



---

# MODURBAN

**FP6 Project: IP 516380**

**EC Contract n°: TIP4-CT-2005-516380**

---

---

## MODONBOARD SUBPROJECT

**– DELIVERABLE REPORT –**

---

Deliverable ID:	<b>D10 - FINAL</b>
Deliverable Title:	Intelligent Automatic driver specification and simulation report
Responsible partner:	ALSTOM
Contributors:	WP2 Partners

**PROPRIETARY RIGHTS STATEMENT**

This document contains information, which is proprietary to the MODURBAN Consortium. Neither this document nor the information contained herein shall be used, duplicated or communicated by any means to any third party, in whole or in parts, except with prior written consent of the MODURBAN consortium.



## Document Information

**Document Name:** Intelligent Automatic driver specification and simulation report  
**Document ID:** D10  
**Revision:** Final V2  
**Revision Date:** 2006-06-30  
**Author:** WP2 Partners  
**Security:** MODURBAN Consortium only

## Approvals

	Name	Company	Date	Visa
<i>Technical Management Committee</i>	B. VON WULLERTSORFF J. CAPEY/L. DURET G. JACQMIN G. LEGOFF A. PETERS U. HENNING M. NOCK JP RICHARD/D. COINEAU Y. AMSLER E. MACRON/S. GAMEZ	UNIFE ALSTOM ALCATEL CSEE BOMBARDIER SIEMENS KNORR BREMSE RATP UITP ALMA	11/09/2006	OK
<i>Coordinator</i>	Bernard VON WULLERSTORFF	UNIFE	15/09/2006	OK
<i>Quality Manager</i>	Bernard VON WULLERSTORFF Etienne MACRON	UNIFE ALMA	15/09/2006	OK

## Documents history

Revision	Date	Modification	Author
V1_A	060220	Creation	ALSTOM
V1_B	060321	Writing of test specifications (Section 5.1) Addition of paragraph on learning specification.(Section 3.1)	ALSTOM
V1_C	060423	Modification of figure 2,3 and 4 to be more explicit Writing of detection module specification (Section S4) Addition of description of the principle of learning and adaptation used for simulation. Writing of section test results (Section 5.3)	ALSTOM
V1_D	060519	Modification asked by WP2 partners comments Addition of section 5: Interface with rolling stock	ALSTOM
V2	060630	Modification following Siemens and Alstom comments: mainly section 3 last paragraph and figures and section 4 last paragraph. Description of alarm "Instability of the command"	ALSTOM



The scope of the document applies to:

Metro systems only	Metro and Light Rail		Light Rail only
	<i>With no differentiation</i>	<i>With specific adaptation(s)/recommendation(s) (1)</i>	
		<i>For metro</i>	
<b>X</b>			

(1) – Put a [D] if these adaptations/recommendations are present in the document and a [L] if they will have to be detailed later.



## SECTION I – DELIVERABLE SUMMARY

### D10 Intelligent Automatic driver specification and simulation report

<b>Deliverable ID , associated WP &amp; Subproject</b>	D10: Intelligent Automatic driver specification and simulation report MODONBOARD / WP2
<b>Type of Deliverable</b>	Specification
<b>Input / Starting stage</b>	-
<b>Output / Final stage</b>	<i>Technical specifications</i>

<b>Lead partner(s)</b>	
<b>Achievement to date (%)</b>	100 %
<b>Expected date of achievement</b>	Month 18
<b>Type of exploitation</b>	<i>Inputs for further WP's work</i>
<b>Exploitation potential</b>	-
<b>Expected budget</b>	<i>See MODONBOARD Budget</i>
<b>Actual costs</b>	<i>See MODONBOARD actual costs</i>
<b>Expected costs to completion</b>	-
<b>Protection</b>	<i>Not Relevant</i>
<b>Protection date</b>	<i>Not Relevant</i>

<b>IP's</b>	<b>Partners, (type, identification, date)</b>
<b>Pre-existing Know-How</b>	
<b>Exploitation Rights</b>	

<b>Associated Risk analysis</b>	<b>Type, solution envisaged, action, actors</b>	<b>Actual Reduction</b>
<b>Before start</b>		
<b>During task implementation</b>		



## D10: Intelligent Automatic driver specification and simulation report

### **Deliverable Abstract**

Objective of WP2 is to think about an intelligent driving to tackle with the problem of time varying train parameters, ageing of train and discrepancies on train parameters of a whole fleet. Intelligent driving will modify the train control in case the command is no more able to reach asked ATC performances. When this adaptation is needed, alarms shall be sent to warn operations staff.

Objective of D10 is to pave the way for future research and implementation of intelligent driving. To do so, first part of the deliverable is specifying intelligent driving by describing alarms and giving several algorithms of adaptations. Second part defines interface between rolling stock and intelligent driving which could be useful to perform efficient learning. Finally simulations performed to test a first reflection on intelligent driving are described.

### **Associated Milestone (if relevant):**

## TABLE OF CONTENT

<b>1. S1 – INTRODUCTION</b> .....	<b>8</b>
1.1. Document Organisation:.....	8
1.2. Objectives: .....	8
1.3. Conventions:.....	8
1.4. Definition: .....	9
<b>2. S2 – INTELLIGENT DRIVING INTRODUCTION</b> .....	<b>11</b>
2.1. Definition of the intelligent driving .....	11
<b>3. S3 – DETECTION MODULE SPECIFICATION</b> .....	<b>12</b>
3.1. Detection specification .....	12
3.2. Alarms specification .....	13
3.2.1. Actual braking different from the one provided by the model .....	14
3.2.2. Over-braking train – Under-braking train .....	14
3.2.3. Gap of braking force before and after substitution too high.....	15
3.2.4. Mechanical braking respond time out of range .....	15
3.2.5. Train at limit of pilotability .....	15
3.2.6. Train out of range of pilotability .....	15
3.2.7. Instability of the command .....	16
3.2.8. Risk of inaccurate stopping .....	16
3.2.9. Insufficient stopping accuracy .....	16
<b>4. S4 – ADAPTATION SPECIFICATION</b> .....	<b>18</b>
<b>5. S5 – INTERFACE WITH ROLLING-STOCK</b> .....	<b>20</b>
<b>6. S6 – SIMULATION</b> .....	<b>21</b>
6.1. Tests environment.....	21
6.2. Tests specification .....	22
6.3. Results and analysis .....	23
6.3.1. Progressive increase of $K_{PB}$ .....	23
6.3.2. Variation of $K_{PB}$ .....	25



## **TABLE OF FIGURES**

Figure 1 : Intelligent driving principle..... 11

Figure 2 : Case 1 ..... 12

Figure 3 : Case 2 ..... 12

Figure 4 : Case 3 ..... 13

Figure 5 : Groups of alarms..... 14

Figure 6 : Actual braking different from the one provided by the model ..... 14

Figure 7 : Train at limit of pilotability ..... 15

Figure 8 : Train out of range of pilotability ..... 16

Figure 9 : Risk of inaccurate stopping ..... 16

Figure 10 : Insufficient stopping accuracy ..... 17

Figure 11 : Algorithm 1 ..... 18

Figure 12 : Algorithm 2 ..... 18

Figure 13 : Algorithm 3 ..... 19

Figure 14 : Algorithm 4 ..... 19

Figure 15 : Control loop ..... 21

Figure 16 : Logical controller ..... 21

Figure 17 : Anti-windup PID..... 22

Figure 18 : Simulation description ..... 22

Figure 19 : Tests specification ..... 23

Figure 20 : Tests 1 results ..... 24

Figure 21 : Tests 2 results ..... 25



## SECTION 2 – DELIVERABLE DETAILED DESCRIPTION

### 1. S1 – INTRODUCTION

The objective of this document is to report on the design and validation of the first intelligent driving prototype.

#### 1.1. Document Organisation:

This document is made of six sections:

**S1 – introduction:** This section addresses the objectives of the document, gives the list of variables used through the document and the standard used for formulas of physics.

**S2 – Intelligent driving introduction:** This section gives a general idea of the different functions needed to perform adaptation of the command.

**S3 – Detection module specification:** This section firstly specifies alarms sent to warn operations staff, this specification includes the description of the learning phase.

**S4 – Adaptation specification:** This section gives several possibilities of adaptations of the train command according to information coming from detection module.

