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A Hybrid ERS Cost Perspective

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Summary

Electric Road Systems technology has the potential to facilitate electric road transport at a lower cost than any other charging solution. However, with a modestly disseminated ERS system there is still a need for hybridized ERS vehicles, so called Slide In Hybrids. On any specific road with an ERS system it is interesting to quantify to what extent the ERS system, the on board battery and the combustion engine in hybrid mode should be utilized for minimum total operational cost. This paper address four different such scenarios. The conclusion is that hybrid mode should be avoided.

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1 Research Questions

Electric road systems (ERS) can be applied in several different ways, with different benefits in total cost for infrastructure, vehicles and the energy used. ERS technology can be used by different types of vehicles and, for a given type of vehicle, to a different extent. With an extensive dissemination of ERS technology it is expected that combustion engines will not be needed. In an initial stage, with limited dissemination of ERS technology, “slide in” hybrid vehicles will be needed and it is important to understand how the total cost of infrastructure + vehicles + energy depends on the extent of ERS dissemination, the size of vehicle batteries, the length of the travelled route and the traffic intensity. This paper is provides a perspective on how these costs aggregate.

This paper is an analysis of the total infrastructure, vehicle and energy cost related to using heavy duty trucks on a simplified road segment given four different philosophies on how to utilize the ERS.

1.1 The simplified road model

The road modelled is a link between two points (A_0 & B_0), where it is assumed that the vehicle in each end make a detour, as illustrated by Figure 1.1.

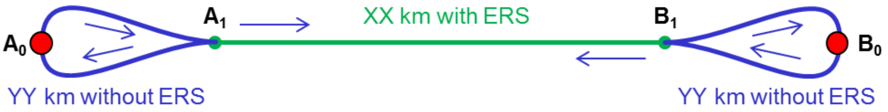

Figure 1.1 Simplified road model

The road between the points A_1 and B_1 is to some extent equipped with ERS technology. It is divided in a number of equally long sections d_{ers}, and each such section is covered with ERS tracks to a certain fraction k_{ers}. With e.g. $k_{ers} = 0.3$ and $d_{ers} = 5$ km, the road between A_1 and B_1 is divided in 5 km sections, each of which consist on 1.5 km ERS and 3.5 km non-ERS road.

The end route from A_1 to A_0 and back to A_1 has no ERS technology, but an opportunity to charge when standing still at A_0 where the vehicle is expected to stop for a certain time. This corresponds to a loading/unloading stop. The same applies to the *B*-end of the road model.

1.2 The vehicle charging strategy

This simplified road model can be used for studying the impact of variations of vehicle-, charging-, and ERS-parameters according to the following 4 scenarios.

S1 The vehicle is a hybrid vehicle that use the ERS tracks and the standstill charging in each end to charge the batteries as much as needed to drive in full electric mode. The vehicle is a hybrid and runs in hybrid mode if the EV range is insufficient.

S2 This is the same as scenario 1, except that static charging at the end stop is not allowed.

S3 This is the same as scenario 2, except that hybrid mode in enforced at all times in the end route.

S4 This is the same as scenario 3, except that hybrid mode is enforced at all times when nor at an ERS track.

