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Possibilities of reduction of the on-board energy for an innovative subway

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Abstract

An innovative subway has been proposed using supercapacitors as energy source. In this paper, are presented different possibilities to reduce on-board stored energy in order to downsize the on-board energy storage subsystem. Special attention is paid to the influence of a feeding rail extension or a downward slope at the beginning of the interstation on the on-board stored energy. A map is built to facilitate the selection of the solution which leads to reduce the on-board energy.

Keywords: on-board energy, energy storage, supercapacitor, ultracapacitor, subway, traction system, energy sizing, energy gain.

1 Introduction

Energy saving is a critical issue for the next decade. The development of new transportation systems takes a part in this challenge [1]-[2]. Because electric drives have better efficiency than internal combustion engine, electric vehicles and hybrid vehicles are developed to propose alternative solutions [2]-[4]. Trains, tramways and subways have been developed a long time ago, and they provide efficient systems for passenger transportation in urban cities. Classical subways are supplied by a DC bus (rail) all along the line. Using electric drives, their efficiency is generally very high. Moreover, regenerative braking can be used leading to re-injecting electrical through the DC bus [5]. This can be made under the assumption that there are other vehicles on the line that are able to absorb this energy. When it is not the case, all braking energy cannot be recovered and braking resistor and/or a mechanical brake are used as complement to dissipate energy [6].

New technologies can be introduced in these systems to increase their efficiency [7] such as supercapacitors [1], [8]-[9], new batteries [9] and flywheels [10]. In this way, the recovered energy can be stored and reused as needed for the next traction operation [11]-[14].

A new subway is developing to propose a more efficient subway traction system. This subway uses an on-board supercapacitors bank for autonomous operation [11]. The supercapacitor bank is charged at each station. When the subway accelerates, the supercapacitor bank is discharged. When the subway decelerates, the regenerative braking charges the supercapacitor bank. In this way, the energy saving is increased. However, a supercapacitor bank installed in the subway can increase the cost and the complexity of the vehicle.

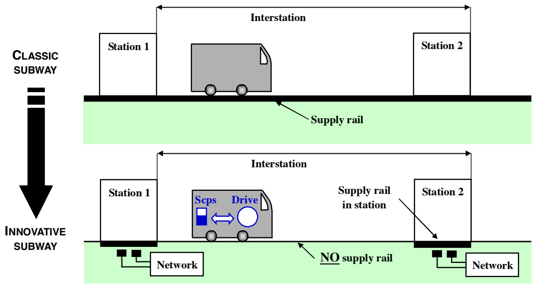


Figure 1: From the classic subway to the innovative subway

The supercapacitors can respond to an important surge of power but can-not store as much energy as batteries; therefore, they are usually used as a power source [9]. Nevertheless, in this innovative subway they are also used as the main energy source. This means that the energy storage design will be larger and heavier than if it were used only as a power source.

The purpose of this paper is to propose different possibilities to reduce the on-board stored energy requirement in order to reduce the size of the on-board energy storage accumulator [12]. In the first part, a reference case and the procedure to evaluate the on-board energy needs are presented. In the second part, the influence of a feeding rail extension at the beginning of the interstation on the on-board stored energy requirement is studied. In the third part, the influence of a downward slope is studied. Finally in the last section, a map is established in order to choose the best solution to reduce the on-board energy requirement.

2 Evaluation of the on-board energy for the reference case

2.1 Reference case

The studied subway is made of three cars. Each car is composed of an energy storage subsystem with supercapacitors, and of a four-drive traction system. Between two stations, the on-board supercapacitors bank is the only source that supplies the vehicle (Figure 1).

When the subway accelerates the supercapacitors bank is discharged. When the subway decelerates, a part of the braking energy is recovered and charges the supercapacitors bank. When the vehicle is stopped in station, the on-board system is charged by an external supply. In this paper, the subway is studied between two stations and the recharge system in station is not considered.

The reference interstation track is at grade and 1000 m long. The chosen rolling conditions are the most stringent in terms of energy consumption: the vehicle rolls with a strong front wind and at its full load capacity. A feeding rail is used to recharge the on-board system while the vehicle arrives at the station and spans the length of a station (Figure 1). While the vehicle accelerates, the on-board supercapacitors bank is not solicited and the energy is directly taken on the feeding rail.