**S5 – Interface with rolling stock:** This section specifies data to be provided by rolling stock.

**S6 – Simulation:** This section specifies the simulation performed to validate the intelligent driving, and gives analysis of the results.

#### 1.2. Objectives:

This document forms part of the Work Package 2 “Onboard Intelligent Driving” which objectives are, according to the [DOW] to define and develop an intelligent automatic driving for the ATO in order to tackle with the problem of time varying train parameters, ageing of trains and discrepancies between trains in a fleet. D10 is a first analysis of this concept and describes several possibilities of learning and adaptation. More complex and more efficient way of performing intelligent driving function may be developed in the future.

#### 1.3. Conventions:

All physical quantity data referred in this document are described using the international system of units, in accordance with standard for Use of the International System of Units (The Modern Metric System, IEEE/ASTM SI 10-2002).

All physical quantity data referred in this document are symbolised using the American National Standard Mathematical Signs and Symbols for Use in Physical Sciences and Technology (IEEE 260.3).

Following table gives the symbols and units of the main physical quantity used through the document.

Physical quantity	Unit	Symbol
Acceleration	$m.s^{-2}$	a
Speed	$m.s^{-1}$	v
Length	Meter (m)	s
Mass	Kilogram (kg)	m
Force	Newton (N)	f
Time	Second (s)	t
Voltage	Volt (V)	u

#### 1.4. Definition:

Following table gives the list of variables used through the document. Variables are not defined here but throughout the document:

Symbol	Definition
$\Delta a$	Gap of braking force before and after substitution in $m.s^{-2}$
a	in $m.s^{-2}$
$a^*$	in $m.s^{-2}$
$a_A^*$	limited acceleration command in $m.s^{-2}$
$a_b$	Acceleration offset appearing after substitution in $m.s^{-2}$
$a_c$	Acceleration set-point in $m.s^{-2}$
$a_d$	white noise on measurement in $m.s^{-2}$
$a_L$	Logical controller output in $m.s^{-2}$
$a_{maximum}$	Maximum acceleration of the train in $m.s^{-2}$
$a_{JKL}$	Jerk Limited Acceleration Command in $m.s^{-2}$
$a_{train}$	Acceleration of the train in $m.s^{-2}$
$a_{desired}$	Desired deceleration for stopping accuracy
C	constant force in N
$C_{AERO}$	Aerodynamic coefficient in $N.m^2.s^2$ ( $Pa.s^2$ )
$C_{CURVE}$	Resistive coefficient due to curves in $m.N.kg^{-1}$
$C_{FRICTION}$	Friction coefficient in $N.kg^{-1}$
$C_{SLOP}$	Track slope in %
$C_{VISCIOUS}$	viscous coefficient in $N.m^{-1}.kg^{-1}.s$
$f_a$	applied force in N
$f_{CURVE}$	perturbation force due to curves in N
$f_{DRAG}$	perturbation force due to drag in N
$f_{PERT}$	perturbation force in N
$f_{SLOPE}$	perturbation force due to slopes in N
g	Gravity in $m.s^{-2}$
$JK_L$	rolling stock Jerk Limitation in $m.s^{-3}$

$K_{EB}$	Electric braking gain
$K_M$	Motoring gain
$K_{PB}$	Pneumatic braking gain
$m_d$	dynamic load of the train in kg, this mass include the rotating mass
$m_s$	static load in kg (this load is changing according to passenger mass)
$r_{CURVE}$	Track curvature radius in m
$s$	Laplace variable
$Satur_{Madrid}$	Constant taken from the Madrid Metro brake curves expressing the reduction of the maximum applicable electric brake force, it is nothing generic. Background is that the power an electric brake can generate is limited. (in $Nm.s^{-1}$ )
$S_{gMax}$	train's length in m
$S_{gx}$	length of the part of the train located on the track portion x in m
state	Actual state of the train (braking, coasting or motoring)
$S_{Train}$	Distance covered by the train in m
$t_{EB}$	Electric braking delay in s
$t_M$	Motoring delay in s
$t_{PB}$	Pneumatic braking delay in s
$U$	Voltage in V
$V_{\Delta a}$	Substitution speed in $m.s^{-1}$
$V_{Train}$	Speed of the train in $m.s^{-1}$
$V_{Target}$	Full speed of train in $m.s^{-1}$
$\tau_{EB}$	Electric braking time constant in s
$\tau_M$	Motoring time constant in s
$\tau_{PB}$	Pneumatic braking time constant in s

## 2. S2 – Intelligent driving introduction

### 2.1. Definition of the intelligent driving

The scope of the intelligent driving is to complete the feedback loop in order to improve the kinematical performances in term of :

- 1 : Acceleration/deceleration
- 2 : Speed
- 3 : Distance

For this purpose, the intelligent driving will:

- Learn the train parameters and verify their deviation
- Send alarms in order to warn operations staff about the train achievable performances in the point of view of ATC
- Adjust adaptive parameters if necessary in order to tackle with the deviation observed on the train

Intelligent driving is divided into two main functions: “train measurements - detection of train parameters deviation” and “Correction of the command according to measurements”. The first function is learning train parameters and is sending alarms while the second is adapting the control.

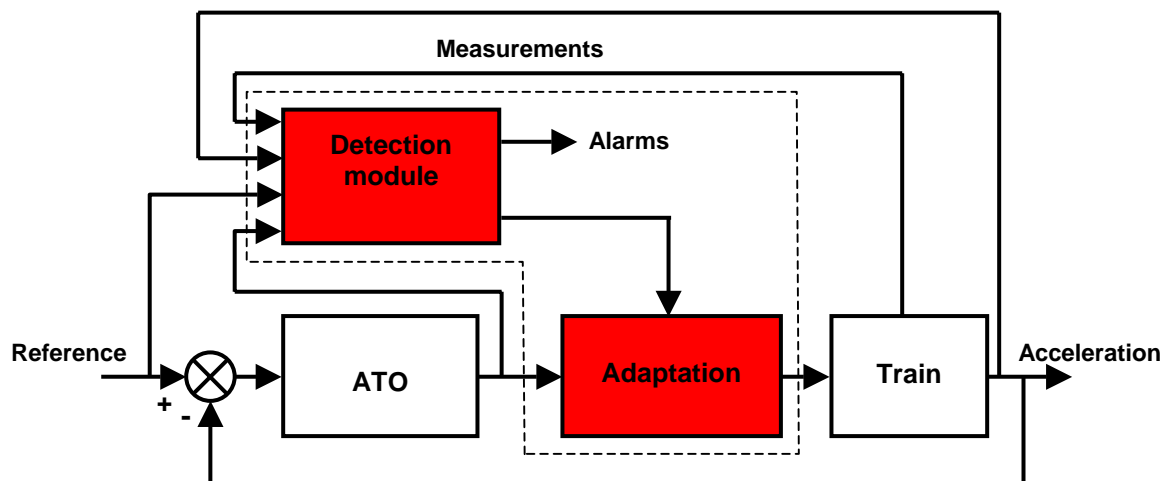


Figure 1 : Intelligent driving principle

Intelligent driving is specified around the stopping accuracy performance. This is including alarms and adaptations.

### 3. S3 – Detection module specification

Detection module is learning train parameters and is detecting deviations. If a deviation is detected as too important to reach ATC performances, it will send an alarm to warn operations staff and ask for a correction of the command.

Intelligent driving is specified to reach the stopping accuracy performance, therefore only alarms linked with *braking* are defined.

#### 3.1. Detection specification

The feedback loop includes the ATO and the intelligent driving but intelligent driving could be useful once train is out of the ATO range of pilotability. This leads to the following possibilities of functioning:

**Case 1:** Range of train parameters discrepancies is inside the ATO range of pilotability. ATO is able alone to command the whole fleet of train without involving intelligent driving. This configuration also allows a drift of train parameters up to the ATO range of pilotability..

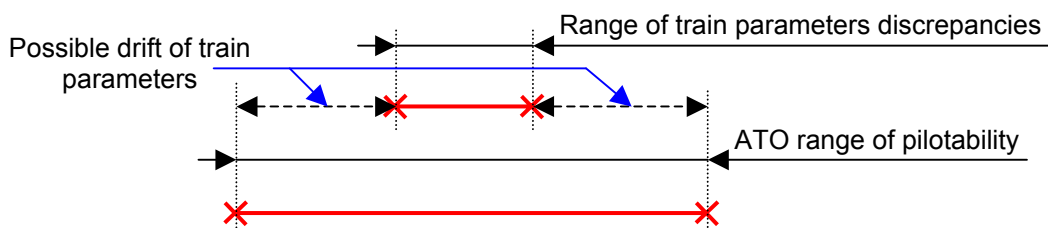


Figure 2 : Case 1

Detection module does not ask for modification of the command.

