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Efficient driving of CBTC ATO operated trains

William Carvajal Carreño

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Efficient driving of CBTC ATO operated trains

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Keywords: Energy efficiency, CBTC signalling system, ATO, Metro, Ecodriving, NSGA-II-F, pseudo-Pareto front, Tracking algorithm, Fuzzy parameters, Moving-block, Train Simulation.

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Abstract

Author: William Carvajal Carreño
Title: Efficient driving of CBTC ATO operated trains
Language: Written in English
Keywords: Energy efficiency, CBTC signalling system, ATO, Metro, Ecodriving, NSGA-II-F, pseudo-Pareto front, Tracking algorithm, Fuzzy parameters, Moving-block, Train Simulation.

Energy consumption reduction is one of the priorities of metro operators, due to financial cost and environmental impact. The new signalling system Communications-Based Train Control (CBTC) is being installed in new and upgraded metro lines to increase transportation capacity. But its continuous communication feature also permits to improve the energy performance of traffic operation, by updating the control command of the Automatic Train Operation (ATO) system at any point of the route.

The present research addresses two main topics. The first is the design of efficient CBTC speed profiles for undisturbed train trajectory between two stations. The second takes into account the interaction between two consecutive trains under abnormal traffic conditions and proposes a tracking algorithm to save energy.

In the first part of the research an off-line methodology to design optimal speed profiles for CBTC-ATO controlled trains is proposed. The methodology is based on a new multi-objective optimisation algorithm named NSGA-II-F, which is used to design speed profiles in such a way that can cover all the possible efficient solutions in a pseudo-Pareto front. The pseudo–Pareto front is built by using dominated solutions to make available a complete set of feasible situations in a driving scenario. The uncertainty in the passenger load is modelled as a fuzzy parameter. Each of the resulting speed profiles is obtained as a set of parameters that can be sent to the ATO equipment to perform the driving during the operation.

The proposed optimisation algorithm makes use of detailed simulation of the train motion. Therefore, a simulator of the train motion has been developed, including detailed model of the specific ATO equipment, the ATP constraints, the traction equipment, the train dynamics and the track.

A subsequent analysis considers the effect in the design of considering the regenerative energy flow between the train and the surrounding railway system.

The second part of the research is focused on the proposal and validation of a fuzzy tracking algorithm for controlling the motion of two consecutive trains during disturbed conditions. A disturbed condition is understood as a change in the nominal driving command of a leading train and its consequences in the subsequent trains. When a train runs close enough to the preceding one, a tracking algorithm is triggered to control the distance between both trains. The following train receives the LMA (limit of movement authority) via radio, which is updated periodically as the preceding train runs. The aim of the proposed algorithm is to take actions in such a way that the following train could track the leading train meeting the safety requirements and applying an energy saving driving technique (coasting command). The uncertainty in the variations of the speed of the preceding train is modelled as a fuzzy quantity. The proposed algorithm is based on the application of coasting commands when possible, substituting traction/braking cycles by traction/coasting cycles, and hence saving energy.

Both algorithms were tested and validated by using a detailed simulation program. The NSGA-II-F algorithm provided additional energy savings when compared to fixed-block distance-to-go configurations, and giving a more even distribution of the solutions. The fuzzy tracking algorithm provides energy savings with a minor impact on running times while improving comfort, because of the reduction of the inefficient traction/braking cycles.

Resumen

Autor: William Carvajal Carreño
Titulo: Conducción eficiente de trenes operados con ATO en sistemas de señalización CBTC
Idioma: Escrita en Inglés
Palabras clave: Eficiencia energética, Señalización CBTC, ATO, Metro, Conducción económica, NSGA-II-F, pseudo frente de Pareto, algoritmo de seguimiento, parámetros borrosos, cantón móvil, simulación ferroviaria.

La reducción del consumo de energía es una de las prioridades de los operadores de metro, debido principalmente a criterios financieros y ambientales. El reciente sistema de señalización, control de trenes basado en comunicaciones (CBTC por sus siglas en inglés), se está instalando en líneas nuevas y en líneas reseñalizadas para permitir el aumento en la capacidad de transporte. La característica de comunicación continua entre tren y vía permite la mejora en el desempeño energético del tráfico ferroviario mediante la actualización de la consigna de conducción del sistema automático de conducción (ATO) en cualquier punto del recorrido entre dos estaciones.

La presente investigación profundiza en dos tópicos principales. El primero es el diseño de perfiles de velocidad eficientes CBTC para el movimiento sin perturbación de trenes entre dos estaciones. El segundo tiene en cuenta la interacción entre dos trenes consecutivos bajo condiciones anormales de tráfico y propone un algoritmo de seguimiento para ahorrar energía.