2.2 Evaluation of the on-board energy

2.2.1 Model and control

A model of the mechanical part of the subway and its control has been used to evaluate the on-board energy to be stored. In order to improve the organization of the simulation model, a graphical description, EMR (Energetic Macroscopic Representation), is used (Figure 2), (Appendix), [15]. EMR is based on the action-reaction principle for organizing the interconnection of sub-systems according to the physical causality (i. e. integral causality). This description highlights energetic properties of the system (energy accumulation, conversion and distribution). Moreover, an inversion-based control can be systematically deduced from EMR using specific inversion rules. The equations of the different blocks of the model and the control are not developed in this paper but are detailed in [16]. The torque and the acceleration limitations of the drive system are taken into account in the control to evaluate the maximum on-board energy. Indeed, the higher the system limitations are, the smaller the actual maximal on-board energy requirement is [16].

2.2.2 On-board energy

The traction energy E_{tract}, is calculated taking into account the traction force F_{tract} and the vehicle velocity v_{sub}. It can be expressed as a sum of several energies to overcome the different resistive forces. When the vehicle accelerates on the feeding rail, this rail supplies an energy E_{rail}. This energy E_{rail} doesn't need to be stored on the vehicle. Therefore, the on-board energy E_{ob}, is defined as the difference between E_{tract} and E_{rail} (1), (2).

$$E_{ob} = E_{tract} - E_{rail} \quad (1)$$

$$E_{tract} = E_{acc} + E_{stat} + E_{visc} + E_{aero} + E_{down} \quad (2)$$

Where E_{acc}, E_{stat}, E_{visc}, E_{aero}, E_{down} are respectively, the supplied energy to overcome the acceleration force (which depends on the mass M and of the acceleration a_{sub} of the vehicle), the static friction force, the viscous friction force, the aerodynamic force and the downgrade force respective.

For the reference case, the energy E_{rail} is equal to the supplied energy by the rail in station E_{rail_stat}. Moreover, as the reference track is flat, the energy E_{down} which is dependant of the slope is equal to zero (3).

$$\begin{cases} E_{rail} = E_{rail\_stat} \\ E_{down} = 0 \end{cases} \tag{3}$$

The on-board supercapacitors bank is sized from the maximum variation of the on-board energy ΔE_{ob_max} which is the difference between the maximum on-board energy level E_{ob_max} and the minimum on-board energy level E_{ob_min} (4) (Figure 3).

$$\Delta E_{ob\_\max} = E_{ob\_\max} - E_{ob\_\min} \tag{4}$$

For the reference case, the on-board energy E_{ob_ref} is equal to zero at the beginning of the interstation, as the vehicle is starting on the rail at station 1 (Figure 3, area 1).

Then, it increases rapidly until the drive reaches it's cruising velocity then continues to increase until it reaches its maximum on-board energy E_{ob_max} just before the deceleration phase ($E_{ob\_ref} = 1$) (Figure 3, parts 2 and 3). When the vehicle decelerates, a part of the braking energy is recovered in the supercapacitors bank and E_{ob_ref} decreases until the vehicle reaches the feeding rail in station 2 (Figure 3, area 4). At this moment the braking energy is recovered through the feeding rail. The energy E_{ob_ref} keeps constant until the subway has come to a complete stop (Figure 3, area 5).

2.3 Possibilities of reduction

Different possibilities for reducing the energy variation ΔE_{ob_max} are conceivable. The general idea consists in reducing the maximal energy E_{ob_max}. So, the energy E_{ob_ref} has to be reduced before it reaches its maximum and in particular during the acceleration phase where the required energy is the most important.

