Design a Realistic Performance of a Passenger Train

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Abstract

The main goal of this paper is to design a realistic performance of a passenger train for regional service and study its energy consumption and running time. For this purpose a mathematical model of the train has been developed, that allowsdetermining time evolution of the speed, acceleration, energy consumption and the distance travelled. Running times defined for different braking modes allowed as to develop an optimal schedule in order to meet time window constraints for terminal and intermediate stations. Limitations due to safety regulations, comfort and others were taken into account.

Keywords **—**energy consumption, high-speed, train performance.

I. LIST OF NOTATION

F_c	Centrifugal force
M	Loaded train mass
M_E	Empty weight of the train
M_{Eq}	Equivalent mass
H_W	Percentage of the rotational inertial effect
v	Speed
h	Cant
d	Rail gauge
a_l	Lateral acceleration
R	Curvature radius
β	Loss coefficient
α_{Lim}	Adhesion limit
P_W	Traction power
F_α	Adhesion limit force
F_{MAX}	Starting tractive effort
F_g	Grade resistance
F_{cv}	Curvature resistance
F_r	Running resistance
F_{REG}	Regenerative braking force
g	Free fall acceleration
i	Slope (negative or positive) in %
a	Acceleration
t	Time
E	Energy usage
η	Train's efficiency

II. INTRODUCTION

The main goal of this paper is to design realistic performance of a passenger train for regional service and study it energy consumption and running times.

The length of the line equals to 200km, it has 7 intermediate stations and two terminal stations where passengers take connection train, which departs 2 minutes after and arrives 2 minutes before each even hour in both directions, and vice versa.

During peak hours there are 350 passengers at the intermediate stations and 200 passengers at the terminate stations. The expected average load factor during peak hours equals 65%.

III. THE LINE

The line being considered is a single track line of 200 km, connecting stations A and I. The line electrified and equipped with ATC/ATP systems. Meeting stations on the line have switches allowing 70km/h. Line section A-E (60km) has three intermediate stations, B, C, D, which are located along the line with the same equidistance of 15km. The line section has many curves of 595m radius and there is no sense to travel faster than the curves permit. Typical super elevation is 140mm, but can be adjusted within permissible limits. The track is horizontal and the resent permissible speed 160km/h.

The line section E-G is of 100km, this line section has only one intermediate station F, which is located 60km from station E and 40km from station G. There are plans, however, to locate three more stations in the future. There are grades at each side of the station F. Line section E-F has a grade of 5‰ which starts 1.5km after station E and ends 4km before station F. Line section F-G has a down-grade of 7.5‰ which starts 700m after station F and ends 1.5km before station G.

The last section G-I has length of 40km with only one intermediate station H which is located in between G and I. Curves with 1000m radius are frequently present and there is no sense in travelling faster than these curves permit. The present super elevation is 135-140mm. The vertical track profile is mostly horizontal, except for a few grades. The signaling system permits for the moment 200km/h.

IV. PRELIMINARY CALCULATIONS

Since the first and the third sections of the line have a lot of curves on its way it is necessary to calculate maximum speed for these sections taking into account curvature of the line.

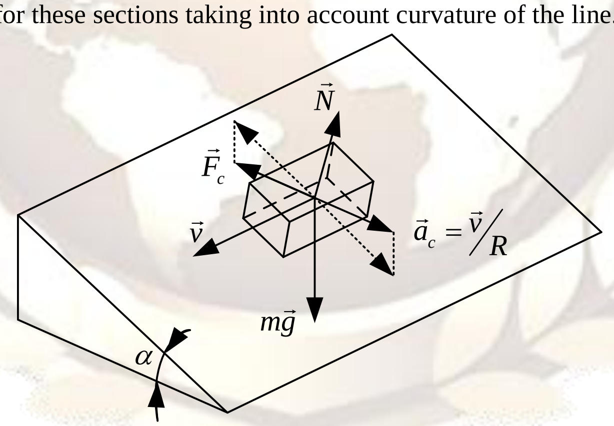

Figure 1. Force diagram of the train in an inclined plane

Projecting forces on the same axle we obtain:

$$F = F_c\,Cos(\alpha) - mg\,Sin(\alpha) \qquad \text{(IV.1)}$$

Since the super elevation angle (α) is usually a small value, we can make the following simplifications:

$$Sin(\alpha)\big|_{\alpha\to 0} = \alpha = h/d;\ \ Cos(\alpha)\big|_{\alpha\to 0} = 1 \qquad \text{(IV.2)}$$

