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Electro-Kinematical Simulation for Flexible Energetic Studies of Railway Systems

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Abstract—Simulation is a valuable tool to evaluate energy consumptions and design of railway systems. In most of cases, electro-mechanical and kinematical studies are dissociated. An ideal velocity profile is previously defined by the kinematical study. This velocity is directly used as input in the electro-mechanical study. However, the effects of electrical limitations (i.e. voltage) and/or mechanical limitations (i.e. torque) of the system are neglected on the kinematical behavior (i.e. velocity). The objective of the paper is to develop an adaptive electro-kinematical simulation, which adapts the kinematical behavior of the system according to its limitations. This simulation is validated by experimental results on a real track. It is then used to study different solutions to increase the transport capacity of a subway system.

Index Terms—Electro-kinematical simulation, railway systems, reference velocity profile, system limitations.

I. INTRODUCTION

ANALYSIS AND DESIGN studies are crucial to develop new transportation systems. Considering the advantages of high speed, punctuality, and environment respect, electric railway transportation was developed a long time ago [1], [2]. However, the global warming and increasing cost of the energy lead to still develop more efficient transportation systems [3]-[7]. Numerous solutions such as Energy Storage Systems (ESS) [8]-[11] and reversible Traction Power Substations (TPS) [12], [13] are thus investigated. Furthermore, the growing number of passengers conducts to improve the transportation systems and their capacities. New subway lines are developed in that aims. Furthermore, actual lines have also to be adapted to increase their performances.

Simulation tools are useful to assess the interests of new developments [14] and especially to estimate the energy consumption of different solutions. Generally the system operation is designed by a first kinematical study [6], [15]. It leads to an ideal velocity profile between the passenger stations, which is based on the respect of commercial speeds and kinematical limitations (jerk, acceleration, velocity). Then, an electro-mechanical study is conducted to design the network infrastructure (number and position of TPS, feeders, etc.) [16], [17]. It is based on safe operations respecting electro-mechanical limitations (voltage, current, torque, etc.).

Most of the simulation tools do not consider any feedback of the electro-mechanical study to the kinematical study [18]-

[20]. Indeed, they consider that the network is well designed to achieve the system operation without any activation of limitations (normal operating conditions). However some limitations can be activated to study different operating conditions (structural modification of existing subway lines, increasing of the traffic, etc.). In that case, the effective velocity can be different than the velocity given by the kinematical study (ideal profile). An interaction between kinematical and electro-mechanical studies can therefore be interesting in such case. For example P. Arboleya et al. reduce the absorbed power of a train according to the supply voltage and the train is disconnected if the minimum voltage limitation is reached [20]. However, the velocity profile is not impacted during the simulation. R. Barrero et al. switch between backward and forward simulation to consider the electro-mechanical limitations [21]. However, the kinematical limitations are not systematically respected.

The paper objective is thus to develop an adaptive electro-kinematical simulation, which adapts systematically the kinematical behavior according to the electro-mechanical limitations. The theoretical contribution is to propose a generic model to recalculate the velocity profile when limitations occurs. Then, the practical contribution is to obtain more accurate results in term of energy consumption and system operation when considering different scenarios. A kinematical model is thus developed and coupled with an existing electro-mechanical model of subway systems [22], [23]. Both models are organized using the Energetic Macroscopic Representation (EMR). EMR is a graphical description, which highlights the energetic properties of a system [24], [25]. It is based on a forward simulation approach [26] and organizes the system according to the action and reaction principle with respect of the physical causality [27], [28]. EMR is thus chosen to highlight the required feedback (action-reaction principle) between electro-mechanical and kinematical simulations. Furthermore, EMR has already been successfully used for the simulation of subways [8], [22] and TPS [23].

Section II presents the principle of electro-kinematical simulation. Section III presents the electro-mechanical model of the subway system. The kinematical model is developed and coupled with the electro-mechanical model in section IV. Finally, the interest of the electro-kinematical simulation is assessed in section V (it is used to study different solutions to increase the transport capacity of an overloaded subway line).

II. PRINCIPLE OF ELECTRO-KINEMATICAL SIMULATIONS

In classical studies, reference velocity profiles are imposed as inputs of electro-mechanical simulation (Fig. 1.a). These profiles are previously defined by a kinematical simulation. They are calculated to reach the next stations (reference positions) with respect to the kinematical limitations. However, because both simulations are decoupled, no feedback exists. Thus, optimal supply conditions are assumed in the kinematical simulation (rated voltage, no voltage constraint). The reference velocity profiles are then directly used in the electro-mechanical simulation. However, actual velocities can differ from these reference velocity profiles if one or several electro-mechanical limitations are activated.