These scenarios are illustrated as in Figure 1.2

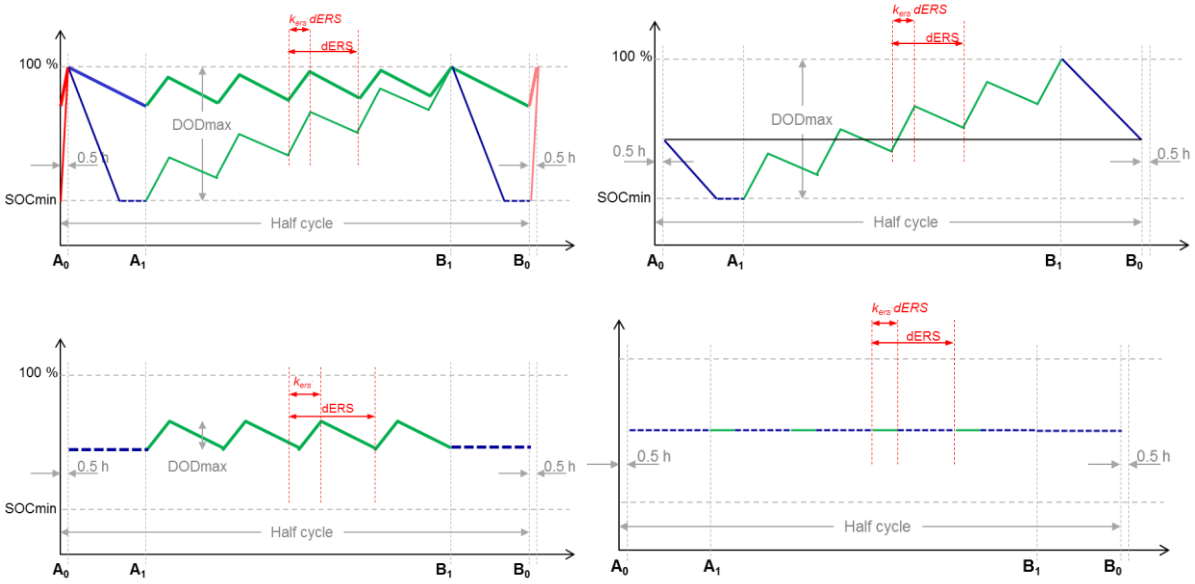

Figure 1.2 Four different charging scenarios: Top left: Scenario 1, Top right: Scenario 2, Bottom left: Scenario 3, Bottom right: Scenario4, Solid line is electric mode. Dashed line is hybrid mode.

1.3 Vehicle specifications

The vehicle studied is a heavy duty plug in hybrid truck. The capacity of the traction battery is a design parameter. The vehicle is assumed to use a galvanically isolated on board DC/DC converter to supply the charging power from the ERS tracks to the battery. The combustion engine is dimensioned to provide good driving performance even on an empty battery and it is the same in all four scenarios. The vehicle parameters used are listed in Table 1.

Table 1: Vehicle specifications

Parameter	**Value**	**Unit**	**Comment**
Vehicle weight	40 000	kg	
Battery size (W_{batt})	25 … 400	kWh	System level
Battery Cost	200	Euro/kWh	System level
Max C-rate	2		
Calendar lifetime	6	years	
Max DoD	70	%	
Fuel cons	0.24	liter/km	Hybrid mode
Cycle life	-	-	See Figure 1.3
Fuel cost	1.5	€/liter	
El energy cons	1	kWh/km	Electric mode
El energy cost	0.1	Euro/kWh	
Work hours	16	Hours/day	
DC/DC conv. cost	100	€/kw	
Work days	200	Days/year	
Speed	80	km/h	
AADT	100 … 2000	vehicles/day	Incl. both directions

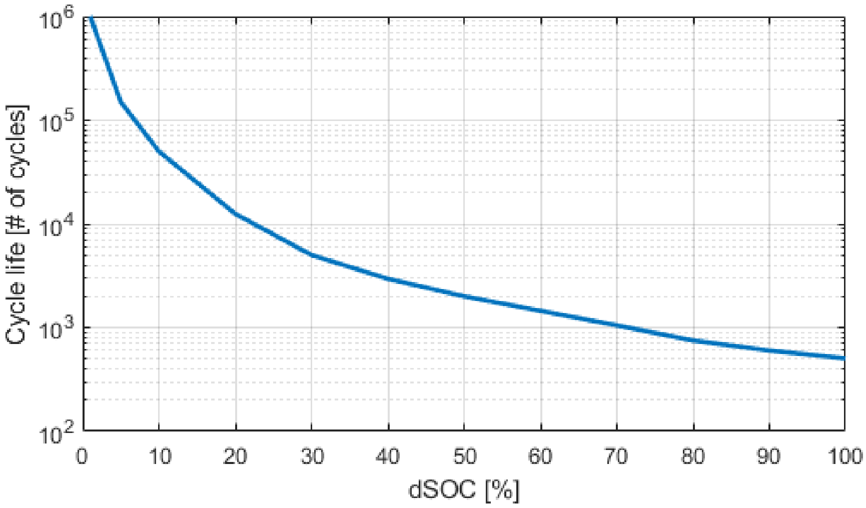

Figure 1.3 Assumed battery cycle life

1.4 Charging technology specifications

The ERS cost (C_{ers}) is based on a cost model developed in [1]:

$$C_{ers} = k_0 * P_{ers} + k_1 * L_{ers} + k_2 * k_{ers} * L_{ers} * N_{ers}$$

Where P_{ers} is the total power drawn from the ERS, L_{ers} is the total length of the ERS and N_{ers} is the number of powered lanes. The scaling factors as well as the isolated DC/DC and the static charger cost parameters are given in Table 2.

Table 2: Charging system cost parameters

Parameter	**Value**	**Unit**	**Comment**
k_0	300	k€/MW	
k_1	150	k€/km	
k_2	500	k€/km	
k_{ers}	0.1 1.0		
Static charger cost	200	€/kW	
Isol DC/DC cost	100	€/kW	

2 Parameter Study

With the given 4 alternative charging scenarios, a set of parameters are scanned in order to study how the total cost build up. The parameter sweep is described in Table 3. The reference settings use the parameters in bold red figures.

Table 3: Parameter study

Parameter	**Range**	**Unit**	**Comment**
AADT	[50 100 **1000** 1500 2000]	Veh/day	Incl both directions
L_{road}	[50 100 **150** 200 250]	km	A_1 to B_1 in Figure 1.1
L_{end}	[10 20 **30** 40 50]	km	A_1 to A_0 to A_1, same for B
d_{ers}	[2 4 **6** 8 10]	km	
ESS lifetime	[2 4 **6** 8 10]	years	
ERS lifetime	[5 10 **15** 20 25]	years	

The results are obtained by looping through the following calculation steps, varying one of the parameters at a time while keeping the others at their reference settings. The results are calculated for all combinations of the ERS factor k_{ers} and the battery size W_{batt}, see Table 1 and Table 2.

1. The round-trip time and the number of round trips per day for one truck are calculated, accounting for the route length, the vehicle speed, the end stop time and the number of work hours per day.
2. The number of vehicles in operation is calculated accounting for the intended Annual Daily Traffic (AADT) flow.
3. The total used electric energy is calculated and the corresponding Depth of Discharge (DoD) is calculated accounting for k_{ers} and d_{ers} and the optional end stop charging time.
4. If the electric energy spent exceeds the battery capacity, Hybrid mode is engaged and the corresponding fuel consumption is calculated.
5. The charging power on the ERS tracks, accounting for k_{ers}, as well as on the optional end stop charger power is calculated.
6. The C-rate when charging the batteries on the ERS tracks is calculated. If the C-rate is too high, see Table 1, the results are disregarded.
7. The life time wear of the batteries is calculated based on life cycle data in Figure 1.3 and the calendar life time.
8. Finally the cost for the electric energy, the fuel, the depreciation of batteries, DC/DC-converters, the ERS system etc is calculated and aggregated to a total operational cost.

3 Results

The results for the reference case are shown in Figure 3.1.. Note that for small values of k_{ers} and small battery sizes, the DoD and C-rate become too high. Note also that the total cost is minimized for relatively small batteries.