**Case 2:** Range of train parameters discrepancies is greater than the range of pilotability of the ATO. ATO is not able to control the train without intelligent driving improvement..

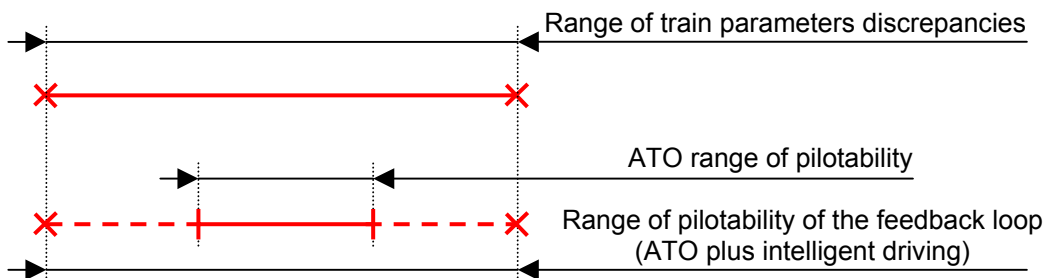


Figure 3 : Case 2

Detection module is asking the adaptation module to modify the command

**Case 3:** Range of train parameters discrepancies is greater than the range of pilotability of the ATO. Even with the intelligent driving improvement the range of pilotability of the whole feedback loop stays lower than the train parameters discrepancies. It is no more possible to control the train and ATC performances cannot be reached.

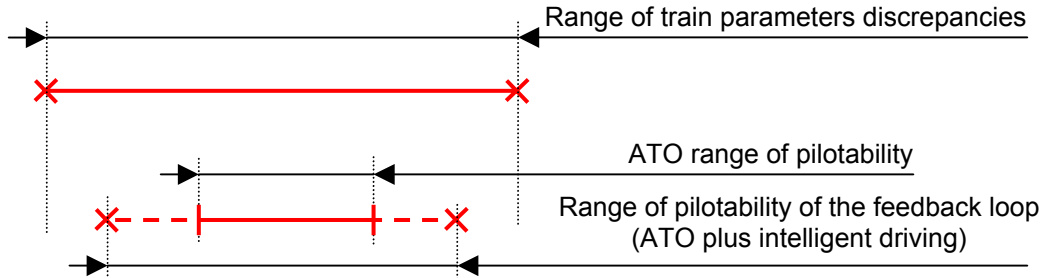


Figure 4 : Case 3

In this case, train is no more controllable even using the full range of adaptation. Detection module will ask for the maximum adaptation.

In each case detection module is “learning” train behavior using an iterative process. During each braking phases, the detection module is checking the ability of the feedback loop to reach stopping accuracy. If the module detects the necessity for the command to be adapted, it will ask adaptation module for a slight modification. This slight modification is applied if necessary, at the time of the next deceleration phases.

This iterative process brings the “learning” to be insensitive to temporary disturbances like greasy rail or tension drop for instance.

The intelligent driving must not encroach on the ATO control. Adaptation will therefore be performed with a time constant much higher than the ATO one. If this is not the case, the whole feed loop (ATO plus intelligent driving) will be instable, ATO trying to compensate intelligent driving and intelligent driving trying to compensate ATO.

### 3.2. Alarms specification

Alarms are used to warn operator staff and adaptation module about the train achievable performances from an ATC point of view. Alarms can be filed into three groups:

- First group: Alarms linked to the train model and parameters tolerances which are raised once a parameter value is out of a pre-defined range.
  - actual braking different from the one provided by the model
  - Over-braking train
  - Under-braking train
  - Gap of braking force before and after substitution too high
  - Response time out of range in braking
- Second group: Alarms linked to ATO are raised once the ATO alone is either no more able or at the limit to reach performances. These alarms are also partially based on first group.
  - Train at limit of pilotability
  - Train out of range of pilotability
  - Instability of the command
- Third group: Alarms linked to both the whole feedback loop (ATO plus intelligent driving) and train parameters tolerances are raised once the ATO plus intelligent driving is either no more able or at the limit for reaching performances.
  - Risk of inaccurate stopping
  - Insufficient stopping accuracy

The following figure shows the difference of concept between these three groups.

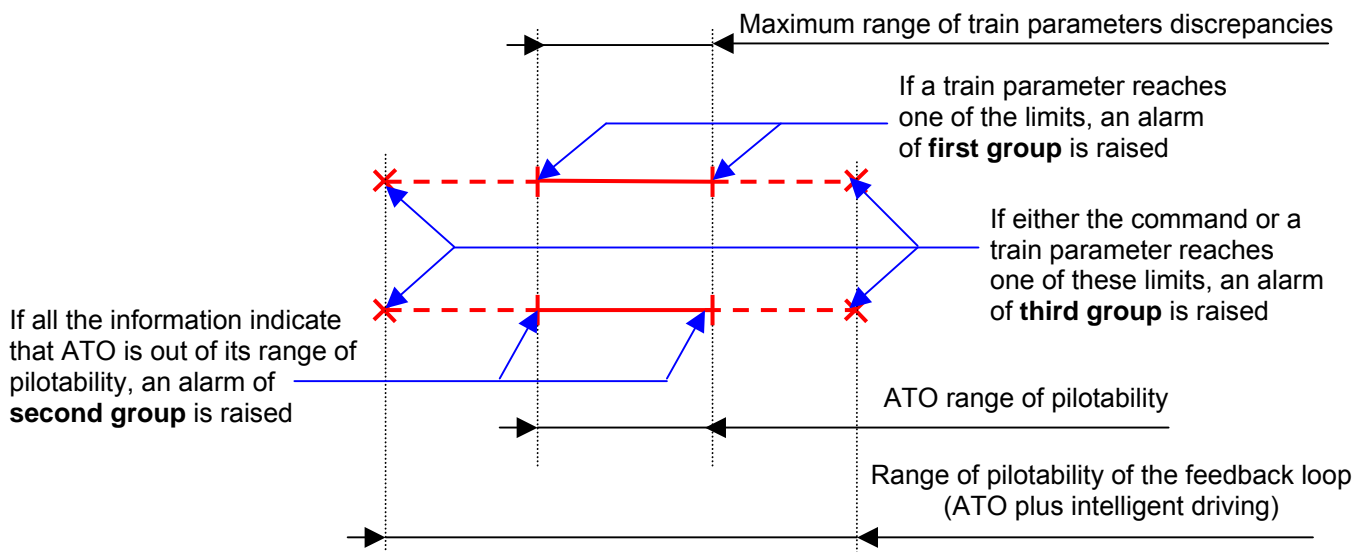


Figure 5 : Groups of alarms

Specification of each of these alarms is described in the following sections.

### 3.2.1. Actual braking different from the one provided by the model

Actual braking different from the one provided by the model warns operator as soon as deceleration is higher or lower than the expected one. The expected deceleration is included between under and over braking thresholds.

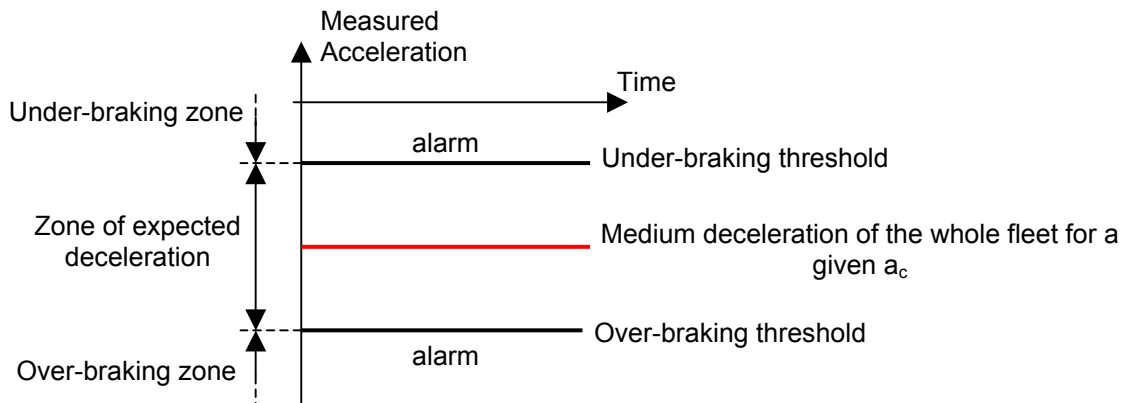


Figure 6 : Actual braking different from the one provided by the model

The two thresholds shall be defined according to rolling stock discrepancies between trains of the whole fleet.