The electro-kinematical simulation proposed in this paper consists in coupling both simulations by using a feedback between the electro-mechanical and the kinematical simulations (Fig. 1.b). In this way, the kinematical model adapts the adaptive generated velocities according to the electro-mechanical limitations. Then, the adaptive reference velocity is determined according to the traffic conditions, the traction system parameters, and the following constraints:

- Kinematical limitations: The jerk, acceleration and velocity of the vehicles are limited. Furthermore, the velocity limitation depends on the position of the vehicle.
- Electro-mechanical limitations: First, the traction torque is limited as a function of the vehicle velocity, which impacts the maximal acceleration. Second the voltage constraints are respected as explained below [29]:

During the traction phases, the vehicles absorb currents on the supply subsystems, inducing voltage drops. If the voltage is close to the minimal constraint, the over-current protection reduces the power demand to not exceed the

minimal voltage. In practice, the traction torque limitation is decreased. This fact has an impact on the kinematical limitations (i.e. acceleration) and the energy consumption.

During the braking phases, vehicles recover energy to increase the efficiency [30], [31]. This energy cannot be recovered through the diode-based TPS but can be re-used directly on the track by other traction vehicles. However, if there are not enough traction vehicles, this energy must be restricted to not exceed the maximal voltage. This function is achieved by the squeeze control, which limits the energy recovery using braking resistors or mechanical brakes. In this paper, the system uses only mechanical brakes without braking resistor. In this case, the energy recovery is limited by a linear increase of the electric braking torque limitations without impact on the actual velocity due to the compensation achieved by the mechanical brakes.

III. SYSTEM MODEL WITH REFERENCE VELOCITY PROFILE

In this section, the models developed and experimentally validated in [22] and [23] are presented. The system is composed of subways supplied by several non-reversible TPS through DC energy rails (Fig. 2). The subways are composed of input filters, auxiliaries, electric drives, mechanical brakes, and mechanical transmissions [22]. The TPS consist in transformers and diode rectifiers to convert AC into DC voltages [23]. In this section, the reference velocity profiles are directly considered as inputs of the subway model.

A. Subway system model

The TPS and DC rails compose the supply subsystem. The model defines the energy consumption $W_{TPS}(t)$ and active power $P_{TPS}(t)$ for each TPS. Furthermore, it determines the rail voltages $u_{rail}(t)$, which supply the subways, according to the supply subsystem parameters and subways currents $i_{sub}(t)$. Furthermore, the non-reversibility of the diode rectifiers is considered using switched models: a TPS imposes the rectified voltage in the on-state and a null current in the off-state [23]. The DC rails model considers time-variant resistances according to the TPS and vehicles positions. More details can be found in [23].

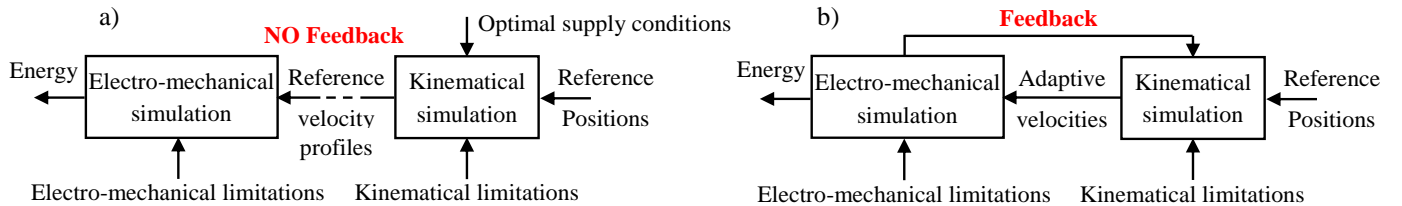


Fig. 1. Principle of: a) classical study, b) adaptive study.

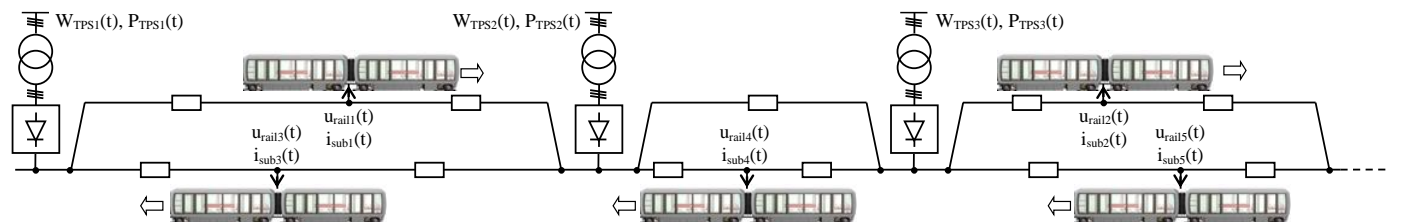


Fig. 2. Studied subway system with vehicles, traction power substations, and DC rails.