En la primera parte de la investigación, se propone una metodología para el diseño off-line de perfiles de velocidad óptimos para trenes con ATO en sistemas CBTC. La metodología se basa en un nuevo algoritmo de optimización multiobjetivo denominado NSGA-II-F para el diseño de perfiles de velocidad de tal forma que cubra todas las posibles soluciones eficientes generando un pseudo frente de Pareto. El pseudo frente de Pareto incluye soluciones dominadas para tener disponible un conjunto completo de posibles situaciones en un escenario de tráfico. La incertidumbre en la masa del tren debido a la carga de pasajeros se modela como un parámetro borroso. Cada uno de los perfiles de velocidad resultantes se programa como un conjunto de parámetros que pueden ser enviados al equipo ATO para ejecutar la conducción deseada.

El algoritmo de optimización propuesto está basado en la simulación detallada del consumo y energía asociados a la marcha del tren. Para ello se ha desarrollado un simulador de marcha que incluye modelos precisos del equipo ATO considerado, de las limitaciones ATP, del sistema de tracción/freno, de la dinámica del tren y de la vía.

Un análisis posterior considera el efecto en el diseño de tener en cuenta el flujo de energía regenerada entre el tren y el sistema ferroviario circundante.

La segunda parte de la investigación se centra en el diseño y validación de un algoritmo borroso de seguimiento para controlar el movimiento de dos trenes consecutivos en condiciones perturbadas. Una condición perturbada se define como un cambio en las condiciones nominales de marcha del tren de adelante y sus consecuencias en los trenes que le siguen. Cuando un tren va muy cerca del tren precedente, el algoritmo de seguimiento controla la distancia entre ambos. El tren que sigue recibe una señal de radio con el límite de autoridad de movimiento (LMA), que se actualiza periódicamente a medida que el tren precedente avanza. El objetivo del algoritmo propuesto es ejecutar acciones de control de tal forma que dos trenes consecutivos mantengan un intervalo de seguimiento respetando los requisitos de seguridad y aplicando técnicas de conducción económica (uso de derivas). La incertidumbre en las variaciones de la velocidad del tren precedente se modela como un número borroso. El algoritmo propuesto se basa en la aplicación de consignas de deriva, sustituyendo ciclos de tracción/frenado por ciclos de tracción/deriva, proporcionando por ello ahorros energéticos.

Los dos algoritmos propuestos han sido ensayados y validados mediante simulación detallada de la marcha del tren. Se ha mostrado que el algoritmo NSGA-II-F proporciona ahorros de energía adicionales, comparado con la conducción eficiente en sistemas de señalización de cantón fijo distancia objetivo. Además permite una distribución más homogénea de las soluciones en tiempos de recorrido disponibles para el sistema de regulación de tráfico. Por otro lado, se ha mostrado que el algoritmo de seguimiento borroso proporciona ahorros de energía respecto del algoritmo de seguimiento básico, con un impacto muy reducido en tiempos de recorrido.

Samenvatting

Auteur: William Carvajal Carreño
Titel: Energiezuinig rijden van treinen met een CBTC-ATO-systeem
Taal: Geschreven in het Engels
Trefwoorden: energie-efficiëntie, CBTC-signaalsysteem, ATO, Metro, eco-driving, NSGA-II-F, pseudo-Pareto front, tracking-algoritme, Fuzzy parameters, moving-block, treinsimulatie

Door de financiële kosten en de gevolgen voor het milieu is de besparing van energieconsumptie één van de prioriteiten van metrobedrijven. Het nieuwe signaleersysteem 'Communications-Based Train Control' (CBTC) wordt momenteel geïnstalleerd in nieuwe en vernieuwde metrolijnen om de transportcapaciteit te vergroten. Omdat deze technologie een continue communicatietechnologie is, kan de efficiëntie van het railgebruik verbeterd worden door een update van het stuurcommando van het 'Automatic Train Operation' (ATO)-systeem tijdens elk punt van de route.

Dit onderzoek richt zich op twee hoofdonderwerpen. Het eerste is het ontwerp van efficiënte CBTC-snelheidsprofielen voor een ononderbroken treinreis tussen twee stations. Het tweede onderzoek let ook op de interactie tussen twee opeenvolgende treinen tijdens abnormale verkeersomstandigheden en stelt een tracking-algoritme voor om energie te besparen.