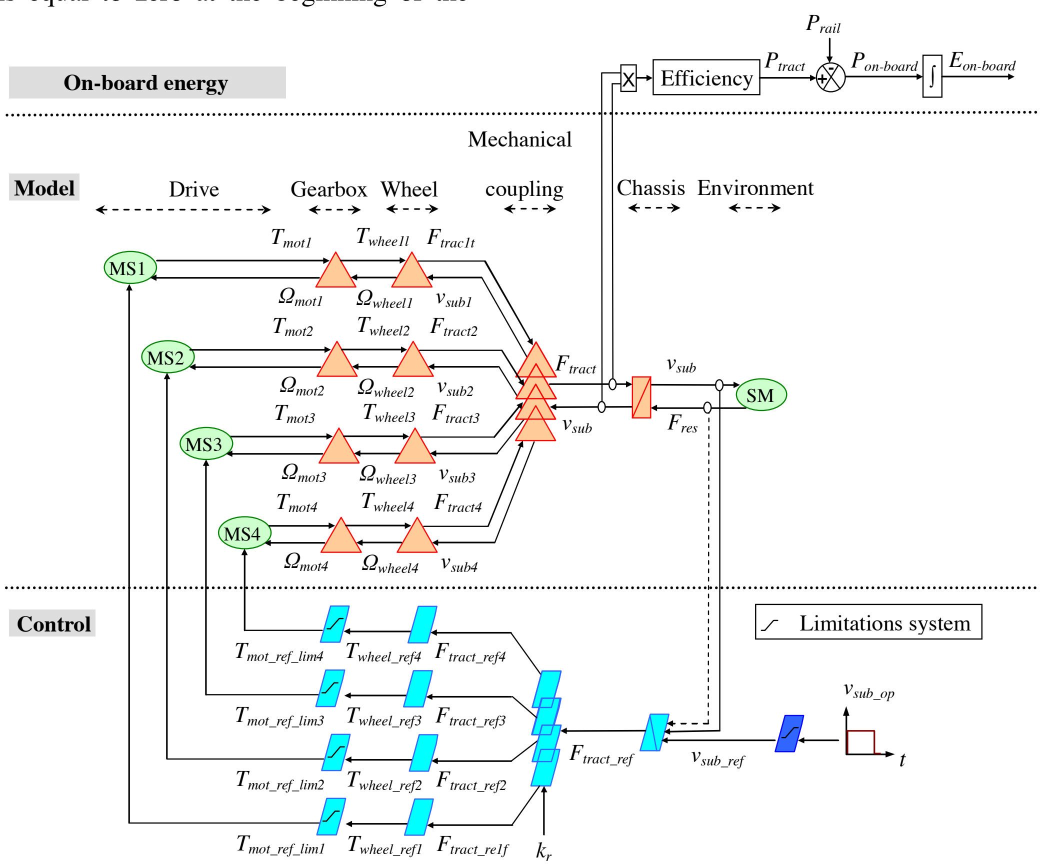


Figure 2: On-board energy calculation [16]

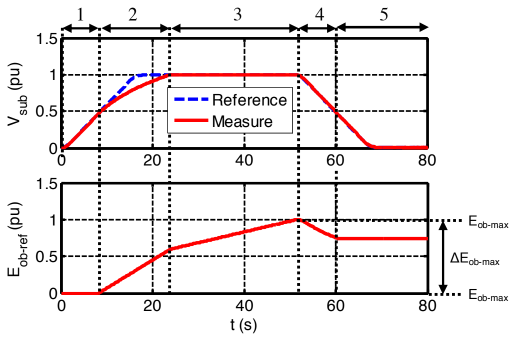


Figure 3: Reference case

The supplied rail in station 1 contributes to reduce the maximum energy E_{ob_max}, because the energy E_{ob_ref} is equal to zero at the beginning of the acceleration phase. A first possibility to be considered for reducing the energy is to extend the rail at the beginning of the interstation.

The recovered energy also contributes to reduce the maximum energy E_{ob_max} during the braking phase [14]. A second possibility of energy reduction could consist in using recovered energy during the acceleration phase. It is possible if a downhill slope is added at the beginning of the interstation.

These two possibilities for reducing the energy variation ΔE_{ob_max} are developed in the following parts.

3 Influence of a feeding rail extension on the on-board energy

3.1 Studied case

At the end of the feeding rail in station, an extension is added at the beginning of the interstation (Figure 4). While the vehicle rolls on the feeding rail extension, the on-board supercapacitors bank is not used. One expects the energy variation $\Delta E_{ob\_test\_max}$ to be lower than the one of the reference case without rail extension $\Delta E_{ob\_ref\_max}$. For the studied case, the energy E_{rail} is equal to the supplied energy by the rail in station E_{rail_stat} and by the rail extension E_{rail_ext} (5).