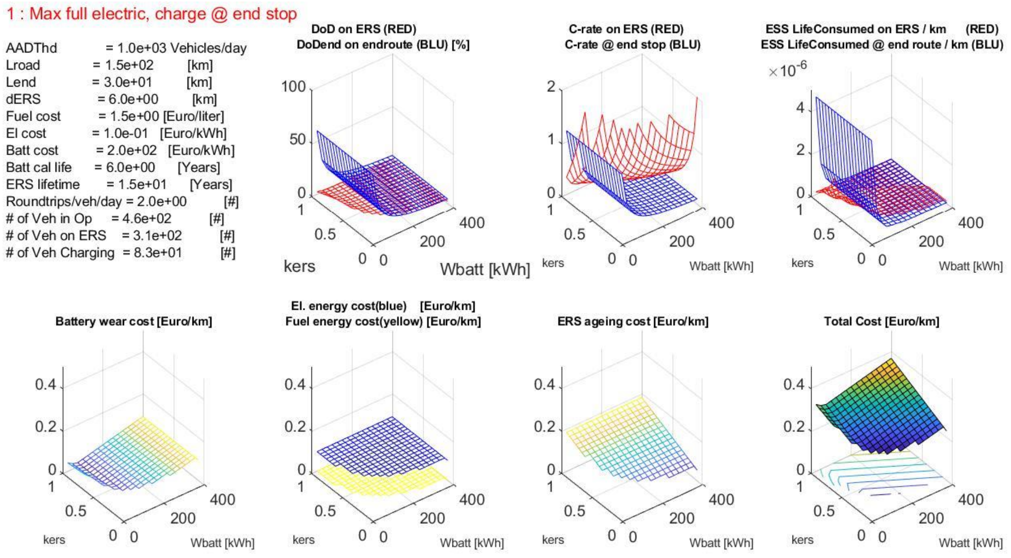

Figure 3.1. Some results for the reference settings and charging Scenario 1.

There are some conclusions that can be drawn from Figure 3.1.:

- With small batteries the DoD becomes high and if k_{ers} is low on top of that, the battery wear becomes too high and that data is omitted.
- The battery wear cost increase with battery size beyond a certain level, due to calendar life.
- The lowest total cost appears at a medium size battery (100 kWh) and a low k_{ers} (0.35). This represents a good combination of low k_{ers}, i.e low ERS cost, and batteries pushed to the cycle life limit.

If all charging scenarios are studied, and the one with the lowest toital cost is saved for each, additional interesting results can be found in

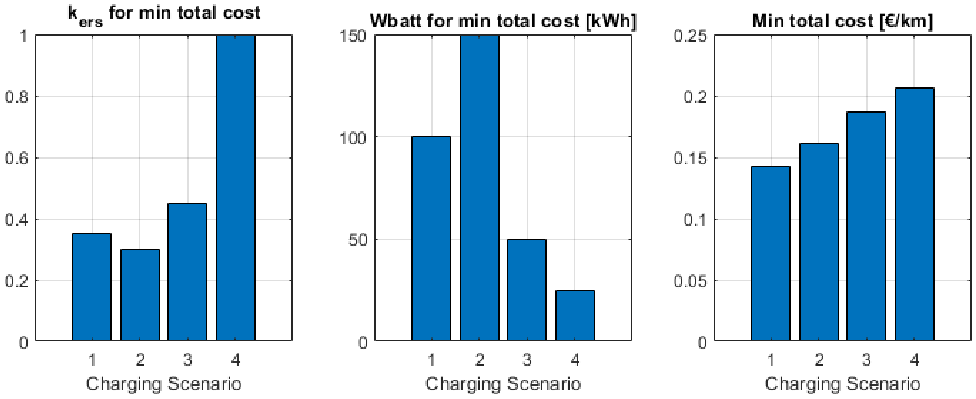

Figure 3.2 The optimal combination of k_{ers} and battery size for each charging scenario,and the corresponding total cost.

Figure 3.2 shows that it is always better to BOTH drive AND charge from the ERS tracks and drive in battery mode only in between ERS tracks, than to ONLY drive on ERS and run in hybrid mode in between. The lowest total cost is achieved with k_{ers}=0.35 and 100 kWh battery.

The full paper will contain a more detailed discussion considering more variables, some sensitivity analysis

4 Acknowledgments

The Swedish Traffic Agency is gratefully acknowledged for inspiring discussions on how to formulate the questions addressed in this paper.

5 References

[1] Gabriel Domingues-Olavarria (2018), Modelling, Optimization and Analysis of Electromobility Systems, PhD thesis, Lund University. TEIE-1090

6 Authors

Mats Alaküla is a professor in Industrial Electrical Engineering since 1994 at Lund University in Lund, Sweden. He has a PhD in control of electrical drives and has worked with applications in the automotive business for 20 years. He is also leader of electrical drive systems research at the Swedish Electro Mobility Centre and a Senior Advisor in electro mobility at AB Volvo.

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