Therefore, equation (IV.1**)** casts into:

$$ma = m\,v^2/R - mg\,h/d \qquad \text{(IV.3)}$$

So, the maximum speed on curves would be

$$v = \sqrt{R\left(a_l + \frac{h}{d}g\right)}\left[{}^{m}\!/\!{}_{s}\right] \qquad \text{(IV.4)}$$

According to the literature, a comfortable value of the lateral acceleration on passenger is $\alpha_l = 0.65\left[{}^{m}\!/\!{}_{s^2}\right]$ [6]. For the standard gauge (d=1435mm) and h=140mm, maximum speed for the section A-E equals 111.2km/h and for the section G-I 144.2km/h.

Going round a curve tilting trains tilt to the same side that the curve allowing the train to reach higher speeds and assuring comfort of the passengers. Thus, the super elevation angle is increased, so is the maximum speed allowed in the curve (without increasing the lateral acceleration). Therefore, a train with a tilt angle of 3.5 degrees has been chosen for this line. Replacing super elevation in equation (IV.4) with maximum speed for the first sections becomes 130km/h and for the third section 169km/h.

$$h_t = h + d\,Sin(3.5^o) = 227mm \qquad \text{(IV.5)}$$

V. Train Performance

During peak hours there are 350 passengers at intermediate stations and 200 passengers at terminal stations, with expected load factor of 65%. There are also time windows constraints for the terminal stations, our trains have to arrive before connection trains arrive and depart after they depart, in order to passengers were able to make a change. For this purpose Siemens Velaro-E train set have been chosen.

Table 1. Technical data of the train

Maximum speed	350 km/h
Length of train	200 m
Empty weight	439 t
Voltage	25kV/50Hz
Traction power	8800kW
Gear ration	2.62
Starting tractive effort	283kN
Brake systems	Regenerative, rheostatic, pneumatic
Number of axles	32(16 driven)
Wheel arrangement	Bo'Bo'+2'2'+Bo'Bo+2'2'+2'2'+Bo'Bo'+2'2'+Bo'Bo'
Acceleration 0-320km/h	380s
Braking distance 320-0km/h	3900m
Number of cars	8
Number of seats	405

The adhesion limit is calculated with Curtis-Kniffler empirical formula

$$\alpha_{Lim} = \frac{7.5}{44 + 3.6v} + 0.161 \qquad \text{(V.1)}$$

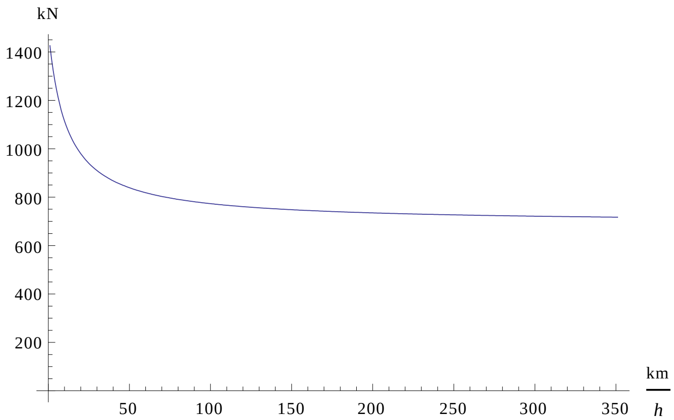

Figure 2. Adhesion limit curve

With technical data of the train we can build tractive effort diagram, regenerative braking effort diagram and running resistance.

$$F = {P_W}/{v}\,[kN] \qquad \text{(V.2)}$$

Running resistance can be calculated with the following empirical formula

$$F_r = C + Bv + Av^2[kN] \qquad \text{(V.3)}$$

where coefficients A, B and C have been taken from the manufacturer data. In the formula (V.3) rolling resistance is in coefficients A and B, and Air drag in coefficients B and C.