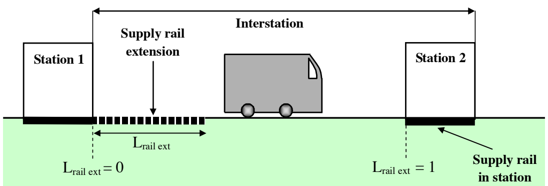


Figure 4: Feeding rail extension

Moreover, as the studied track is flat, the energy E_{down} is equal to zero (5).

$$\begin{cases} E_{rail} = E_{rail\_stat} + E_{rail\_ext} \\ E_{down} = 0 \end{cases} \qquad (5)$$

3.2 On-board energy gain

An on-board energy gain G_{E_ob} is introduced. It is the relative gain between the energy variations $\Delta E_{ob\_ref\_max}$ and $\Delta E_{ob\_test\_max\_}$ expressed in percentage (6).

$$G_{E\_ob}(\%) = \frac{\Delta E_{ob\_ref\_max} - \Delta E_{ob\_test\_max}}{\Delta E_{ref\_max}} 100 \qquad (6)$$

The evolution of the energy gain G_{E_ob} with the length of the feeding rail extension $L_{rail\ ext}$ can be divided in four parts (Figure 5). During the acceleration phase, while the covered distance by the vehicle is higher or equal to the feeding rail extension length, the energy gain G_{E_ob} increases (Figure 5, part 1). Indeed, the feeding rail extension contributes to reduce the maximum energy $E_{ob\_test\ max}$ during the acceleration phase where the required energy is the most important (Figure 6, $L_{rail\_ext} = 250\ m$). It is also the case during a part of the constant velocity phase (Figure 5, area 2).

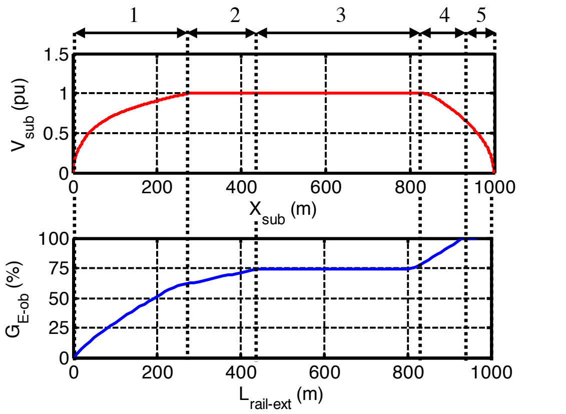


Figure 5: Energy gain thanks to feeding rail extension

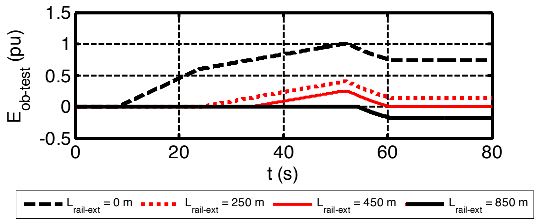


Figure 6: On-board energy for different feeding rail extension lengths

Then, the energy variation $\Delta E_{ob\_test\_max}$ is equal to the recovered energy (Figure 6, $L_{rail\_ext} = 450$ m). The recovered energy is constant, therefore the energy gain G_{E_ob} is constant (Figure 5, part 3). After, the energy gain G_{E_ob} increases again when the vehicle begins to brake on the feeding rail in station 2 (Figure 5, part 4).

Indeed, the braking energy is recovered through this rail and the energy variation $\Delta E_{ob\_test\_max}$ decreases (Figure 6, $L_{rail\_ext} = 850$ m). Finally, the vehicle rolls on the feeding rail extension during all its braking phase, the braking energy is completely recovered through this rail, therefore the energy gain G_{E_ob} is equal to zero (Figure 5, part 5).

3.3 On-board energy sizing

This study shows that the energy variation ΔE_{ob_max} can be reduced significantly when an extension feeding rail is added at the beginning of the station. For example, for a rail extension of 200 m, the energy gain is equal to 50%. It means that the energy to store on-board is reduced down to 50% in comparison with the reference case (without rail extension) (Figure 5).
However, for the studied track, it is not interesting to add an extension rail higher than 450 m because, the on-board energy gain G_{E_ob} is constant. Moreover, a compromise has to be found. On the one hand, the addition of a feeding rail means an additional cost and maintenance. On the other hand, the reduction of the energy variation ΔE_{ob_max} means a reduction of the on-board accumulator, avoiding so a bulky, heavy and costly storage subsystem.

