)	
	Transmission	Manual 13 speeds	
	Differential ratio	3.7	
	Tires	275/80R22.5	
	Tare Weight (kg)	8 500	
Semi-trailers			
	Type	Closed van	
	Number of axles	2	4
	Tires	275/80R22.5	
	Tare weight (kg)	6500	10000
	Payload (kg)	18500	29000
	GVW (kg)	33500	47500
	GVW limit (kg)	41500	57500

CONSTRUCTION HAULING

A study conducted with four categories of dump trucks is presented in [4]. Twelve different vehicles had been instrumented and monitored during work shifts composed by 4 to 5 duty cycles each. A representative duty cycle, with duration of 1.2 hours, is composed of loading at the charging point, delivering the load to destination, dumping, and returning to the charging point. The duty cycle is a combination of nine operation modes defined by a function dependent on travel speed (V , km/h), acceleration (a , m/s²) and engine power demand (D_p , kW/kg). Engine power demand is given by the equation:

$$D_p = V \times a \quad (1)$$

Figure 3 shows the structure of a representative cycle and Table 2 presents the definitions of operation modes. It can be observed that idling is a significant part of the cycle, more than half of the distance was covered in cruise mode, and deceleration mode represents almost 15% of the total distance. The duration of the round trip cycle is approximately 28 min. Vehicle specification is presented in Table 3.

The analysis of the database allowed us to choose a route on which the representative vehicle model could perform a duty cycle with a structure similar to those presented in Figure 3. The duty cycle, obtained by simulation, is shown in Figure 4. The cycle corresponds to a round trip (going loaded and back empty) on an 11 km length route, with total duration of 29 min.

OFF-HIGHWAY HAULING OF RAW MATERIALS

The off-highway hauling of raw materials, such as forestry transport, includes transport with Class 8 tractor -trailers as well as with off-highway tractor-trailer combinations. A large amount of operational data for logging transport was analyzed to determine representative trips and routes.

An example of a representative logging operation with Class 8 vehicles is a trip with a length of 158 km, from which 115 km is on gravel forestry roads, and a total duration of 2 h 25 min. The corresponding duty cycles is presented in Figure 5, obtained through simulation using a vehicle model as detailed in Table 4.

An example of a representative logging operation with off-highway tractor-trailer combinations is a trip with length of 110 km on gravel forestry roads, and a total duration of 2 h 18 min. The corresponding duty cycle is presented in Figure 6, obtained through simulation using the vehicle model detailed in Table 4.

DYNAMIC DEMANDS

Kinetic energy variation (ΔE_c , in kW) between two moments (t_0 and t_f) can be calculated as a function of speed (V_0 and V_f) and of vehicle mass (M_v), with the following equation (adapted from [5]):

$$\Delta E_c = \frac{M_v \times (V_f^2 - V_0^2)}{2} \quad (2)$$

Table 2. Operation modes for dump duty cycle (adapted from [4])

Mode	Definition
Idle	$V = 0 \text{ km/h}$, $a = 0 \text{ m/s}^2$
Acceleration	
Low	$a \geq 0.45 \text{ m/s}^2$ and $D_p \leq 0.004 \text{ kW/kg}$
Medium	$a \geq 0.45 \text{ m/s}^2$ and $0.004 \leq D_p \leq 0.004 \text{ kW/kg}$
High	$a \geq 0.45 \text{ m/s}^2$ and $D_p \geq 0.004 \text{ kW/kg}$
Cruise	
Low	$0 \text{ km/h} \leq V \leq 50 \text{ km/h}$
Medium	$50 \text{ km/h} \leq V \leq 70 \text{ km/h}$
High	$V \geq 70 \text{ km/h}$
Deceleration	$a \leq -0.44 \text{ m/s}^2$
Dumping	-



Table 3. Vehicle type specification for construction haul

Road type	Asphalt and gravel
Tractor	
Number of axles	3
Rated power, kW (HP)/rpm	339 (454) / 2100
Peak torque Nm (lb-ft)	2115 (1560)
Transmission	Manual 13 speeds
Differential ratio	5.13
Tires	11R24.5
Weight (kg)	8300
Semi-trailers	
Type	Open box
Number of axles	2
Tires	11R24.5
Tare weight (kg)	6500
Payload (kg)	18200
GVW (kg)	33000
GVW limit (kg)	41500