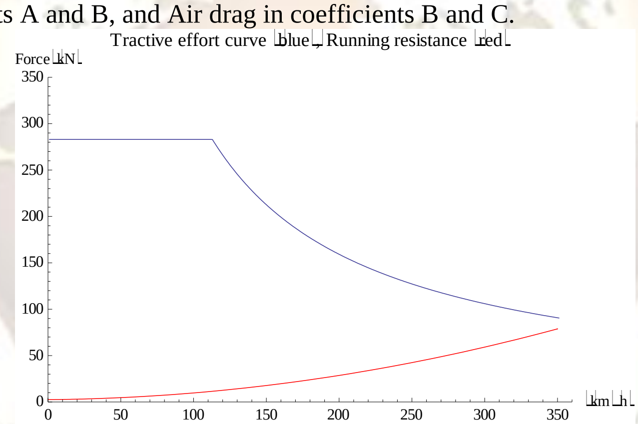

Figure 3. Tractive effort and Running resistance

Calculating running resistance in different sections we also have to take into account grade resistance for the 2nd section and curvature resistance for the 1st and the 3rd sections.

$$F_g = Mg\frac{i}{1000}[kN] \qquad \text{(V.4)}$$

$$F_{cv} = Mg\frac{K/R}{1000}[kN] \qquad \text{(V.5)}$$

where *i* represents grade in ‰(per mil), K=900 for the standard gauge.
Regenerative braking curve of the train is given by manufacturer [5].

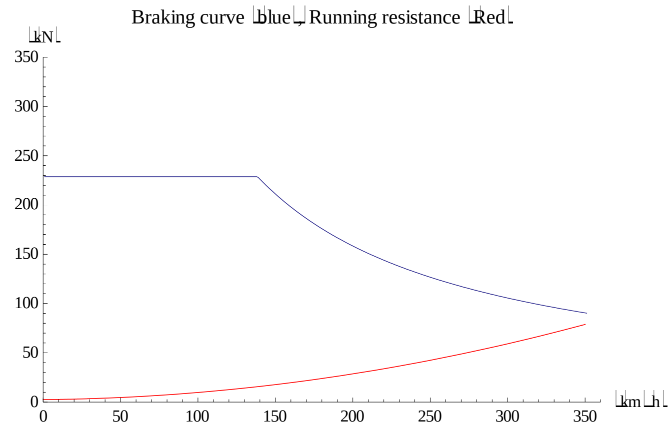

Figure 4.Regenerative braking effort and Running resistance.

VI. MODEL DESCRIPTION

In order to define running times and energy consumption we built up a mathematical model with software package Wolfram Mathematica.The model's logic is expressed in the following flow chart