4 Influence of a downward slope on the on-board energy

4.1 Studied case

The track is adapted in order to launch the subway in its acceleration phase [12]. The studied track is composed of a downhill slope at the beginning of the interstation, then a flat part and an uphill slope at the end of the interstation. When the vehicle is rolling downhill, it losses potential energy. That energy is partially converted into kinetic energy and can be recovered. If the vehicle goes down during its acceleration phase, one expects the energy variation $\Delta E_{ob\_test\_max}$ to be less important than the one of the reference case without slope $\Delta E_{ob\_ref\_max}$.

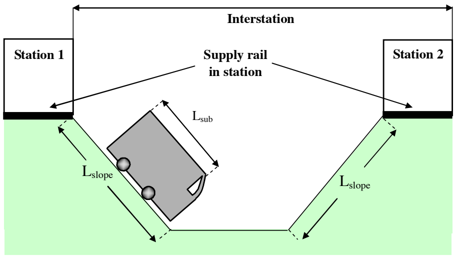


Figure 7: Particular track

For the studied case, the extension rail is not considered and the energy E_{rail} is equal to the supplied energy by the rail in station1, E_{rail_stat}. Moreover, as the studied track is not flat, the energy E_{down} has to be considered (7). It is negative if the vehicle is in a downward slope (the slope s is negative) and is positive if the vehicle is in an uphill slope (the slope s is positive) (2).

$$\begin{cases} E_{rail} = E_{rail\_stat} \\ E_{down} = \int_0^t v_{sub}(t) M \ g \ s(X_{sub}(t)) dt \end{cases} \tag{7}$$

Where v_{sub} is the vehicle velocity, g is the gravity and X_{sub}, the position of the subway.

4.2 On-board energy gain

The evolution of the energy gain G_{E_ob} with the slope length L_{slope} can be divided in three parts (Figure 8). At the beginning of the acceleration phase, the subway is starting on the feeding rail at station 1; therefore the energy gain G_{E_ob} is equal to zero (Figure 8, part 1). Then, while the distance covered by the vehicle during the acceleration phase is higher or equal to the length of the slope, the energy gain increases (Figure 8, part 2). Indeed, when the vehicle goes down, a part of its kinetic energy is recovered and contributes to reduce the maximal energy E_{ob_max} (Figure 9, $L_{slope} = 170$ m). It is also the case during a part of the constant velocity phase. After, the subway begins to slow down as soon as it reaches the uphill portion of the track slope. The energy supplied during the uphill slope becomes higher than the recovered energy (Figure 9, $L_{slope} = 450$ m). Consequently, the maximum energy E_{ob_max} increases, therefore the energy gain G_{E_ob} decreases (Figure 8, part 3).

4.3 On-board energy sizing

This study shows that the energy variation ΔE_{ob_max} can be reduced significantly when there is a downward slope at the beginning of the station.

For example, for a length of the downward slope of 200 m, with a slope of 6%, the energy gain is equal to 25%. It means that the on-board energy to store is reduced of 25% in comparison with the reference case (without slope) (Figure 8).

5 Influence of a feeding rail extension and a particular track on the on-board energy

5.1 Studied case

The studied case combines both energy gain solutions presented previously. A feeding rail extension and a downward slope are added at the beginning of the interstation (Figure 10).

For the studied case, the energy E_{rail} is equal to the supplied energy by the rail in station E_{rail_stat} and by the rail extension E_{rail_ext} (8). Moreover, as the studied track is not flat, the energy E_{down} is also considered (8).

$$\begin{cases} E_{rail} = E_{rail\_stat} \\ E_{down} = \int_0^t v_{sub}(t) M\ g\ p(x_{sub}(t))dt \end{cases} \quad (8)$$

5.2 Energy gain map

In order to choose the best solution to reduce the on-board energy needs, a two dimensional map is constructed. It gives the energy gain G_{E_ob} as a function of the rail extension length L_{rail_ext} and as a function of the slope length L_{slope} for a given slope s (Figure 11).