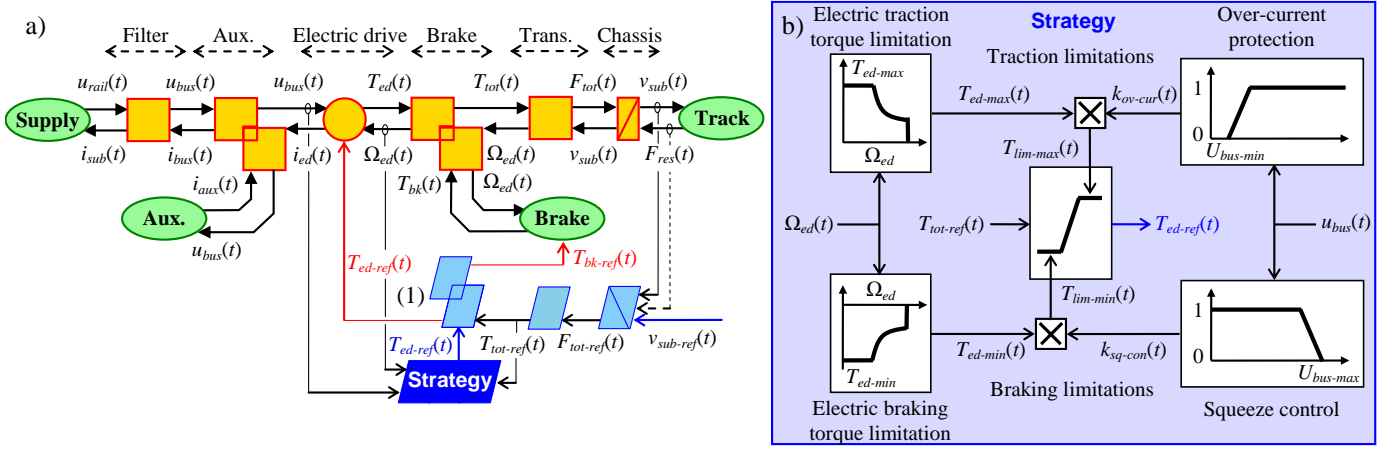


Fig. 3. Subway model with reference velocity profile: a) EMR, b) strategy (Energy Management Strategy).

The subway model is organized using the EMR (Fig. 3.a). It determines the subway current $i_{sub}(t)$ according to the subway parameters, the rail voltage $u_{rail}(t)$ and the reference velocity profile $v_{sub-ref}(t)$ [22]. It is composed of: the power system (orange elements), its control (light blue elements), and the Energy Management Strategy (EMS) (dark blue elements).

- The power system consists in different elements that convert energy between the supply system and the track. It considers the input filter, electric drive, mechanical brake and transmission, auxiliary, and resistive force $F_{res}(t)$ (slope, friction, etc.). Furthermore, the main dynamics are taken into account using a quasi-static model [22].
- The control is deduced from EMR using inversion rules [24]. It imposes the reference velocity profile $v_{sub-ref}(t)$ by calculating the appropriate total reference torque $T_{tot-ref}(t)$ to produce. Furthermore, during the braking phase, the negative torque $T_{tot-ref}(t)$ can be achieved by the electric drive (recovery) and/or the mechanical brake (dissipation). The power sharing is determined by the EMS, which imposes directly the electric drive reference torque $T_{ed-ref}(t)$. Thus, the mechanical brake reference torque $T_{bk-ref}(t)$ is determined by (1).

$$T_{bk-ref}(t) = \begin{cases} 0 & \text{in traction phases} \\ T_{tot-ref}(t) - T_{ed-ref}(t) & \text{in braking phases} \end{cases} \quad (1)$$

- The EMS (strategy) is explained in the next section.

B. Electro-mechanical limitations of the subway system

The reference torque $T_{ed-ref}(t)$ is defined by the EMS to maximize the energy saving during the braking phases (Fig. 3.b). However, limitations, which impact $T_{ed-ref}(t)$, have to be respected to ensure safe operations. The mechanical constraints are the traction $T_{ed-max}(t)$ and braking $T_{ed-min}(t)$ torques limitations, which are due to the electric drive design. They depend on the rotation speed $\Omega_{ed}(t)$. The electrical constraints are the voltage limitations: too high voltages can damage the components; too low voltages can conduct to too important currents and the black out of the supply subsystem. Maximal $U_{bus-max}$ and minimal $U_{bus-min}$ threshold voltages are thus imposed. The subway operation must be adapted

according to the DC bus voltage $u_{bus}(t)$ using the over-current protection and the squeeze control. Coefficients, which are comprised between 0 and 1, are used to adapt the electrical torque reference $T_{ed-ref}(t)$ (Fig. 3.b) with respect to the different limitations as explained below:

- During braking phases, the electric drive operates as generator to recover energy. However, if the voltage is close to the maximal threshold $U_{bus-max}$, the squeeze control coefficient $k_{sq-con}(t)$ is decreased linearly. It thus increases the minimal electric torque limitation $T_{lim-min}(t)$ according to the braking torque limitation $T_{ed-min}(t)$ (Fig. 3.b). In that case, the mechanical brakes are used as complement to achieve the total required reference torque $T_{tot-ref}(t)$ (1). This fact reduces the recovered energy but have no impact on the kinematical behavior.
- During traction phases, the electric drive operates as motor. However, if the voltage is close to the minimal threshold $U_{bus-min}$, the over-current protection coefficient $k_{ov-cur}(t)$ is decreased linearly. It thus reduces the maximal torque limitation $T_{lim-max}(t)$ according to the traction torque limitation $T_{ed-max}(t)$ (Fig. 3.b). In that case, the mechanical brakes cannot be used to achieve $T_{tot-ref}(t)$ (1), meaning that actual total torque $T_{tot}(t)$ differs from $T_{tot-ref}(t)$. Thus, the reference velocity cannot be achieved.