In het eerste deel van dit onderzoek wordt een offline methode voorgesteld om optimale snelheidsprofielen voor CBTC-ATO-gecontroleerde treinen te ontwerpen. De methode is gebaseerd op een nieuw ´multi-objective´ algoritme genaamd NSGA-II-F, welke gebruikt wordt om snelheidsprofielen zo te ontwerpen dat het alle mogelijke efficiënte oplossingen in een pseudo-Pareto front omvat. Het pseudo-Pareto front is met behulp van gedomineerde oplossingen gemaakt om een complete set van mogelijke situaties in een rijdend scenario te creëren. De onzekerheid van de passagiersbelasting is gemodelleerd als een fuzzy parameter. Elke van de resulterende snelheidsprofielen is verkregen als een set parameters die naar de ATO-apparatuur kan worden gestuurd om de gewenste aandrijving uit te voeren.

Het voorgestelde optimalisatie-algoritme gebruikt een gedetailleerde simulatie van de treinbeweging. Een simulator van de treinbeweging is hiervoor ontwikkeld, welke een gedetailleerd model van de specifieke ATO-apparatuur, de ATP-beperkingen, de tractie-apparatuur, de treindynamica en de rails omvat.

Een volgende analyse onderzoekt wat er gebeurt als er rekening wordt gehouden met de regeneratieve energiestromen tussen de trein en het omgevende railsysteem.

Het tweede deel van dit onderzoek richt zich op het voorstel en de validatie van een fuzzy tracking-algoritme om de beweging van twee opeenvolgende treinen gedurende verstoorde omstandigheden te besturen. Een vertoorde omstandigheid wordt gedefinieerd als een verandering in het nominale rijcommando van de voorste trein en de gevolgen voor de volgende treinen. Als een trein te dichtbij de voorgaande trein komt, wordt een tracking-algoritme gestart om de afstand tussen de twee treinen te besturen. De volgende trein ontvangt een LMA ('limit of movement authority')-signaal via de radio, welke regelmatig vernieuwd wordt terwijl de voorgaande trein verder rijdt. Het doel van het voorgestelde algoritme is dat de achterste trein het spoor kan volgen van de voorste trein terwijl aan de veiligheidsvoorschriften wordt voldaan. Een energiebesparende rijtechniek wordt toegepast (uitrolcommando). De onzekerheid in de snelheidsvariaties van de voorgaande trein is gemodelleerd als een fuzzy hoeveelheid. Het voorgestelde algoritme is gebaseerd op de toepassing van uitrolcommando's wanneer mogelijk, door tractie/rem-cycli te vervangen door tractie/uitrol-cycli en bespaart zo energie.

Beide algoritmes zijn getest en gevalideerd met behulp van een gedetailleerd simulatieprogramma. Het NSGA-II-F algoritme levert extra energiebesparingen op wanneer deze wordt vergeleken met 'fixed-block distance-to-go'-configuraties en geeft een meer evenredige verdeling van de oplossingen. Het fuzzy tracking algoritme levert energiebesparingen met een klein effect op de rijtijden terwijl het het comfort verhoogt door de vermindering van inefficiënte tractie/rem-cycli.

Sammanfattning

Författare: William Carvajal Carreño
Titel: Effektiv körning av ATO-styrda tåg med signal- och styrsystemet CBTC
Språk: Engelska
Nyckelord: Energieffektivitet, signal-och styrsystemet CBTC, ATO (Automatic Train Operation), tunnelbana, sparsam körning, ecodriving, optimeringsalgoritmen NSGA-IIF, pseudo-Paretofront, följningsalgoritmoskarp logik, rörlig blocksträcka, tågsimulering.

Att minska energiförbrukningen är viktigt för tunnelbaneoperatörer av både ekonomiska och miljömässiga skäl. Det nya signal-och styrsystemet Communications-Based Train Control (CBTC) installeras på nya och upprustade tunnelbanelinjer för att öka transportkapaciteten. Dessutom kan det minska energiförbrukningen genom att ändra styrkommandot till ATO-systemet (som kör tågen automatiskt) varsomhelt längs linjen i och med att kommunikationen med tåget sker kontinuerligt och inte bara vid vissa punkter.

Denna doktorsavhandling behandlar två aspekter. Den första är att beräkna effektiva CBTC-fartprofiler för tåg mellan två stationer i normaldrift för tidtabellsplanering. Den andra tar hänsyn till påverkan mellan två närliggande tåg vid störda förhållanden och föreslår en följningsalgoritm för att spara energi.