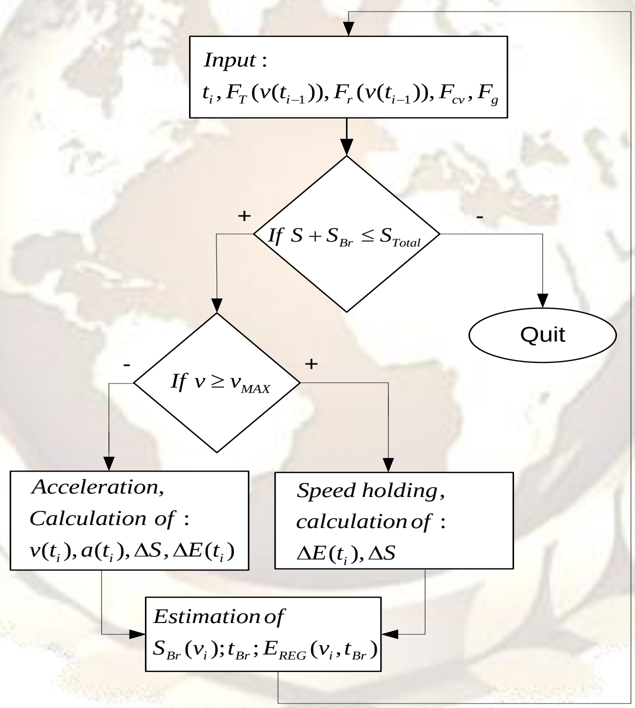

Figure 5. Simulation model flow chart

As it can be seen, at the input of the model we introduce running resistance, tractive effort, braking effort as functions of speed, and curvature resistance and grade resistance if they present in the current line section. With this data we start simulation of each section, calculating speed, acceleration, energy consumption and distance travelled per each second. At the same time, for each iteration we estimate time *(t_{Br})* and distance needed to brake *(S_{Br})* as a function of current speed, taking into account grade and curvature resistance. Calculation stops if travelled distance + braking distance exceed length of the line section.
As an output of this model we obtain running time, acceleration time, speed holding time, braking time, and energy consumption (generation) and speed evolution per each section.

VII. RUNNING TIMES

Using mathematical model running times have been calculated for regional trains running from A to I and from I to A for pure regenerative and blended braking modes.

As it can be seen in Table 2, it takes 5838 seconds (97.3 min) to go from the station A to I and 5801 second (96.3 min) running form I to A with pure regenerative braking.

In case of blended braking, deceleration assumed to be constant and equal 0.55 (m/s^2), the running times presented in the Table 3. Comparing running times for both cases, it takes 60 seconds longer to get from A to I with pure regenerative braking and about 25 seconds longer running from I to A with pure regenerative braking.

Since connection trains leave at each even hour our train has to arrive before and leave after connection train, so the passengers were able to make a change. Therefore, in our case it is preferable to use regenerative braking, because there is only 1 min difference running from A-I and about 30 seconds difference running from I to A, and in both cases we fit into our time windows constraints. In the Figure 6 you can see Speed evolution through the distance running from A to I and in the Figure 7 running from I to A with pure regenerative braking mode.

Direction	From A to I																
	A		B		C		D		E		F		G		H		I
Distance (km)		15		15		15		15		60		40		20		20	
Travel Time (s)		484	60	484	60	484	60	484	120	907	60	667	120	511	60	511	
Time Margin 5% (s)		24.2		24.2		24.2		24.2		45.35		33.35		25.55		25.55	
Extra time (s)		45		45		45		45		180		120		60		60	
Total (s)		553.2		553.2		553.2		553.2		1132.35		820.35		596.55		596.55	
Total (s)	5838.6																
Direction	From I to A																
	A		B		C		D		E		F		G		H		I
Distance (km)		15		15		15		15		60		40		20		20	
Travel Time (s)		484	60	484	60	484	60	484	120	854	60	685	120	511	60	511	
Time Margin 5% (s)		24.2		24.2		24.2		24.2		42.7		34.25		25.55		25.55	
Extra time (s)		45		45		45		45		180		120		60		60	
Total (s)		553.2		553.2		553.2		553.2		1076.7		839.25		596.55		596.55	
Total (s)	5801.85																

Table 2. Running times of the regional train running from A to I with pure regenerative braking

Direction	From A to I																
	A		B		C		D		E		F		G		H		I
Distance (km)		15		15		15		15		60		40		20		20	
Travel Time (s)		478	60	478	60	478	60	478	120	881	60	613	120	506	60	506	
Time Margin 5% (s)		23.9		23.9		23.9		23.9		44.05		30.65		25.3		25.3	
Extra time (s)		45		45		45		45		180		120		60		60	
Total (s)		546.9		546.9		546.9		546.9		1105.05		763.65		591.3		591.3	
Total (s)	5778.9																
Direction	From I to A																
	A		B		C		D		E		F		G		H		I
Distance (km)		15		15		15		15		60		40		20		20	
Travel Time (s)		478	60	478	60	478	60	478	120	824	60	668	120	506	60	506	
Time Margin 5% (s)		23.9		23.9		23.9		23.9		41.2		33.4		25.3		25.3	
Extra time (s)		45		45		45		45		180		120		60		60	
Total (s)		546.9		546.9		546.9		546.9		1045.2		821.4		591.3		591.3	
Total (s)	5776.8																