### 3.2.2. Over-braking train – Under-braking train

Over-braking train alarm is raised when intelligent driving detects that during deceleration phase the measured deceleration is lower than the over-braking threshold.

Under-braking train alarm is raised when intelligent driving detects that during deceleration phase the measured deceleration is higher than the under-braking threshold

Contrary to actual braking different from the one provided by the model alarm, under and over braking train alarms are both raised in case the event appears at the time of several deceleration phases. This number of detections before raised alarms has to be defined with operators.

**3.2.3. Gap of braking force before and after substitution too high**

A large difference in the braking force of electrical and mechanical braking at the substitution point may cause the train to fail precise stopping according to the substitution speed and the response time of the closed loop.

Alarm Gap of Braking Effort Before and After Substitution Too High is raised as soon as the gap is detected higher than a predefined threshold. This threshold is defined such that according to rolling stock substitution speed, announced deviation between Electrical and Mechanical Brakes by Rolling Stock, and response time of the closed loop, the stopping accuracy could be degraded.

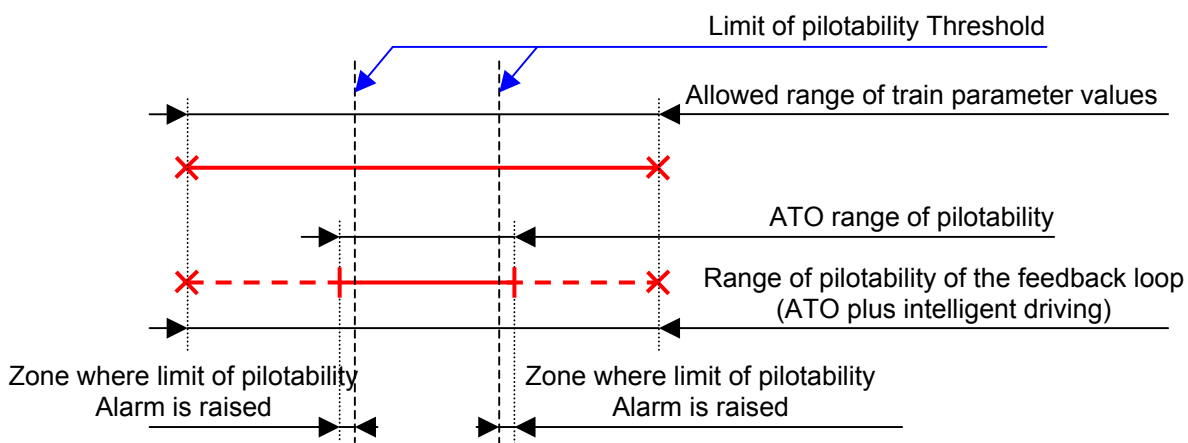
**3.2.4. Mechanical braking respond time out of range**

As for the gap of braking before and after substitution, a response time out of range in mechanical braking may degrade performance of stopping accuracy.

The Mechanical Braking Respond Time Out of Range alarm is raised as soon as the response time is higher than a predefined threshold. This threshold is defined such that according to rolling stock substitution speed, the stopping accuracy could be degraded.

**3.2.5. Train at limit of pilotability**

Train at limit of pilotability alarm is raised when ATO is still able to control the train without intelligent driving. But a weak drift of train parameters can activate intelligent driving corrections.



**Figure 7 : Train at limit of pilotability**

Limit of pilotability thresholds are defined according to ATO and intelligent driving range of pilotability. This range of pilotability is function of the supply industry’s design.

**3.2.6. Train out of range of pilotability**

Train out of range of pilotability alarm is raised when ATO is not able to reach the stopping accuracy by itself. The performance can be possible only with the use the intelligent driving.

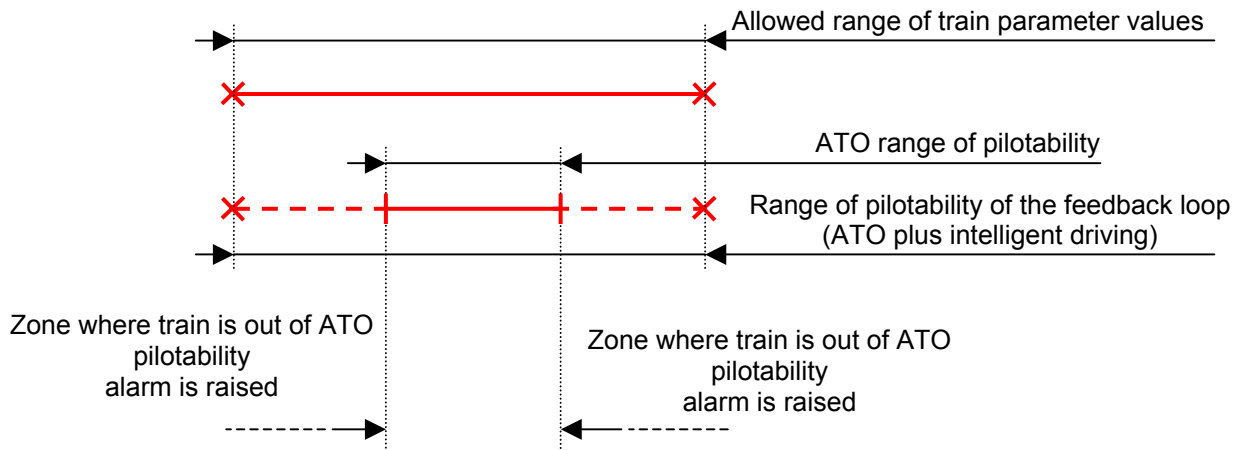


Figure 8 : Train out of range of pilotability

**3.2.7. Instability of the command**

This alarm is necessary to inhibit the learning when the ATO output is instable. Detection of the instability is done when system is expecting a steady state and the motoring/braking command (output of the ATO) is not reaching this state.

A standard threshold for the detection cannot be defined as it can be fundamentally different with regards to the design. For instance the ATO output is different if the train command is performed through a Train Command Management System or with a direct link. Furthermore, some rolling stock are using a notch command, in that case, the detection module must be insensitive to an oscillating command since this is the steady state.

**3.2.8. Risk of inaccurate stopping**

Risk of inaccurate stopping alarm is raised when ATO and intelligent driving are still able to reach performance, but a weak drift of train parameters can damage the stopping accuracy.

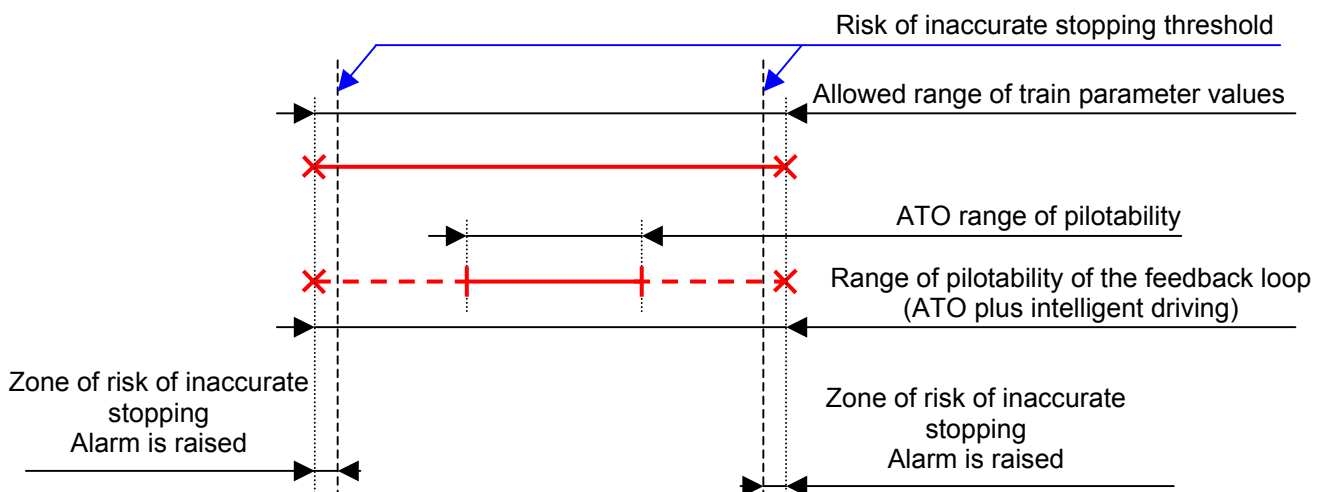


Figure 9 : Risk of inaccurate stopping

Risk of inaccurate stopping thresholds are defined according to ATO and intelligent driving range of pilotability. The range of pilotability is a function of the supplier's intelligent driving design.