Most of electro-mechanical simulations do not consider the impact of voltage constraints on the kinematical behavior because reference velocity profiles are directly used without adaptation [18]-[20]. Some limitations are often neglected. For example, it is not possible to study the system when the train over-current protection is activated without deviation between actual and reference velocities. As consequences, the simulation results differ from real figures. In order to be able to obtain more accurate and more physical results, a more generic model is developed in the next section. It consists in developing a kinematical model able to generate an adaptive velocity. An electro-kinematical simulation is thus obtained.

IV. SUBWAY SYSTEM MODEL WITH ADAPTIVE VELOCITY

The electro-kinematical simulation couples electro-mechanical and kinematical models using a feedback (Fig. 4). The exchanged data are the resistive force $F_{res}(t)$, the actual

$v_{sub}(t)$ and reference $v_{sub-ref}(t)$ velocities, and the traction torque limitation $T_{lim-max}(t)$ (considering the over-current protection) (see Fig. 3.b). The objective of the kinematical model is to impose a time-optimal adaptive velocity reference $v_{sub-ref}(t)$ to the electro-mechanical model [32], [33]. This velocity has to respect the maximal and minimal values of the velocity, acceleration and jerk. The principle is to reach the next station as fast as possible, but respecting all the limitations [16], [34].

A. Extension of the subway system model

The kinematical model is composed of two parts (Fig. 4). The first one determines the maximal acceleration allowed by the traction system $\gamma_{tr-max}(t)$ (2). It depends on the traction torque limitation $T_{lim-max}(t)$, the mechanical transmission ratio K_{trans} , the mechanical transmission efficiency η_{trans} , the resistive force $F_{res}(t)$ and the dynamical subway mass M_{sub} .

$$\gamma_{tr-max}(t) = \frac{[K_{trans} \eta_{trans} T_{lim-max}(t)] - F_{res}(t)}{M_{sub}} \quad (2)$$

The second part is the adaptive velocity generator, which respect the kinematical limitations. It is extended from an existing algorithm still used in real subways [35], where a reference velocity $v_{ref}(t)$ is integrated all along the track. The track acts as position controller and delivers reference velocity steps. However, these steps induce discontinuities that the subway cannot achieve without excessive values of jerk and acceleration. Velocity and acceleration closed-loops are thus inserted on-board to limit these values and obtain a smooth reference velocity $v_{sub-ref}(t)$ [35]. These cascaded control loops are conserved to design the kinematical model (Fig. 4).

The velocity closed-loop defines a reference acceleration $\gamma_{ref}(t)$ from the reference velocity $v_{ref}(t)$ with respect to maximal $\Gamma_{max}(t)$ and minimal Γ_{min} acceleration values. Furthermore, $\Gamma_{max}(t)$ is time-variant according to the maximal acceleration allowed by the traction system $\gamma_{tr-max}(t)$. Then, the acceleration closed-loop defines a reference jerk $J_{sub-ref}(t)$ with respect to the maximal J_{max} and minimal J_{min} jerk values. Finally, the smooth reference velocity is obtained from $J_{sub-ref}(t)$ (3). More information on these closed loops, as well as, specific design of proportional velocity controller k_v and proportional acceleration controller k_γ can be found in [35].

$$v_{sub-ref}(t) = \iint J_{sub-ref}(t) \quad (3)$$

However, the existing algorithm used in real subways is not enough flexible to be adaptive. Indeed, $v_{ref}(t)$ depends on fixed positions on the track. The simulation of new topologies, limitations and/or traction systems, is thus very complex because new position marks should be first defined. The algorithm is thus extended to integrate a position controller. A specific Variable Structure Position Controller (VSPC) [36]-[39] is defined. It determine the reference velocity $v_{ref}(t)$ to reach the next position $x_{sub-ref}(t)$ allowing the automatic determination of the adaptive velocity $v_{sub-ref}(t)$. The VSPC imposes the maximal velocity $V_{max}(t)$ until the deceleration phase, where a new target velocity $V_w(t)$ is imposed. The switching surface $\sigma_x(t)$ of the VSPC is defined below:

$$v_{ref}(t) = \begin{cases} V_{max}(t) & \text{when } \sigma_x(t) > \Delta x_d(t) \\ V_w(t) & \text{when } \sigma_x(t) \leq \Delta x_d(t) \end{cases} \quad (4)$$

with $\sigma_x(t) = x_{sub-ref}(t) - x_{sub}(t)$

where $\Delta x_d(t)$ is the instantaneous required distance to decelerate from the actual kinematical subway behavior (i.e. instantaneous velocity $v_{sub}(t)$ and acceleration $\gamma_{sub}(t)$) until the new target velocity. $\Delta x_d(t)$ can be expressed as (5) knowing the different kinematical limitations and actual variables. A similar equation and its derivation are given in [40].