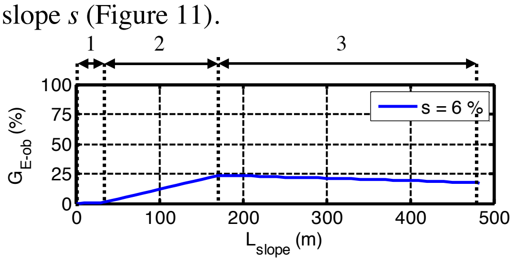


Figure 8: Energy gain thanks to a particular track

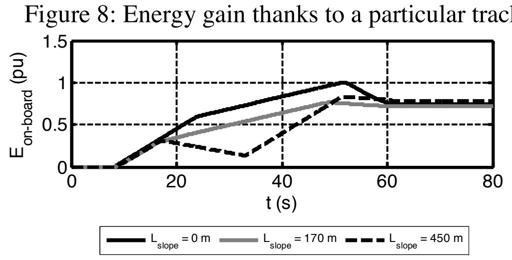


Figure 9: On-board energy or different slope lengths

Firstly, the L_{slope} is fixed and the variation of the G_{E_ob} with the L_{rail_ext} is studied. Secondly, the L_{rail_ext} is fixed and the variation of the G_{E_ob} with the L_{slope} is studied.Finally the variation of the G_{E_ob} is studied when the L_{rail_ext} and the L_{slope} varies (Figure 11). For the studied case, the slope s is considered equal to 6%. For a given L_{slope}, for example 150 m, without rail extension, the G_{E_ob} is equal to 20% (Figure 12). If a rail extension L_{rail_ext} is added, the G_{E_ob} increases ($G_{E\_ob\_P1} < G_{E\_ob\_P2} < G_{E\_ob\_P3}$).

Considering the point P_2, as an exemple, the extension rail is equal to 200m and the G_{E_ob} varies from 20% to 60%. However it is possible that the G_{E_ob} does not always increase with the extension rail.

For a given L_{rail_ext}, for example 200 m, without slope, the G_{E_ob} is equal to 30% (Figure 13). If a downward slope L_{slope} is added, G_{E_ob} increases ($G_{E\_ob\_P3} < G_{E\_ob\_P4}$) and then decreases ($G_{E\_ob\_P4} > G_{E\_ob\_P5}$). For example, for the point P_4, the slope length is equal to 200 m and the G_{E_ob} varies from 30% to 60%.This study shows that it is not interesting to add a slope length higher than 175 m because beyond that the G_{E_ob} decreases.

This map can be divided in different areas. Every area can be characterized by the sign of the derivative of the length slope L_{slope} in relation with the rail extension L_{rail_ext}. The different cases are summarized in Table 1. The most interesting area is the one where this derivative is negative, identified by the greyed area (Figure 11). Indeed, in this area if the L_{rail_ext} increases or if the L_{slope} increases, the G_{E_ob} always increases

For example, for a rail extension L_{rail_ext} of 200 m and a slope length L_{slope} of 150 m, the G_{E_ob} is reduced of 60%.

6 Conclusion

An innovative subway without feeding rail is under development.