Den första delen presenterar en metod för att i förväg bestämma optimala fartprofiler för förarlösa tåg med signalsystemet CBTC. Metoden baseras på en nyoptimeringsalgoritm för flera mål kallad NSGA-II-F, som skapar fartprofiler som täcker alla möjliga effektiva lösningar i pseudo-Paretofronten. Fronten är uppbyggd från dominerade lösningar vilka i sin tur ger en fullständig mängd av möjliga lösningar i körscenariet. Osäkerheten i mängden passagerare modelleras som en oskarp parameter. Varje fartprofil blir till en uppsättning parametrar som kan skickas till ATO-systemet som kör tåget.

Den föreslagna optimeringsalgoritmen baseras på en detaljerad simulering av tågets rörelse. Därför har en simulator utvecklats med en detaljerad modell av ATOsystemet, ATP-systemets villkor för att tillåta tågrörelser, framdrivningssystemet, tågets dynamik och spåret.

En fortsatt analys tar med återmatningen av energi från tåget till elsystemet vid inbromsning.

Den andra delen av avhandlingen består av utvecklingen och verifieringen av en följningsalgoritm baserad på oskarp logik för att styra körningen av två tåg i följd vid störda förhållanden, vilket avser en förändring av styrningen till det främre tåget och dess konsekvenser för de bakomvarande. När ett tåg kommer tillräckligt nära det framförvarande, startas en följningsalgoritm för att styra avståndet mellan tågen. Det bakre tåget får en LMA (limit of movement authority)-signal via radio som uppdateras när det främre tåget rör sig. Algoritmen syftar till att det bakre tåget kan köra både säkert och ekonomiskt. Osäkerheten i det främre tågets fart hanteras med en oskarp variabel. Algoritmens mål är att ersätta drivning/bromsningscykler med drivning/rullningscykler och därmed spara energi.

Båda algoritmerna har verifierats genom en detaljerad simulering av tågets körning. Resultatet är att NSGA-II-F-algoritmen spar mer energi än sparsam körning i system med fasta blocksträckor. Dessutom skapar algoritmen en jämnare fördelning av möjliga körtider, vilket underlättar planeringen. Följningsalgoritmen med oskarpa parametrar spar energi med en mindre påverkan på körtider och samtidigt förbättras komforten, på grund av minskningen av ineffektiva dragkraft/bromscykler.

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List of symbols

Symbol	Description
CBTC	Communications-Based Train Control.
ATP	Automatic Train Protection.
GoA	Grade of Automation.
ATO	Automatic Train Operation.
D2G	Distance-to-go.
LMA	Limit of movement authority [m].
S_{target}	Target point distance [m].
V	Speed [km/h].
S	Distance [m].
ZC	Zone controller.
ATO_{out}	Output of the ATO. Normalised.
a_g	Gradient acceleration correction. Dimensionless.
k	Gain of the ATO [h/km].
V_{target}	Target speed of the ATO [km/h].
F_m	Traction motor force [N].
$F_{max}(V)$	Maximum traction motor force as a function of the speed [N].
$\Delta a/\Delta t$	Jerk [m/s^3].
M_{eq}	Equivalent train mass [kg].
a	Acceleration [m/s^2].
F_r	Running resistance [N].
F_g	Gradient resistance [N].
F_c	Curve resistance [N].
A	Running resistance coefficient [N].
B	Running resistance coefficient [N-h/km].
C	Running resistance coefficient [N-h^2/(km)^2].
v	Davis formula train speed [km/h].
R	Curvature radius [m].
g	Acceleration of gravity [m/s^2].
p	Grade of the track [‰].
m	Mass of the train [kg].
ΔE	Energy consumed during the simulation step [kWh].
Δt	Time step [s].
μ	Motor efficiency. Dimensionless.