$$\begin{aligned} \Delta x_d(t) = & \frac{1}{3} \frac{\gamma_{sub}(t)^3}{J_{max}} + \frac{\gamma_{sub}(t)}{J_{max}} v_{sub}(t) \\ & + \frac{1}{2\Gamma_{max}(t)} \left[v_{sub}(t)^2 + \frac{\gamma_{sub}(t)^4}{4J_{max}^2} + \frac{\gamma_{sub}(t)^2 v_{sub}(t)}{J_{max}} - V_w(t)^2 \right] \\ & + \frac{\Gamma_{max}(t)}{2J_{max}} \left[v_{sub}(t) + \frac{1}{2} \frac{\gamma_{sub}(t)^2}{J_{max}} + V_w(t) \right] \end{aligned} \quad (5)$$

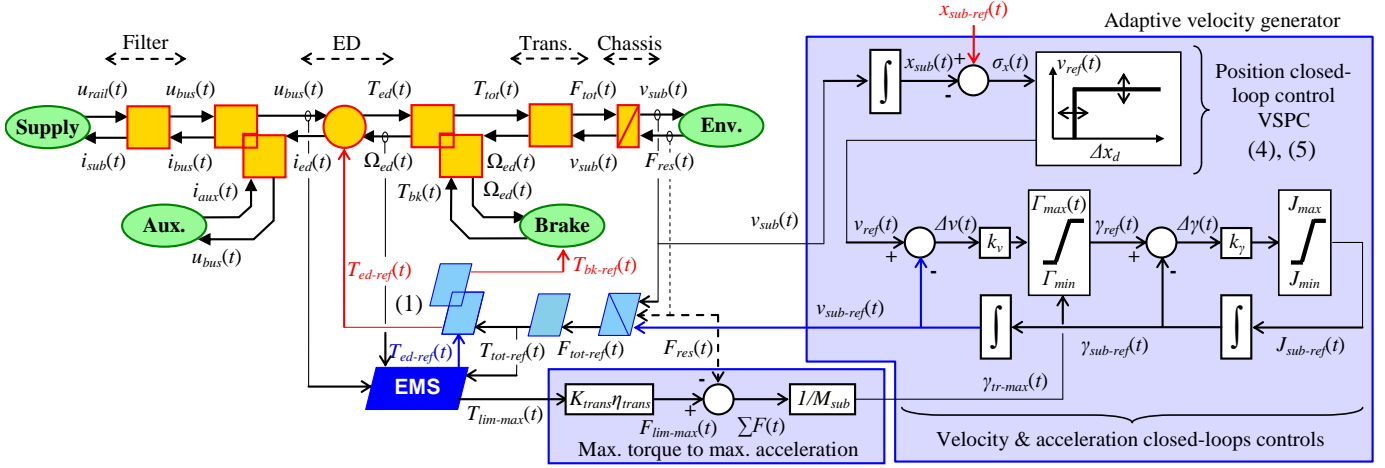


Fig. 4. Subway model with adaptive velocity (electro-kinematical model).

B. Validation of the electro-kinematical model

The proposed kinematical model interacts with the electro-mechanical model. It determines a time-optimal velocity reference $v_{sub-ref}(t)$, which is imposed to the subway model. This velocity respects all the limitations, allowing adaptive and flexible electro-kinematical simulation of railway systems. This electro-kinematical simulation is experimentally validated using measurement on a real subway in operation (line 2 of Lille, France). The station positions are used as input reference steps $x_{sub-ref}(t)$. When the stop time at the actual station is finished, the next station position is imposed as new reference position step. The subway starts thus a new drive cycle, which is automatically generated by the kinematical model according to the limitations. The simulation is carried out using Matlab-Simulink©. The simulation results of the subway (position, velocity, and acceleration) are compared with the measurements (Fig. 5). The jerk is not compared due to its too noisy estimation from the available measurements.

The electro-kinematical simulation is able to generate the velocity to the subway model according to the kinematical and electro-mechanical limitations. The simulated and measured positions and velocities are close (1.5% average error on the velocity). The acceleration is also reasonably estimated as well as the energy consumption (2% average error). On another hand, the adaptive electro-kinematical simulation allows better accuracy either on the energy consumption and the running time estimations [34]. For example, the same simulation (line 2 of Lille, France) without the electro-mechanical limitations leads to an over estimation of the energy consumption of 2.6% (average error). The error can be more important according to the studied cases, as presented in [34].