**3.2.9. Insufficient stopping accuracy**

Insufficient stopping accuracy alarm is raised when the whole feedback loop is no more able to reach the stopping accuracy performance.

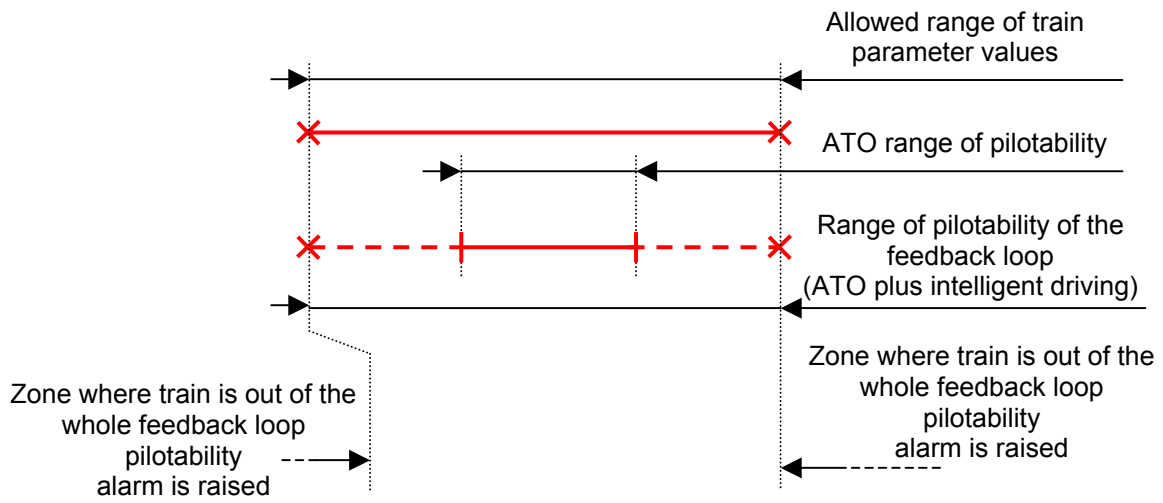


Figure 10 : Insufficient stopping accuracy

#### 4. S4 – Adaptation specification

Adaptation can be carried out in many ways. This section only gives several possibilities but future solutions could be implemented with more efficient algorithms issued from deeper analysis.

To be more explicit, explanations and figures of this section are showing learning and adaptations of acceleration, but they could also be performed on speed or localization.

Learning and adaptation are performed using an iterative process. After deceleration phases if the detection module detects the system in case 2 or 3 as defined in section 3.1, it will send to adaptation module information about the last learning. Since the learning is performed during deceleration phases, it will ask for an adaptation at the time of next deceleration phases. This adaptation will modify deceleration rate. The learning will therefore be different and a new adaptation will be applied. Process ends once system is back in the stopping accuracy window.

Adaptation can be performed using different algorithms. D10 describes a few of them:

##### Algorithm 1:

Algorithm 1 consists in a full correction of the command as soon as adaptation module is asking for a correction. This solution is purely theoretical to show the concept of intelligent driving. It does not take into account differences between measurement, noise on measurement and possible failed stop due to external event like drop of voltage or slippery rail for instance.

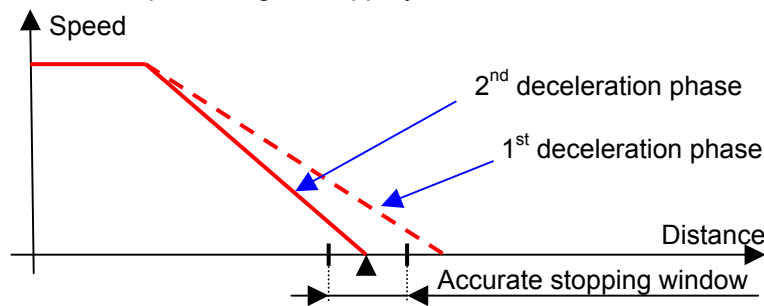


Figure 11 : Algorithm 1

##### Algorithm 2:

The second algorithm consists of performing a constant slight adaptation. Train command for  $n^{\text{th}}$  deceleration is modified by a constant adaptation. Adaptation is performed if the gap between expected deceleration and the one measured during the  $(n-1)^{\text{th}}$  deceleration phase is higher than the value of the constant. In case of wrong learning due to external event the next stop will only be slightly impacted.

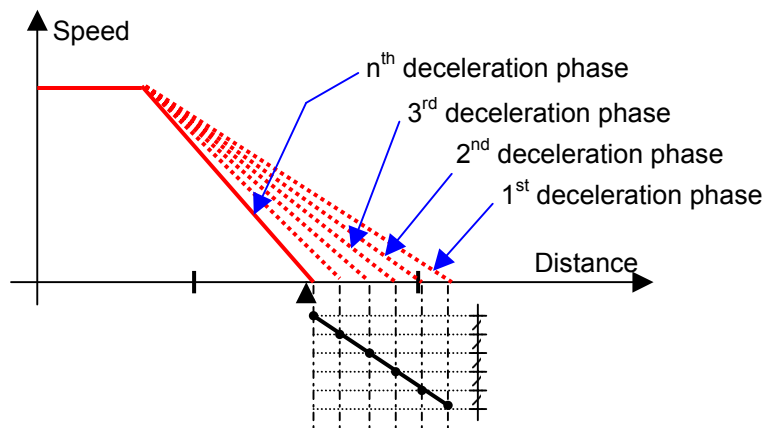
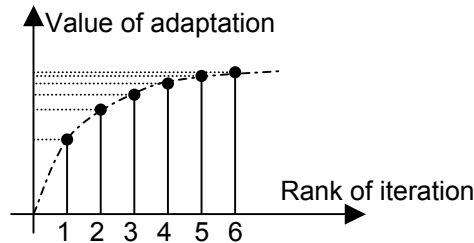


Figure 12 : Algorithm 2

**Algorithm 3:**

This third algorithm has been developed to show the feasibility of intelligent driving. It is used for simulations and tests.

Value of adaptation set by this algorithm is dependent of the rank of the iteration and is following a logarithmic curve as shown on figure 13.

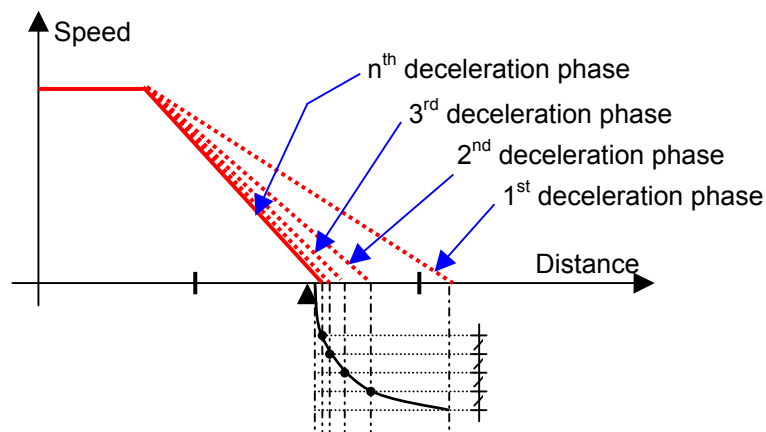


**Figure 13 : Algorithm 3**

Value of adaptation is independent of the gap between learnt deceleration and the expected one.