Table 3. Running times of the regional train running from A to I with blended braking

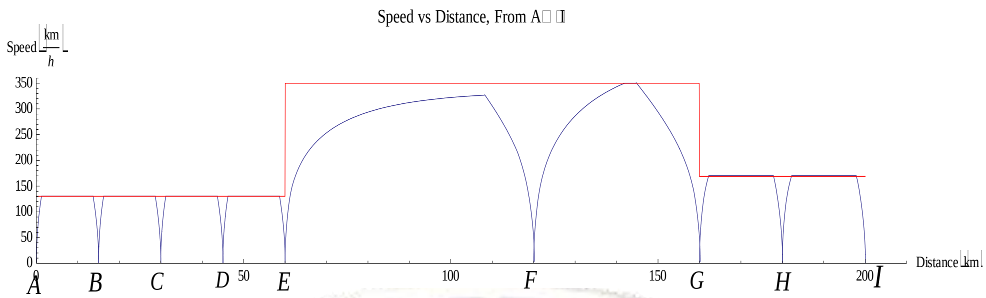

Figure 6. Speed vs Distance graph of the regional train running from A to I

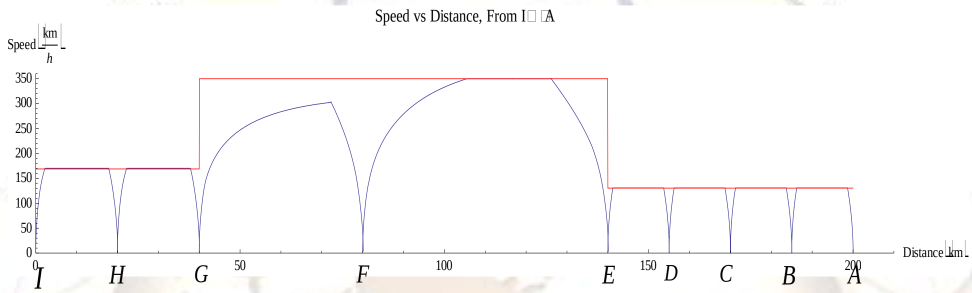

Figure 7. Speed vs Distance graph of the regional train running from I to A

VIII. Timetable

It is required to introduce regional trains in both directions. Regional trains have stopping time of about 8 min at stations A and I because passengers need to make a change to connecting trains. The stopping time at the intermediate stations E and G must be at least 2 min. At other stations, 1 min is considered to be enough. Our regional train departs every even hour in both directions in order to satisfy the passenger flow. Since connection train arrives 2 minutes before each even hour and departs 2 minutes after, therefore our regional train has to arrive before connection train arrives and depart after connection train departs. It is also necessary to include a 5% time margin and also extra time table margin of about 5min per 100km. With these data and running times taken from the Table 2 the following time table has been designed.