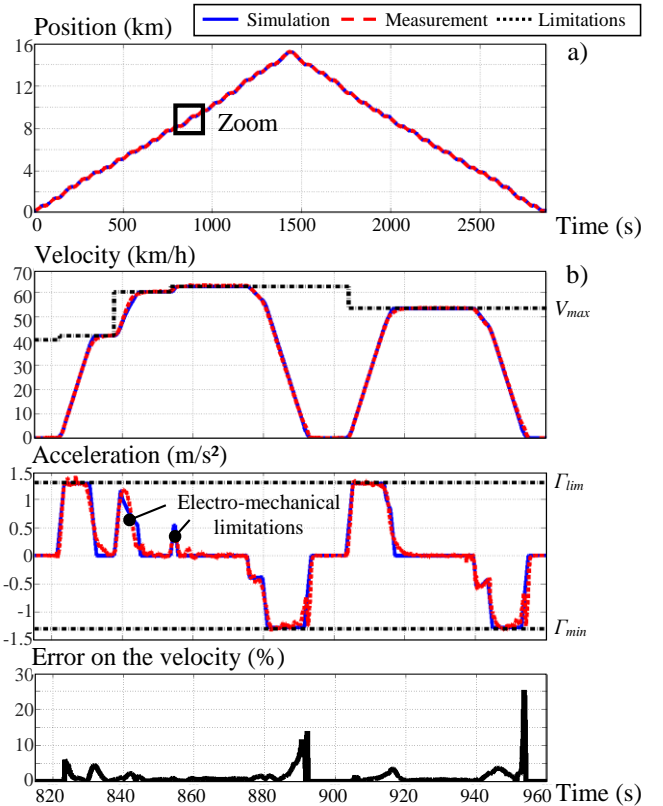


Fig. 5. Validation: a) entire cycle, b) zoom on inter-stations.

V. APPLICATION OF ELECTRO-KINEMATICAL SIMULATIONS

The interests of the electro-kinematical simulation are assessed through a study, which compares different solutions to increase the capacity of an overloaded subway line.

A. Increase of the transport capacity: Problematic

A subway line (Rennes B, France), which has been designed for a minimal headway of 148s between the trains, is studied (data have been changed for confidentiality reasons). The line is composed of 1 garage, 15 stations and 5 TPS (in bold) (TABLE I) (Fig. 6). The trains are composed of 2 cars. Each car can transport 75 passengers. The main limitations and data are summarized in Table II. The over-current

protection linearly decreases the traction torque from 600 V to 500 V (minimal value). The squeeze control linearly decreases the energy recovery from 900 V to 950 V (maximal value).

TABLE I
STATIONS, GARAGE, AND TPS OF THE SUBWAY LINE

Name	Position (m)	
GAT	Garage (TPS 1)	0
SJG	Saint-Jacque – Gaîté	612.1
COU	La Courrouze	1360.1
CLE	Cleunay	2212.6
MAB	Mabilais (TPS 2)	3581.5
COL	Colombier	4380.4
GAR	Gares	5208.9
SGE	Saint-Germain	6305.9
SAN	Sainte-Anne (TPS 3)	6862.0
JFE	Jules Ferry	7884.6
GCH	Gros-Chêne	8808.6
GAY	Les Gayeulles	9601.9
IJC	Irène Joliot-Curie (TPS 4)	10486.1
BUN	Baulieu – Université	11557.3
ATA	Atalante	12568.8
CVI	Cesson – Viasilva (TPS 5)	13514.6

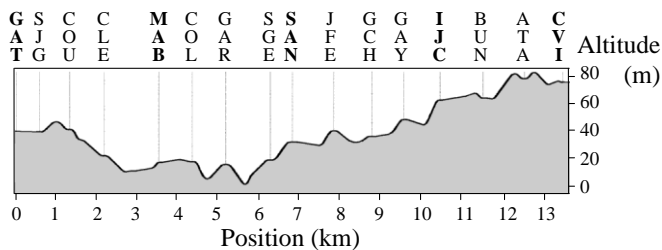


Fig. 6. Subway line topology.

TABLE II
MAIN LIMITATIONS AND DATA

Rated DC voltage	$V_{rail-rt}$	750 V
Rail resistance per meter	$R_{rail-lin}$	26 $\mu\Omega/m$
Auxiliary power of a car	$P_{aux/car}$	7.5 kW
Max. traction power of a car	$P_{max/car}$	300 kW
Max. traction force of a car	$F_{max/car}$	50.3 kN
No-load mass of a car	M_{car}	17.6 t
Transmission ratio	K_{trans}	11.3
Transmission efficiency	η_{trans}	93%
Maximal velocity	V_{max}	20 m/s
Max/min acceleration	$\Gamma_{lim}/\Gamma_{min}$	± 1.3 m/s ²
Max/min jerk	J_{max}/J_{min}	± 0.7 m/s ³
Over-current protection	$U_{bus-min}/U_{bus-ov}$	500/600 V
Squeeze control	$U_{bus-sq}/U_{bus-max}$	900/950 V

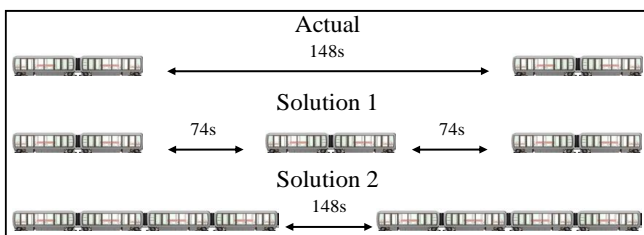


Fig. 7. Studied solutions.