**Algorithm 4:**

The fourth algorithm consists on performing an adaptation dependent of the gap between the deceleration expected and the one measured during the (n-1)<sup>th</sup> deceleration phase. The more significant the gap, the more significant the adaptation is.



**Figure 14 : Algorithm 4**

A progressive adaptation allows the command to filter a wrong learning by having only a slight impact on the next deceleration.

Value of adaptation is computed according to previous decelerations measurements. To filter a wrong learning due to an external event like slippery rail or drop of voltage it is necessary to use several learning phases. As example, the effective value of adaptation could be a moving average of the last x computed values.

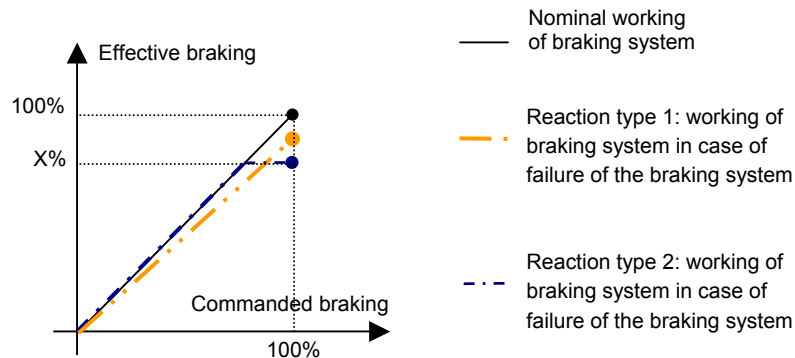
The four algorithms describe adaptation as if braking was performed by a single system, but deceleration for an accurate stopping is divided into three phases, electrical braking, substitution and finally mechanical braking. Intelligent driving can be used to compensate several abnormal train behaviors. To do so, several parameters may need to be learnt (a delay on the command, a gain, a braking force...), and therefore several adaptations may be set on train command

## 5. S5 – INTERFACE WITH ROLLING-STOCK

To perform an efficient detection of discrepancies and parameters variation, intelligent driving needs to obtain some information directly coming from rolling-stock. The following described interface has been validated by rolling stock suppliers.

- **Train load:** This data is useless for braking phases. Rolling-stock is already making the load compensation to provide a constant deceleration. But the load compensation is not performed by all rolling stock suppliers for motoring phases and it could be necessary to adapt effort during this phases.
- **Percentage of motoring:** This data gives the percentage of motoring available on rolling stock in case of inverter failure. (For instance, if one over eight inverters fails the percentage of motoring is 87.5%).

Concerning braking system, two types of reaction have been observed. Percentage of braking deterioration is among other things function of the failed braking system location.



For mechanical and electrical braking phases, two data are needed to detect the type of reaction:

- **Constant percentage of electrical braking** gives the constant percentage of electrical braking degradation. Needed in case of rolling stock reaction 1.
- **Maximum percentage of electrical braking** gives the maximum electrical braking available. Needed in case of rolling stock reaction 2.
- **Constant percentage of mechanical braking** gives the constant percentage of mechanical braking degradation. Needed in case of rolling stock reaction 1.
- **Maximum percentage of mechanical braking** gives the maximum mechanical braking available. Needed in case of rolling stock reaction 2.
- **Pressure in brake cylinder:** This data can be useful to anticipate the learning
- **Dead time of the mechanical brake system** is dependant of the brake pad wear.

Intelligent driving is used to learn and to adapt train behavior. Some data are therefore needed to make the separation between train behavior and external events like slippery rail or drop of voltage. These data are:

- **Supply voltage** can affect the motoring or the electrical braking.
- **Train speed measured by rolling stock**
- **Slip/Slide detection on axle n (Boolean):** n can be anyone of the axle. Train speed and detection of slip/slide can allow the detection of a slippery rail.

## 6. S6 – SIMULATION

### 6.1. Tests environment

Simulation is carried out to test effects of train parameters variation on the stopping accuracy using the intelligent driving. In front of this hypothesis, simulations are not carried out on all alarms specified in section 3.1 but more specifically linked to it. Therefore the following alarms are simulated:

- Over and under braking train
- Train at limit of pilotability
- Train out of range of pilotability
- Risk of inaccurate stopping
- Insufficient stopping accuracy.

Furthermore, to analyze effects of train parameters variation on the stopping accuracy, the full control loop has been defined as follow.

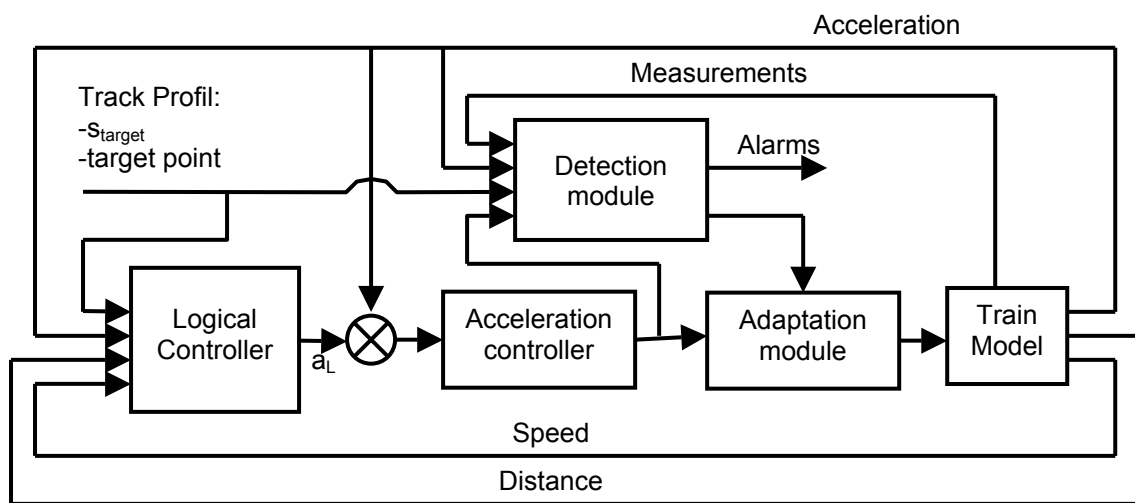


Figure 15 : Control loop

Objective of simulation is to verify effects of adaptation on stopping accuracy. Intelligent driving is therefore carried out on the mechanical braking gain ( $K_{PB}$ ) using algorithm 3 described in section 1.1.

Logical controller use to carry out simulations is made up of a logical controller and an acceleration controller. The logical controller is taking three different states according to transition described in figure 16.

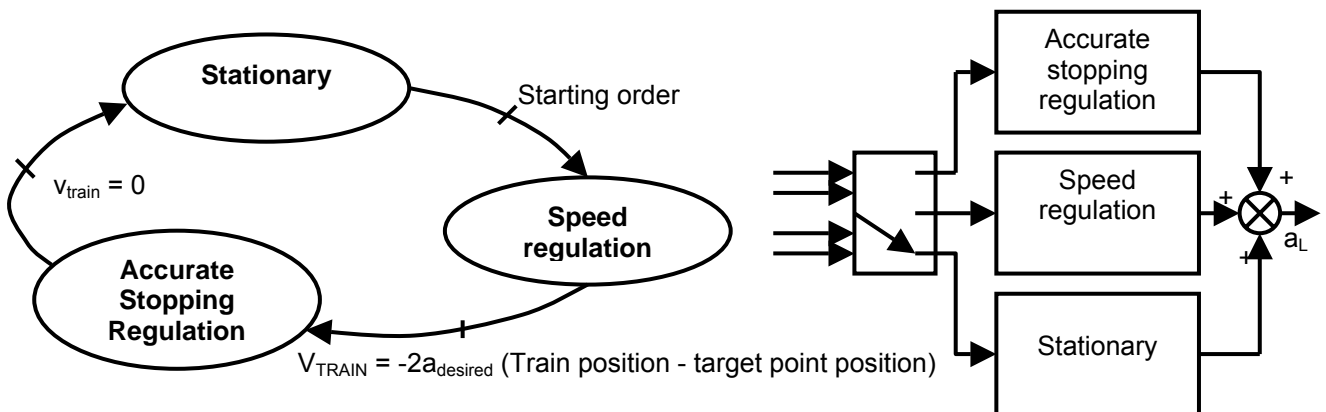


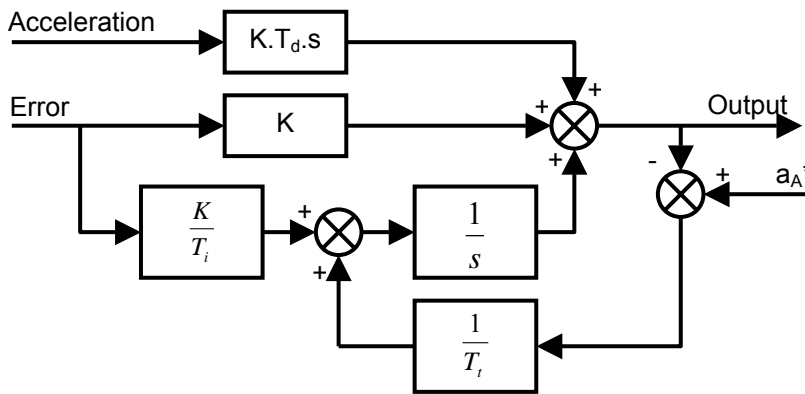
Figure 16 : Logical controller

The logical controller output acceleration ( $a_L$ ) is equal to:

- If logical controller is in state speed regulation:  $a_L = K(v_{T\text{ target}} - v_{T\text{ train}})$  with K in  $s^{-1}$
- If logical controller is in state accurate stopping regulation:  $a_L = -\frac{v_{T\text{ train}}^2}{2 * \text{distance to target point}}$
- If logical controller is in state stationary:  $a_L = 0$

Once train reaches a speed of close to zero, acceleration is set to the fix value of  $0.5 \text{ m.s}^{-2}$

The acceleration controller has been defined after several simulations, PI and PID appears to be not fast enough and that is why the “anti-windup PID” has been chosen.



**Figure 17 : Anti-windup PID**

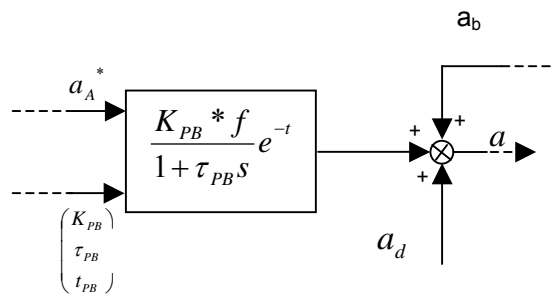
Train model used for simulation is described in document D9: Train model.

## 6.2. Tests specification

Studies of intelligent driving aim at to increase stopping accuracy, and therefore the braking performances. To perform an accurate stopping, the most crucial phase is the mechanical braking. That is the reason why simulations are focused on mechanical over and under braking train.

To simulate a variation of the braking level, the gain  $K_{PB}$  of the first order filter of the model (See figure 18 extract from D9: Train Model) will be multiplied by a factor (f).

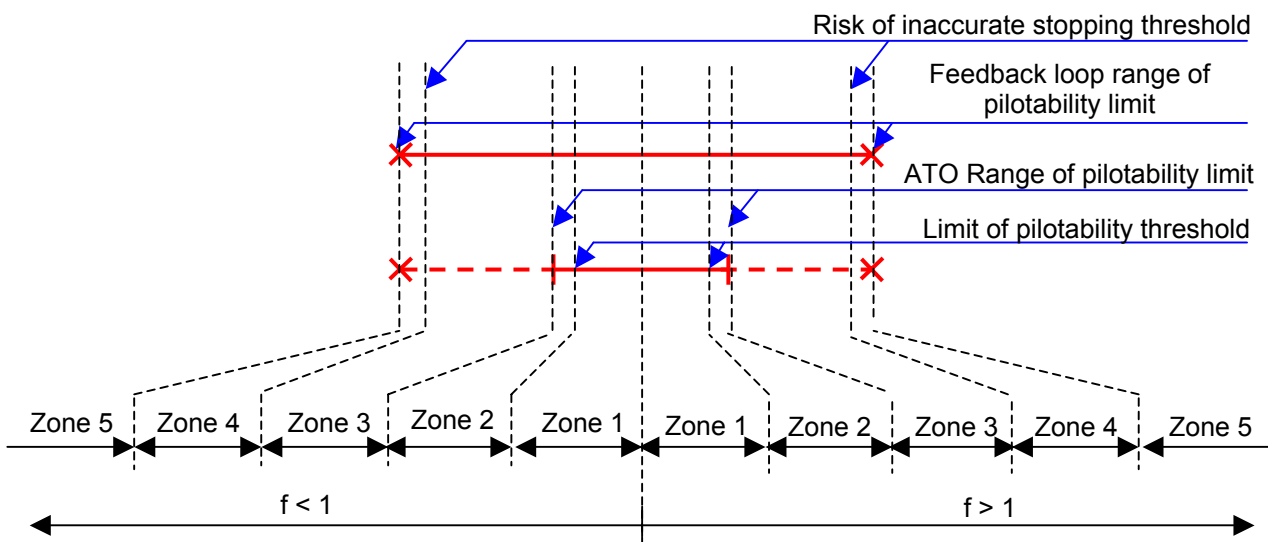
- An over-braking train is simulated with  $f > 1$
- An under-braking train is simulated with  $f < 1$



**Figure 18 : Simulation description**

For the two first tests factor  $f$  and therefore  $K_{PB}$  will progressively increase in order for the feedback loop to pass through all functioning zone described in section 12:

- Zone 1: System controllable by ATO itself: No adaptation and no alarm
- Zone 2: System between limit of pilotability threshold and ATO range of pilotability limit: No adaptation but alarm “Train at limit of pilotability” is raised.
- Zone 3: System between ATO range of pilotability limit and risk of inaccurate stopping threshold: Alarm “Train out of range of pilotability” is raised and intelligent driving is starting to perform adaptation, the stopping accuracy should increase
- Zone 4: System between risk of inaccurate stopping threshold and feedback loop range of pilotability limit: Alarm “Risk of inaccurate stopping” is raised and stopping accuracy should decrease.
- Zone 5: System no more controllable by the feedback loop: Alarm “Insufficient stopping accuracy” is raised and the feedback loop is asking for the maximum adaptation.



**Figure 19 : Tests specification**

A Third test will be carried out to check the working of intelligent driving by simulating various variation of  $K_{PB}$ .

### **6.3. Results and analysis**

#### **6.3.1. Progressive increase of $K_{PB}$**

This section gives result of the simulations which consist of progressively increasing and then decreasing  $K_{PB}$