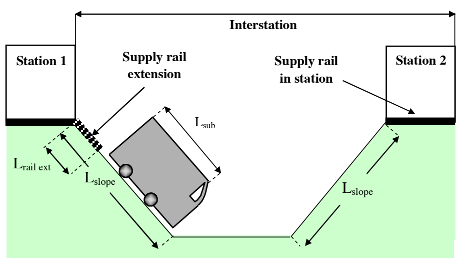


Figure 10: Particular track with a feeding rail extension

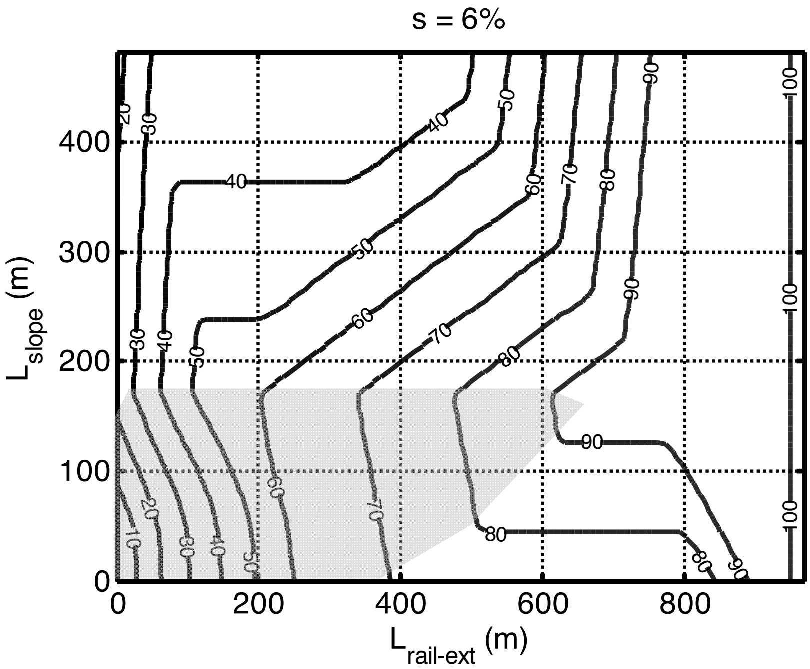


Figure 11: Energy gain map

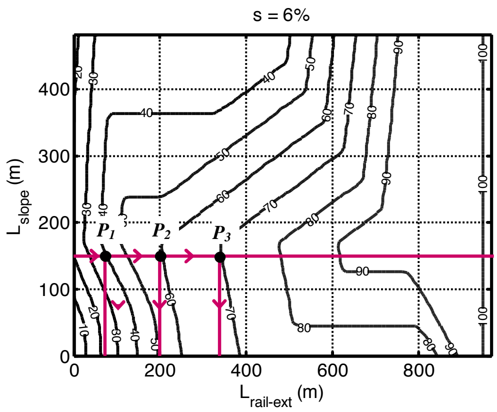


Figure 12: Analyse for a given L_{slope}

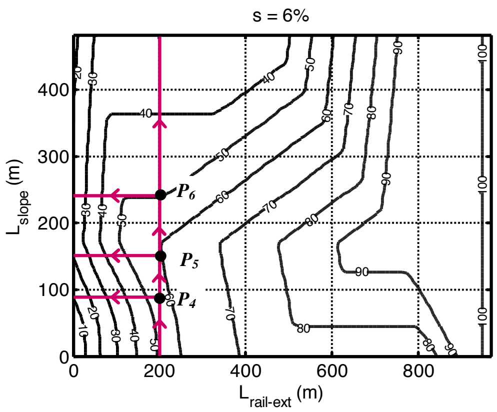
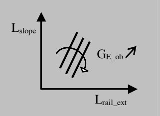
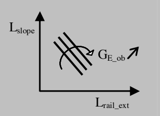
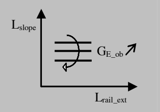
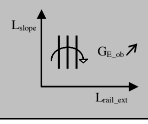


Figure 13: Analyse for a given L_{rail_ext}

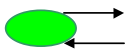
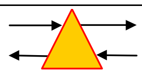
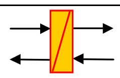
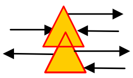
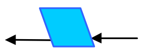
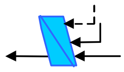
Table 1: Different areas of the iso-energy gain map

$\frac{dL_{slope}}{dL_{rail\_ext}}$	L_{slope}	L_{rail_ext}	G_{E_ob}
> 0 	↗	constant	↘
	constant	↗	↗
< 0 	↗	constant	↗
	constant	↗	↗
$= 0$ 	↗	constant	↗
	constant	↗	constant
$\rightarrow \infty$ 	constant	↗	constant
	↗	constant	↗

An on-board energy storage system using supercapacitors supplies the vehicle with energy between two stations.

Different possibilities to reduce the on-board energy to be stored have been studied. The first solution consists in adding a feeding rail extension at the beginning of the interstation. The second solution consists in changing the track profile with a downward slope at the beginning of the interstation. For these two possibilities, the on-board energy to be stored can be reduced significantly, in particular during the acceleration phase. The third solution is a combination of both solutions. The energy gain map help to choose the optimal solution.

Appendix: Synoptic of Energetic Macroscopic Representation (**EMR**)

		
Source of energy	Mechanical converter (without energy accumulation)	Element with energy accumulation
		
Coupling device (energy distribution)	Control block without controller	Control block with controller

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