During the rush hours, the actual subway line requires 18 trains, which travel a total of 633.5 km and consume 3015.6 kWh in 1h. The transport capacity is 95025 p.km/h (passengers transported over 1 km in 1h). The required energy

per passenger and per km is 31.7 Wh/p.km. But, the growing number of passengers requires to increase the transport capacity. Furthermore, the line topology cannot be changed: same number of TPS, same positions, same rails, etc.

The study consists thus to investigate two solutions to increase the transport capacity (Fig. 7). Solution 1 keeps the same subways (same number of cars) but reduce the headway between the trains. Thus, more vehicles are required. Solution 2 keeps the same headway (same number of trains) but increase the number of cars. The transport capacity can thus be doubled. Simulation results of the actual line, solution 1 and solution 2 are compared during the rush hours.

B. Increase of the transport capacity: Simulations

Firstly, the adaptive electro-kinematical simulation results are presented. The velocity is automatically adapted to respect the system limitations. The corresponding positions of trains are presented (Fig. 8). The difference between the actual case and solution 2 is not observable on this figure (there is only a delay of 10s) but a zoom on the electro-kinematical behavior of a train highlights the differences (Fig. 9). On another hand, the classical electro-mechanical simulation results help to understand the interest of the developed adaptive simulation (Fig. 10). In this case, the actual velocity profile (Fig. 9) is used as reference (without adaptation). The simulated velocity is thus the same for the actual case, solution 1, and solution 2.

Classical and adaptive simulations lead to identical results for the actual case because the limitations are never activated. Indeed, the actual line has been designed according to the actual velocity profile. However, the results are different for solutions 1 and 2. In these cases the voltage is close to the minimal voltage. Thus, the adaptive simulation activates the over-current protection (as in reality), which reduces the kinematical performances and induces a delay on the velocity (Fig. 9). At the opposite, the classical simulation cannot reduce the kinematical performances. The limitations cannot thus be respected (Fig. 10). The voltage become lower than the minimal value, which would lead in reality to the collapse of the feeding system. The classical simulation is thus not able to reproduce the system behavior when limitations are activated. In terms of accuracy, the energy is overestimated of approximately 4% by the classical simulation.

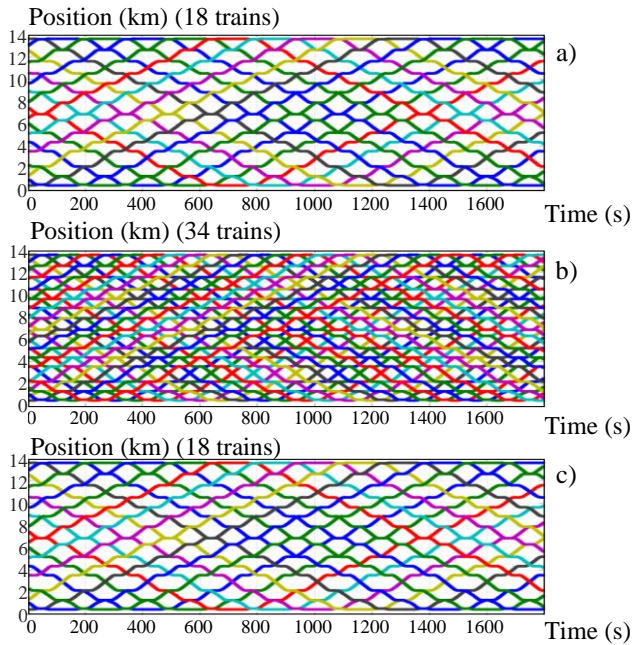


Fig. 8. Positions of trains: a) actual, b) solution 1, c) solution 2.

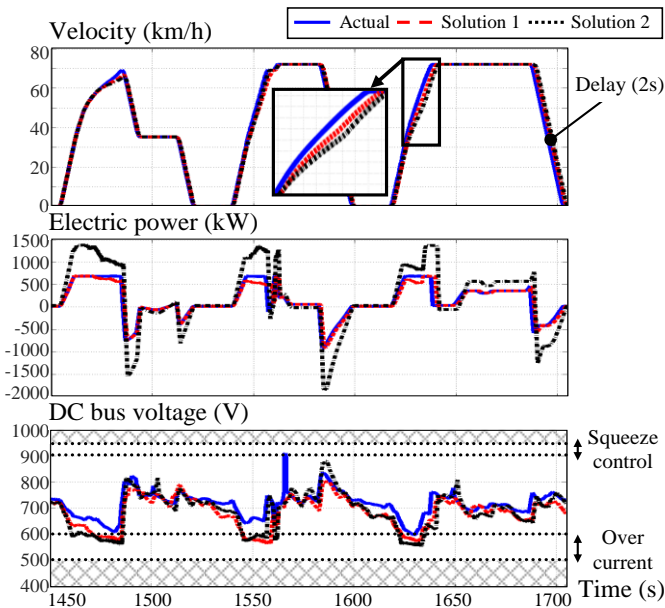


Fig. 9. Simulation results of one train (adaptive simulation).