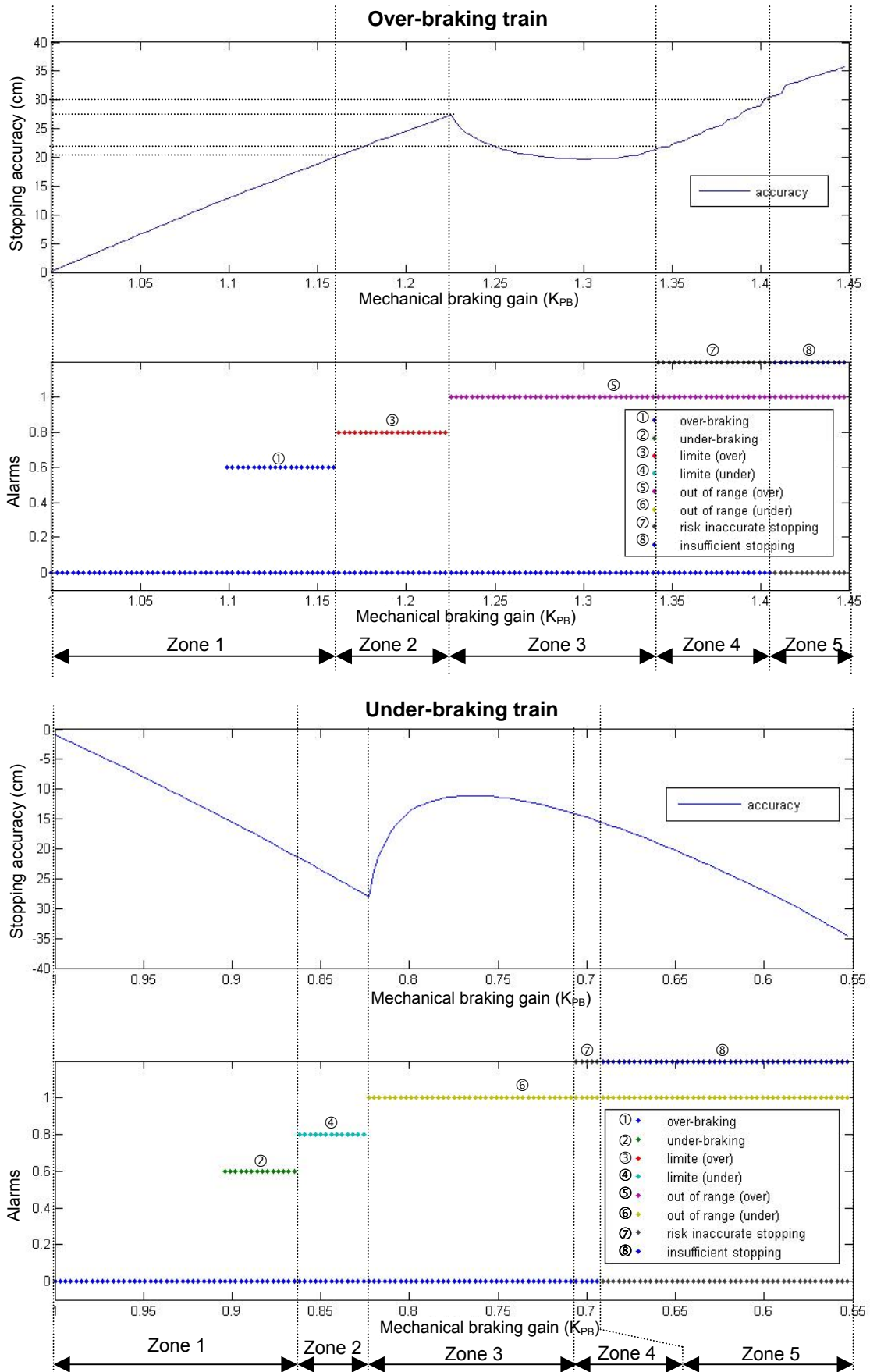
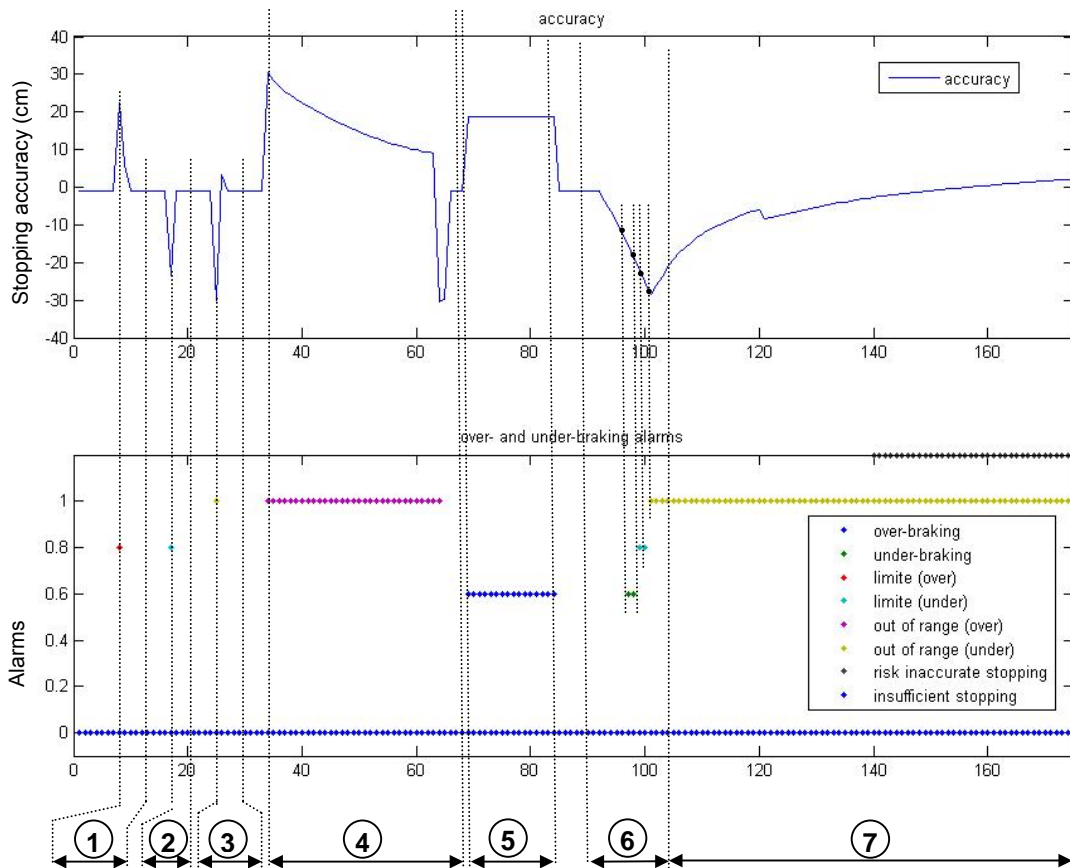


Figure 20 : Tests 1 results

- Zone 1 :  $K_{PB}$  is increasing (decreasing) from its nominal value to the ATO limit of pilotability. Stopping accuracy is decreasing. Over (under) braking train alarm is raised once intelligent driving detects the deceleration in over (under)-braking zone (see section 3.2.2).
- Zone 2: ATO is at limit of pilotability and alarm is raised.
- Zone 3: Train is out of range of ATO pilotability. Intelligent driving is starting to adapt the command. Stopping accuracy is improved in first time but, since  $K_{PB}$  is still increasing (decreasing) a degradation of the stopping accuracy can be observed.
- Zone 4: Feedback loop (ATO plus intelligent driving) is soon no more able to reach stopping accuracy, Risk of inaccurate stopping alarm is raised.
- Zone 5: Stopping accuracy is no more enforced even with a full adaptation. Alarm insufficient stopping accuracy is raised.

### 6.3.2. Variation of $K_{PB}$

Second simulation consists of to vary  $K_{PB}$  in order to test intelligent driving in various situations:



**Figure 21 : Tests 2 results**

- ①:  $K_{PB}$  suddenly increases to a value which brings train behavior just after the limit of pilotability threshold in over-braking. Alarm “Train at limit of pilotability” is therefore raised but ATO is still able to control the train by itself. Detection module does not ask for correction.  $K_{PB}$  is then brought back to its nominal value without impacting the following stopping.
- ②:  $K_{PB}$  suddenly decreases to a value which brings train behavior just after the under-braking threshold in under-braking. Alarm “train at limit of pilotability” is therefore raised but ATO is still able to control the train by itself. Detection module does not ask for correction.  $K_{PB}$  is then brought back to its nominal value without impacting the following stopping.



- ③:  $K_{PB}$  suddenly decreases to a value which brings train behavior outside the ATO range of pilotability in under-braking. Performance of stopping accuracy is missed and alarm “train out of range of pilotability” is raised. As defined, detection module is asking for a correction of the command at the time of the following stopping.  $K_{PB}$  is then brought back to its nominal value and correction is applied.
- ④:  $K_{PB}$  suddenly increases to a value which brings train behavior outside the ATO range of pilotability in over-braking. Performance of stopping accuracy is missed and alarm “train out of range of pilotability” is raised. As defined, detection module is asking for a correction of the command. This correction is gradually applied according to previous learning. As correction has been applied for several braking phases, it creates a significant effect on the command.  $K_{PB}$  is then brought back to its nominal value. It takes a few precise stopping phases for intelligent driving to detect that the train has returned to its nominal behavior, and to determine that the correction can be removed.
- ⑤:  $K_{PB}$  suddenly increases to a value which brings train behavior just after the over-braking threshold. Alarm “over-braking train” is therefore raised. ATO is still able to control the train by itself and therefore detection module does not ask for correction.
- ⑥:  $K_{PB}$  progressively decreases bringing train behavior over under-braking, limit of pilotability and Train out of range of pilotability thresholds. For each of these thresholds corresponding alarms is raised. Once “train out of pilotability” threshold is reached, stopping accuracy increases because of corrections.
- ⑦:  $K_{PB}$  is no more decreasing and intelligent driving progressively applies its corrections.  $K_{PB}$  drift is too important for the correction capacity of intelligent driving which reach the “Risk of inaccurate stopping threshold”, alarm is raised.