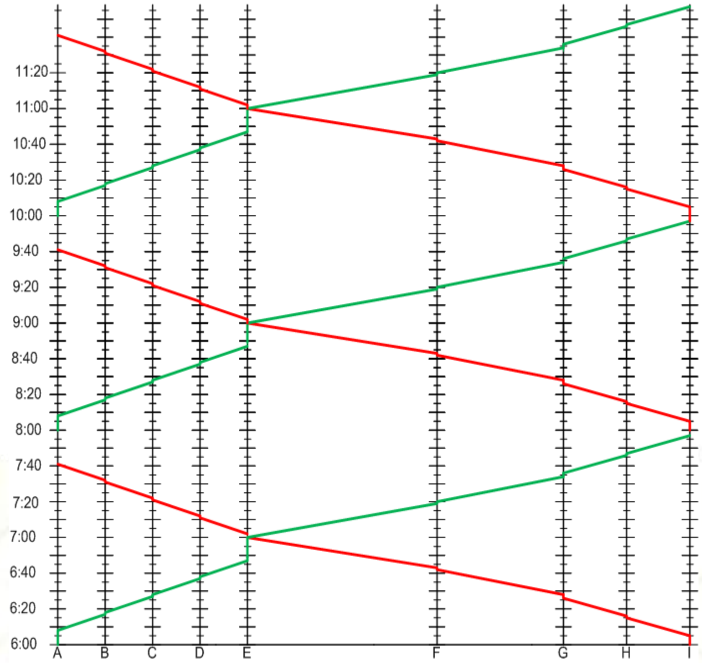

Figure 8. Timetable

IX. ENERGY CONSUMPTION

The energy consumption of the regional trains running in both directions has been calculated for both, regenerative and blended braking modes.Results are shown in Table 4 and 5.

A. Traction

To calculate energy consumption when the train accelerates to achieve maximum speed the following equation has been used

$$E_i = \frac{\left(F_{wi} v_i (1+\zeta)\right)\Delta t_i}{\eta}[W] \qquad \text{(IX.1)}$$

replacing slippage with

$$\zeta \approx \frac{\omega r - v}{v} \qquad \text{(IX.2)}$$

Equation (IX.1) casts into

$$E_i = \frac{\left(F_{wi} v_i\right)\Delta t_i}{\eta}[W] \qquad \text{(IX.3)}$$

replacing

$$\begin{gathered} M_{Eq} a = F_T(v) - (F_r(v) + F_g + F_{cv}) \ or \\ F_T(v) = M_{Eq} a + (F_r(v) + F_g + F_{cv}) \end{gathered} \qquad \text{(IX.4)}$$

we obtain

$$E_i = \frac{M_{Eq} a(v_i) v_i \Delta t_i + (F_r(v_i) + F_g + F_{cv}) v_i \Delta t_i}{\eta \ 3.6 * 10^6}[kWh] \qquad \text{(IX.5)}$$

B. Speed holding

When the train achieves the maximum speed, traction force must overcome running, grade and curvature resistance for speed holding. Therefore, acceleration in these moments is 0 and energy usage equals

$$E_i = \frac{(F_r(v_{MAX}) + F_g + F_{cv}) v_{MAX} \Delta t_i}{\eta \ 3.6 * 10^6}[kWh] \qquad \text{(IX.6)}$$

C. Regenerative Braking

Energy generation during regenerative braking can be calculated with the following formula

$$E_i = \frac{\eta F_{REG} v_i (1+\upsilon)\Delta t_i}{3.6*10^6}[kWh] \qquad \text{(IX.7)}$$

wherecreepage equals

$$\upsilon \approx \frac{v-\omega r}{v} \qquad \text{(IX.8)}$$

and

$$\begin{gathered} M_{Eq} a = F_{REG}(v) + (F_r(v) + F_g + F_{cv}) \ or \\ F_{REG}(v) = M_{Eq} a - (F_r(v) + F_g + F_{cv}) \end{gathered} \qquad \text{(IX.9)}$$

replacing everything we obtain:

$$E_i = \frac{\eta (M_{Eq} a(v) - (F_r(v) + F_g + F_{cv})) v_i \Delta t_i}{3.6*10^6}[kWh] \qquad \text{(IX.10)}$$

D. Blended braking

In case of blended braking we use combination of regenerative and mechanical braking. A constant deceleration of 0.55 m/s^2 in this case assumed

$$E_i = \frac{\eta (M_{Eq} *0.55 - (F_r(v_i) + F_g + F_{cv})) v_i \Delta t_i}{3.6*10^6}[kWh] \qquad \text{(IX.11)}$$

Energy consumption has been calculated with help of simulation model described in the section VI. Within this model we can calculate energy consumption of the train per each second of the trip (for acceleration, speed holding and braking). Auxiliary systems and comfort systems power consumption assumed equal 25kWh per car. Simulation results are presented in Table 4 and Table 5.