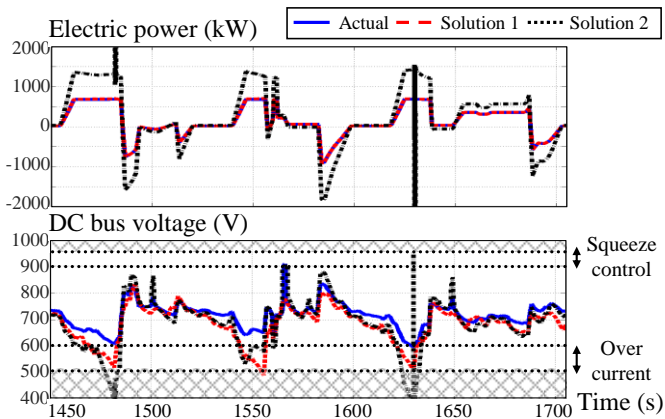


Fig. 10. Simulation results of one train (classical simulation).

C. Increase of the transport capacity: Results

The adaptive electro-kinematical simulation is used to compare solutions 1 and 2. It allows the estimation of the physical behavior of the system even in limitations. By this way the accuracy is better than using the classical simulation. Table III summarizes the mains results during the rush hours. Solution 1 is more comfortable for passengers because it reduces the waiting time between trains. Furthermore, due to the numerous trains in operation, more exchanges of energy between the trains are achieved, which smooths the power consumption at TPS (Fig. 10). However, the energy consumption is higher with solution 1 than with solution 2 (+10.3%). Indeed, solution 1 requires 33.7 Wh/p.km compared to 30.2 Wh/p.km. It is due to the increase of the total front surface (more trains in operation), which impacts the resistive force and requires more traction energy (Fig. 10).

VI. CONCLUSION

An adaptive electro-kinematical simulation has been proposed for flexible energetic studies of railway systems. It consists in coupling the electro-mechanical and the kinematical models. In comparison with classical simulation, the adaptive simulation does not use a reference velocity profile but generates automatically an adaptive velocity according to the constraints of the system. It can thus study the impact of mechanical (torque constraints) or electrical (squeeze control and over-current protection) limitations on the kinematical behavior (velocities, accelerations, jerks, etc.). The proposed simulation has been experimentally validated.

The interest of such a simulation has been assessed using a concrete study. Two solutions, which increase the transport capacity of an overloaded subway line, have been compared. The first one reduces the headway between trains. The second one uses heaviest trains with more cars. With both solutions, the over-current protection is activated, which conducts to limit the vehicle performances. The simulation has enabled to adapt the generated adaptive velocity according to these constraints. Simulation results have highlighted drawbacks and advantages for both solutions. Solution 1 reduces the maximal TPS powers, whereas solution 2 reduces energy consumption. Such studies would not be possible without the developed adaptive electro-kinematical simulation.

This simulation tool could also be extended to take into consideration the disturbances and system uncertainties in the design and simulation process of the studied system. Such methods have been developed in robotic field [41], [42] and could be adapted to railway systems.

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TABLE III
OPERATIONS OF THE SUBWAY SYSTEM DURING RUSH HOURS

	Actual	Solution 1	Solution 2
Headway (s)	148	74	148
Number of trains	18	34	18
Number of cars per train	2	2	4
Transport capacity (p.km/h)	95 025	190 140	190 080
Travel distance in 1h (km)	633.5	1267.6	633.6
Total energy in 1h (kWh)	3015.6	6403.2	5745.5
Energy for 1 passenger over 1 km (Wh/p.km)	31.7	33.7	30.2

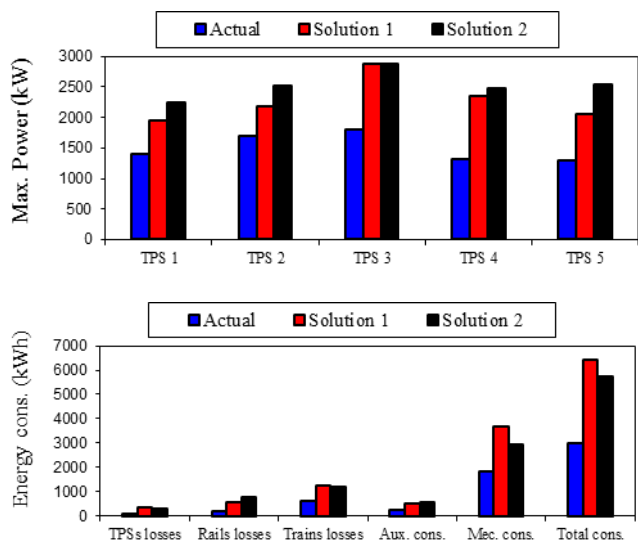


Fig. 10. Comparisons between actual case, solution 1 and solution 2.

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