Symbol	Description
EC	Traction energy consumption [kWh].
GA	Genetic algorithm.
NSGA-II-F	Non-dominated sorting genetic algorithm II with fuzzy parameters.
ANN	Artificial neural networks.
ACO	Ant colony optimisation.
PSO	Particle swarm optimisation.
MOPSO	Multi-objective particle swarm optimisation.
IBEA	Indicator based evolutionary algorithm.
MPGA	Multi-population genetic algorithm.
$\widetilde{M}$	Fuzzy train mass [kg].
$\mu_{\widetilde{M}}(m)$	Membership function of the fuzzy mass.
$m_{1,2,3}$	Limits for the fuzzy mass model [kg].
α-cut	Alpha-cut of a fuzzy number.
$x^{\underline{\alpha_k}}$	Lower limit of the α_k-cut of x.
$x^{\overline{\alpha_k}}$	Upper limit of the α_k-cut of x.
$N(x^{\alpha})$	Necessity of x^{α}.
α	Possibility level.
$\Pi(A)$	Possibility of *A*.
$J(x)$	Objective function of the optimisation process.
$T(x)$	Running time associated to an evaluated solution x [s].
$E(x)$	Energy consumption associated to an evaluated solution x [kWh].
CD	Crowding distance.
$A \prec B$	*A* dominates *B*.
$\tilde{A} \prec \widetilde{B}$	*A* fuzzy-dominates *B*.
$\tilde{T}$	Fuzzy running time [s].
$\tilde{E}$	Fuzzy energy consumption [kWh].
α^{wd}	Possibility level for weak fuzzy-dominance.
n^{SD}	Necessity level for strong fuzzy-dominance.
$\widetilde{CD}(x_k)$	Fuzzy crowding distance for a solution x_k.
n_{GAP}	Necessity level for the identification of the time gap.
ΔE	Maximum energy tolerance limit defined for the dominated solutions.
$e^{\overline{\alpha}}, t^{\overline{\alpha}}, m^{\overline{\alpha}}$	Upper limit of the α-cut for energy consumption, running time and train mass.
$e^{\underline{\alpha}}, t^{\underline{\alpha}}, m^{\underline{\alpha}}$	Lower limit of the α-cut for energy consumption, running time and train mass.
hv	Hypervolume indicator. Normalised.
RC	Recovery coefficient.
$E^{t}_{cons_{sub},b}$	Energy consumption supplied by substations in the base case [kWh].
$E^{t}_{cons_{sub}}$	Energy consumption supplied by substations [kWh].
$E^{t}_{reg_{sub}}$	Regenerative energy back to substation [kWh].
E^{t}_{reg}	Energy regenerated by the train t not used by the auxiliary systems [kWh].
LC	Energy losses coefficient.
E^{t}_{cons}	Energy consumed by the train t [kWh].
ECS^{t}	Energy consumption in substation of a train [kWh].
I_M	Measured time interval to the braking curve [s].
$\widetilde{I_C}$	Fuzzy reference interval [s].
$\widetilde{V}_1$	Fuzzy speed of the leading train [m/s].
$\mu_{\widetilde{V_1}}(V)$	Membership function of the fuzzy speed of the leading train.
V', V''	Value of the limits for the fuzzy speed of the leading train model [m/s].
V_2	Speed of the following train [m/s].

Symbol	Description
S_2	Instantaneous position of the following train [m].
S_b	Position of the point with speed V_2 in the braking curve [m].
I_0	Base interval [s].
α_m	Possibility level for the fuzzy comparison of intervals.
$I_C^{\overline{\alpha_m}}$	Upper limit of the α_m-cut of $\widetilde{I_C}$ [s].
$V_1^{\underline{\alpha_m}}$	Lower limit of the α_m-cut of $\widetilde{V_1}$ [m/s].
$I_C^{\underline{\alpha_m}}$	Lower limit of the α_m-cut of $\widetilde{I_C}$ [s].
$V_1^{\overline{\alpha_m}}$	Upper limit of the α_m-cut of $\widetilde{V_1}$ [m/s].
n	Necessity level for the interval comparison.
$I_C^{\underline{\alpha_n}}$	Lower limit of the α_n-cut of $\widetilde{I_C}$ [s].
$V_1^{\overline{\alpha_n}}$	Upper limit of the α_n-cut of $\widetilde{V_1}$ [m/s].

Chapter 1

INTRODUCTION

With the development, improvement and subsequent application of steam locomotives at the beginning of the XIX century in the United Kingdom, the railway industry started a successful race which made that railway lines spread worldwide. By the end of the XIX century, electricity started to be an option to supply energy for trains and the construction of electrified metro lines and tramways began in big and mid size cities. After some years of deceleration and unpopularity in favor of highways and air transportation, when the railway development was stagnated, it started a new momentum with the oil crisis in the 70s.

Transporting massively freight and people has been the main goal from the creation of any means of public transportation. This aim requires a complex infrastructure to operate adequately all the system components. As the length of the networks extends, the quantity of circulating vehicles increases, it is required the development of safety equipment for avoiding accidents. In railway systems the concept of signalling began naming the configuration of all the required signs and codes to permit the safe motion of trains along the track. In modern railway lines not only signals are required, sophisticated communication systems have been applied to the system taking the place of the signals or supporting them. Even that, the coined term, *signalling system* is still applied to broadly define the set of equipment required for giving safety to the railway system.

After guaranteeing the safety conditions of operations, quality of service (punctuality and regularity) is the main objective in rail operation. However, nowadays energy efficiency is an important concern in the scale of priorities due to the present market and competitiveness requirements. Efficiency in the human resource management, infrastructure and rolling stock administration and sustainable operation are mandatory requirements to permit the financial health of a company and a positive perception from the point of view of sustainable development.