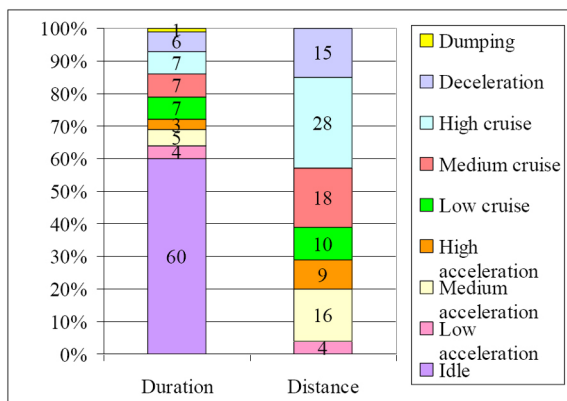


Figure 3. Construction haul duty cycle structure (adapted from [4]).

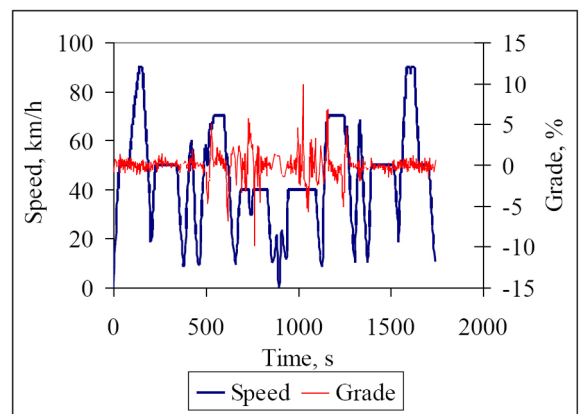


Figure 4. Duty cycle for construction haul.

Equation (3) gives the power dissipated by this variation:

$$P_c = \frac{\Delta E_c}{t_f - t_0} \quad (3)$$

The operation modes can be defined based on kinetic energy variation and fuel consumption (C_c), as shown in Table 5.

The structure of the analyzed duty cycles is presented in Figure 7. Kinetic energy variation and fuel consumption were calculated using dynamic simulation.

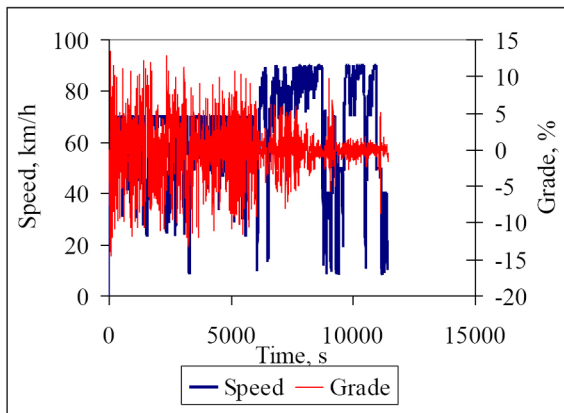


Figure 5. Duty cycle for off-highway hauling of raw materials with a class 8 tractor-trailer.

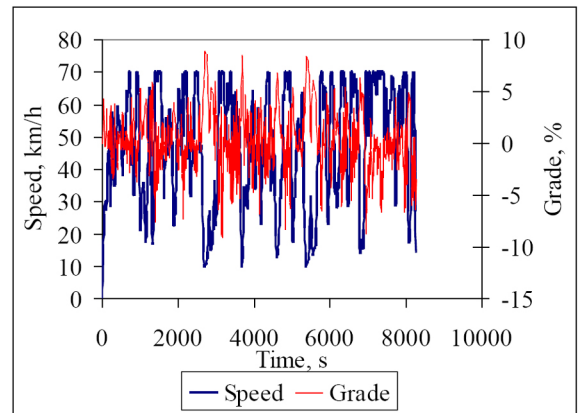


Figure 6. Duty cycle for off-highway hauling of raw materials with off-highway tractor-trailer.

Table 4. Vehicles type specifications for off-highway hauling of raw materials

Type of combination		Class 8	Off-highway
	Road type	Gravel and asphalt	Gravel
Tractor			
	Number of axles	3	
	Rated power, kW (HP)/rpm	373 (500) / 2100	447 (600) / 1800
	Peak torque Nm (lb-ft)	2 508 (1850)	2 779 (2050)
	Transmission	Manual 18 speeds	
	Differential ratio	4,3	9,52
	Tires	11R22.5	14.00R25
	Tare Weight (kg)	8 900	23 000
Semi-trailers			
	Type	Logging semi-trailer	
	Number of axles	4	
	Tires	11R22.5	14.00R25
	Tare weight (kg)	10000	25000
	Payload (kg)	36500	100000
	GVW (kg)	55400	148000
	GVW limit (kg)	57500	-