Energy consumption (kWh) (From A to I)																			Total | per pas*km
		A		B		C		D		E		F		G		H		I	
Regenerative braking	Traction		114.4		114.4		114.4		114.4		1861.01		905.1		195.6		195.6		2671.69
	Speed holding		85.8		85.8		85.8		85.8		0		41		132.1		132.1		
	Braking		-80.44		-80.44		-80.44		-80.44		-644.2		-711.3		-135.8		-135.8		
	Aux. & Comfort stms		147.52								130.18				79.54				0.05
Blended Braking	Traction		114.4		114.4		114.4		114.4		2022		905		195.6		195.6		3142.36
	Speed holding		87.1		87.1		87.1		87.1		0		147		132.1		132.1		
	Braking		-79.5		-79.5		-79.5		-79.5		-567.1		-588.4		-134.4		-134.4		
	Aux. & Comfort stms		145.84								124.58				78.84				0.06
Pure Mechanical Braking	Traction		114.4		114.4		114.4		114.4		2022		905		195.6		195.6		4884.66
	Speed holding		87.1		87.1		87.1		87.1		0		147		132.1		132.1		
	Braking																		
	Aux. & Comfort stms		145.84								124.58				78.84				0.09

Table 4. Energy consumption (kWh) running from A to I

Energy consumption (kWh) (From I to A)																			Total | per pas*km
		A		B		C		D		E		F		G		H		I	
Regenerative braking	Traction		114.4		114.4		114.4		114.4		1029.1		1382.09		195.6		195.6		2756.92
	Speed holding		85.8		85.8		85.8		85.8		378.2		0		132.1		132.1		
	Braking		-80.44		-80.44		-80.44		-80.44		-709.9		-540.2		-135.8		-135.8		0.05
	Aux. & Comfort stms		147.52								127.73				79.54				
Blended Braking	Traction		114.4		114.4		114.4		114.4		1029.1		1468.7		195.6		195.6		3080.82
	Speed holding		87.1		87.1		87.1		87.1		496.5		0		132.1		132.1		
	Braking		-79.5		-79.5		-79.5		-79.5		-633.1		-504.8		-134.4		-134.4		0.06
	Aux. & Comfort stms		145.84								124.44				79.54				
Pure Mechanical Braking	Traction		114.4		114.4		114.4		114.4		1029.1		1468.7		195.6		195.6		4805.52
	Speed holding		87.1		87.1		87.1		87.1		496.5		0		132.1		132.1		
	Braking																		
	Aux. & Comfort stms		145.84								124.44				79.54				0.09

Table 5. Energy consumption (kWh) running from I to A

X. CONCLUSIONS

From this study some conclusions can be outlined:

- It is possible to increase maximum speed in curves with a tilting train, higher tilting angle gives higher speed.
- Selected train shows very good performance and great running times comparing with others. With this train it is only necessary to introduce one train per two hours in each direction, while for other trains it is necessary to introduce one train per hour in order to meet passenger flow requirements and time windows constraints for terminal stations.
- Running time increases using pure regenerative braking instead of blended or pure mechanical braking, as it was expected. However this time difference is not that significant, unlike difference in power consumption.
- The lowest energy consumption is achieved with pure regenerative braking. Difference between blended braking and regenerative braking is about 300-500kWh and energy consumption with pure mechanical braking is almost twice higher than pure regenerative braking.
- Difference in running times between pure regenerative braking and blended/pure mechanical braking is about 30-60 seconds, depending on direction. However difference between energy consumption is about 300-500kWh, so there is no sense of using blended or pure mechanical braking instead of regenerative braking.
- It is possible to decrease power consumption by developing more sophisticated model that takes into account time margins and uses it for more energy efficient driving.

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