This research work is intended to study the energy-efficient operation of metropolitan trains with the recent Communications-Based Train Control (CBTC) signalling system. The rest of the present chapter defines some concepts required as a background for a proper study of the document, and the motivation, objectives and general outline of the thesis are described.

1.1. AUTOMATIC TRAIN PROTECTION (ATP) SYSTEM

Safety is the main concern in the design and operation of railway systems, from the design of components to infrastructure and rolling stock operation and configuration for the safe motion of trains. Regardless the driving is manual or automatic, the safety critical system assures the separation of trains, a clear route for the train motion and protects the train of surpassing speed limits. In general, all the equipment and protocols necessary to protect the railway system are called automatic train protection system. ATP system should be in coordination with interlocking which is the equipment in charge of making the track and infrastructure changes and modifications (switches) to provide the clearance and blocking of routes in a safe way. The basic functions of ATP are the detection of the position of the train (it means to identify the section of track where the train is, or a punctual position of the train), to avoid collisions among trains, to avoid derailment because of violation of the civil speed limits, to avoid the train entrance to sections of the track that form part of the route of other trains, and to ensure the train integrity (Allotta et al., 2015).

ATP systems currently in use go from basic wayside and onboard signals (as the balise-antenna set) for the emergency braking application, to information of movement authority transmitted to the train via radio. The higher the grade of automation (GoA), the higher the number of components involved in the system and its complexity (Tang and Xun, 2014).

ATP calculates and supervises the maximum speed constraints according to the permanent speed limit information and most restrictive condition of all the infrastructure and operation constraints. ATP applies emergency brakes if these constraints are violated.

In recent signalling systems as the CBTC, the ATP functions described according to the IEEE standard 1474.1 (IEEE, 2004; Quan et al., 2011) are: train location (front, rear and direction) and speed determination, safe train separation by the calculation and enforcement of an ATP curve and a safe braking model, overspeed protection and brake rate assurance, rollback protection, door opening interlock, emergency braking and route interlocking in the case of absence of any auxiliary wayside or separated interlock equipment. In CBTC, the ATP equipment calculates the braking curve and the maximum permitted curve to be provided to the automatic train operation system (ATO), described in the next section.

1.2. AUTOMATIC TRAIN OPERATION (ATO) SYSTEM

The Automatic Train Operation system executes automatically the driving commands typically received from the control centre. Automatic train operation involves mainly the control of the train motion by calculating and executing the required traction and braking commands. Automatically operated trains should receive in their onboard equipment all the necessary track and train information to calculate the next control notch during the motion of the train (Allotta et al., 2013; Domínguez et al., 2008; Fernández-Rodríguez et al., 2015). A schematic representation of an ATO system is shown in the Figure 1-1. The ATO module interprets and executes the driving commands received and always observes the safety constraints imposed by the ATP system. Along with the speed, position and ATP constraints, the inputs of the ATO module are the driving commands that the train receives from the control centre such as traction, speed holding, coast (null traction) and coasting-remotoring cycles. In addition, a deceleration rate used for speed reductions and service braking processes is supplied (Carvajal-Carreño et al., 2014, 2014; Cucala et al., 2012a; Domínguez et al., 2008). The output of the ATO system is a signal for the traction motors in form of an acceleration/deceleration value or a percentage of the maximum tractive/braking effort.

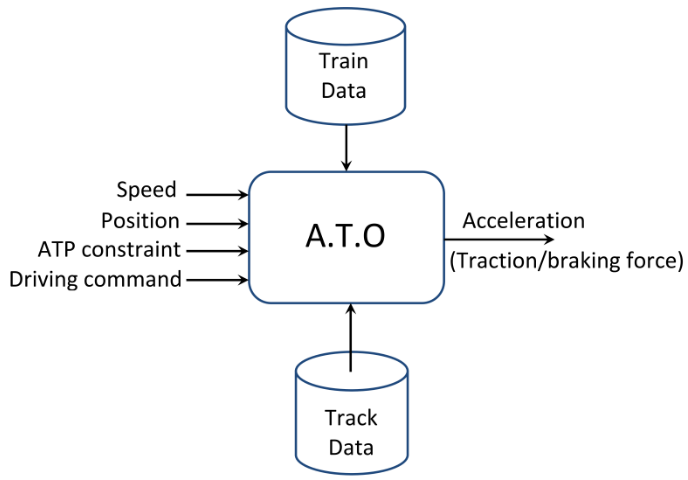


Figure 1-1. General ATO data structure

A schematic representation of ATP and ATO systems and subsystems located onboard and in the trackside for a CBTC equipped train is shown in Figure 1-2. The location of each of the system components is determined in the IEEE Recommended Practice for CBTC System Design and Functional Allocations (IEEE, 2008). The automatic train supervision subsystem is in charge of monitoring the trains, controlling the performance of individual trains to maintain schedules and it provides data to adjust service to minimise inconveniences caused by irregularities (IEEE, 2004).