Table 5. Operation modes

Mode	Definition
Acceleration	$Cc \geq 0$ and $\Delta Ec \geq 0$
Cruise	$Cc \geq 0$ and $\Delta Ec = 0$
Deceleration	$Cc \geq 0$ and $\Delta Ec \leq 0$
Engine braking	$Cc = 0$ and $\Delta Ec \leq 0$

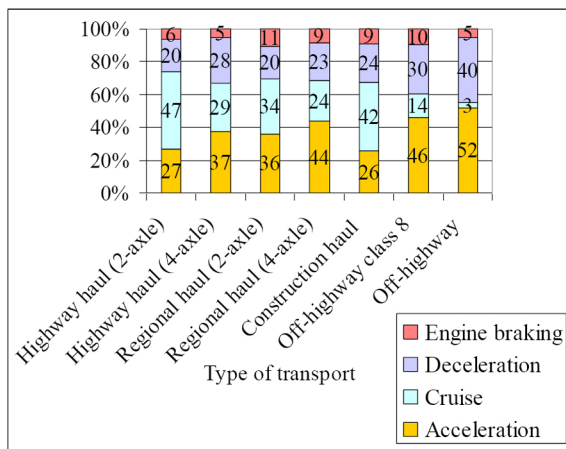


Figure 7. Duty cycles structure for the analyzed transport activities.

The cycles that would offer a more efficient usage of regenerative braking and hybrid system would be those with lesser cruise time and more engine braking and deceleration (Figure 7), as well as those showing more substantial kinetic energy losses and dissipated power (Table 6). Based on these criterions, it can be preliminarily concluded that most appropriate cycles would be those corresponding to the off-highway hauling of raw materials.

HYBRID ELECTRIC SEMI-TRAILER CONCEPT

The analysis of the concept considered the architecture of the system, the degree of hybridization, and the secondary source of energy.

SYSTEM ARCHITECTURE

In the heavy-duty tractor - motorized semi-trailer hybrid electric combination concept, besides the main power coming from the combustion engine, the wheels of one or more trailer axles are powered by electric motors [1].

The system would improve the braking performances of the vehicle combination and would increase the climbing ability. When needed, the electric powered axles of the trailer would assist the tractor's power train. The trailer would be equipped with means for controlling the power, speed and acceleration and grade sensors would be used for automatically activate the electric driven axles, either in acceleration or in deceleration modes. A manual control would also be provided. The batteries, installed on the trailer or on the tractor, would be recharged by using a regenerative braking system or other sources of energy, such as tractor's engine or a fuel cell.

Several configurations are possible. Figure 8 presents the version with the electric motor installed on the semitrailer's axle that it drives, whose motor is controlled by an electronic control module that communicates with the vehicle's electronic control module. In another variant, the electric motor is always installed on the semitrailer, but external to the axles: the axles are driven through a drive shaft and a differential. Another version uses wheel electric motors.

Two main architectures are possible for the hybrid electric systems: series and parallel. In the case of the series systems, the primary power source, which is a combustion engine, does not power the drive train directly; it propels the vehicle through the secondary power source, which is the electric motor. For the parallel hybrids, the engine or the electric motor can propel the vehicle independently, or in combination.

The heavy-duty tractor and motorized semi-trailer hybrid electric combination corresponds to the parallel-split architecture, in which the engine drives one or more axles (on the tractor), while the electric motor drives other axles (on the semi-trailer, in the case of this concept). Contrary to the classic parallel system, the parallel-split version does not require any integration with tractor's power train and allows the use of wheel motors. On the other hand, the control system would be more complicated, because it must assure the synergy between tractor's power train and semi-trailer's power train. The parallel-split architecture would offer the advantage of supplementary traction, but it would complicate the regenerative braking, the charging of the batteries, and the control of propelling and braking, because in some cases the semi-trailer axles could work in regenerative braking mode, while the tractor's drive axles could work in propelling mode [6].

DEGREE OF HYBRIDIZATION

Hybrid systems are also frequently classified as mild hybrids and full hybrids according to the degree of hybridization, based on the ratio between the energy supplied by the primary source (combustion engine) and the energy supplied by the secondary source (electric motor). The mild hybrids are not intended to operate in pure electric mode: the electric motor assists the engine for starting and launching the vehicle, or accelerating it, or for powering some auxiliary systems. In the case of full hybrids, additionally to the functionalities of mild