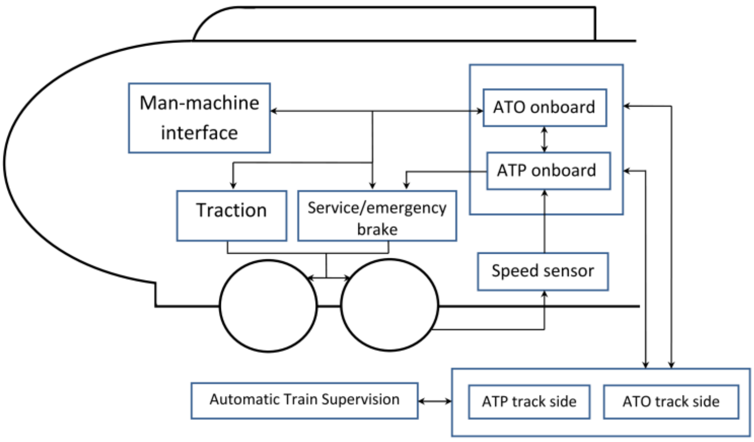


Figure 1-2. ATO and ATP system location

1.3. FROM FIXED-BLOCK TRACK CIRCUIT BASED TO MOVING-BLOCK COMMUNICATIONS BASED SIGNALLING SYSTEMS

Railway signalling is a branch of the transportation technology that seems to evolve to a slower pace, the main reason is that railway signalling is based on proven and reliable technology because of the high safety levels required to avoid catastrophic accidents. The criteria used in the design and construction of critical components in railways should be the failsafe concept, it means, that in the worst failure condition all the system components should go to a safe operation state to ensure the integrity for persons and equipment.

Signalling systems have evolved from the wayside signal scheme, low automation level and highly human dependent until complete automated radio-based systems (Chen, R. and Guo, J., 2010; Morar, 2012; Pascoe and Eichorn, 2009). A chart showing the evolution of signalling systems is shown in Figure 1-3. There are two clearly distinguished categories in signalling: the fixed-block and the moving-block systems. Even though, some customised mixed schemes exist to harmonise the built systems with new technologies implementation or to give a fallback option in presence of system failure.

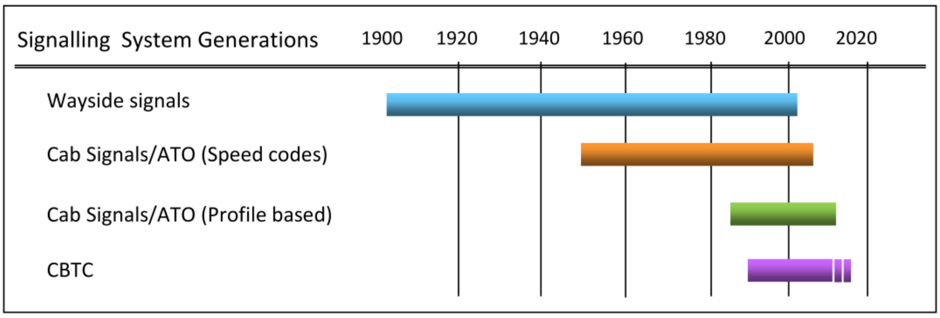


Figure 1-3 Evolution of signalling systems (Morar, 2012)

In the wayside signalling, the train is moving mainly according to the indication of wayside signals (color light indicators) which determine the limit of movement authority or maximum running distance up to the nearest obstacle, additional safety margins and speed limitations are considered. The signals are located at specific points in the infrastructure such as: sections of tracks, level crossings, switches or stations. The quantity of aspects (light indicators) and its interpretation are determined by the railway administrator in conjunction with the railway equipment supplier.

In fixed-block signalling the track is physically divided into sections called track circuits. The motion of the train is controlled according to which track circuits are occupied. One track circuit is considered occupied even if a small portion of it is touched by the train wheels. Some empty track circuits can be added as a buffer to increase safety, so the trains are separated and the capacity of the system is not fully exploited. While more track circuits, more resolution, but the physical infrastructure and maintenance costs increase and the availability rates are lower because of the quantity of components.

There are two main methods to supervise the speed in fixed-block based signalling. The first one is based on speed codes and the second one is called distance-to-go (D2G) system.

In the speed codes method, wayside equipment selects speed codes (speed limit for a given section of the track) and transmits them to the onboard equipment to enable supervision of the maximum speed onboard the train. The basic structure of the codes is the authorised speed for the current block and the authorised speed for the next block (for example 60/30 [km/h]). In case of manual driving, the driver should take action to reach the next block within safety limits, and in case of automatic operation, the automatic train operation system (ATO) calculates the deceleration curve to enter to the next block at the desired speed.

In the distance-to-go method, the limit of movement authority (LMA) of the train is located at the end of the last track circuit occupied by the tail of the previous train or obstacle. Distance-to-go permits to reduce the headway, without compromising the safety, by reducing the number of unoccupied track circuits between two consecutive trains. There is an accurate and constant checking of the braking curve by the train, so an onboard computer calculates the braking curve required (based on the distance-to-go) to the stopping point, and generally using a track map contained in the train computer memory.

In the moving-block system, the LMA is moving along the route as the train moves. The flexibility of the system is increased and the usage of infrastructure and rolling stock is optimised. The distance between trains is reduced, compared to fixed-block schemes, and trains can travel at shorter safety distances. These distances can be variable because they depend of the braking capability of each individual train plus safety margins.

Speed codes, distance-to-go and moving-block principles are shown, and the resulting headway differences in the three systems are compared, in Figure 1-4.

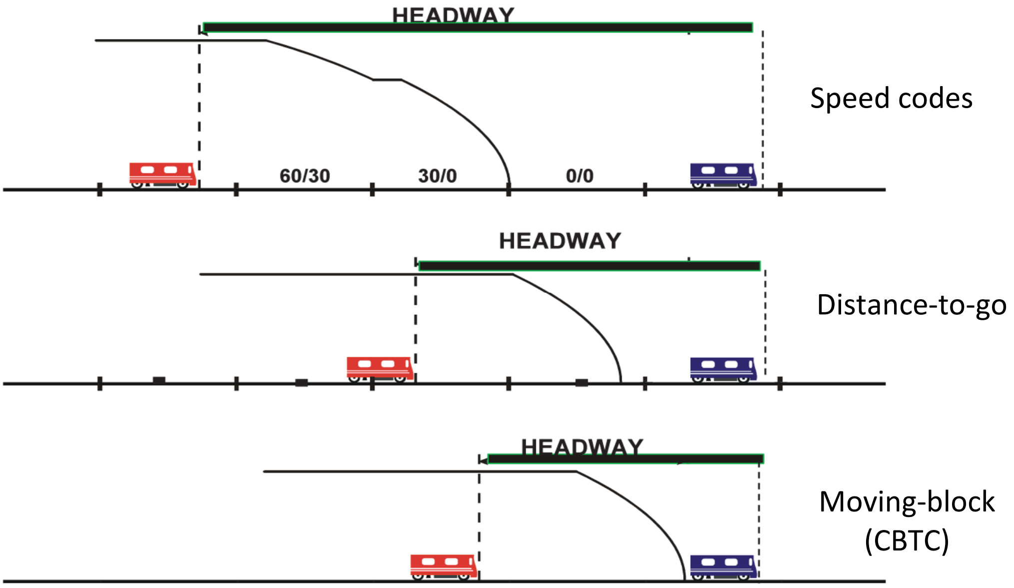


Figure 1-4. Comparison among the three signalling systems (Montes, 2011)

In sum, each signalling system keeps the safety separation during the operation of trains with different features and constraints. One of the most relevant is the operation headway, which defines the transportation capacity of the system.

The basics for the moving-block signalling system were first established by Pearson (Pearson, 1973). At that time only the theoretical principles of pure moving-block were established because the possibility of continuous bidirectional communications between train and a wayside controller was limited by the existing technological capabilities. A quantised version of the moving-block principle was then stated and it had practical applications. Short track loops (20-40m) as shown schematically in Figure 1-5, were used to setup the continuous communication between the train and the track, in this way a staircase shape with the resolution given by the loop length was obtained. In this system, the speed and position of the train were calculated by the train itself (Hill and Bond, 1995). The first approaches that implemented the quasi-moving-block signalling system were reported in Vancouver, London and San Francisco light rail networks using track conductor loops. A similar system was found in the German LZB system (Ho, Mark, 1999).

Other concepts, such as the relative moving-block were explored. The relative approach considered the leading train as a moving vehicle so that the headway could be reduced upon considering that, if the leading train had to stop, it could take some time and distance to get it. This concept did not meet the safety requirements and the 'brick wall stop' criterion (leading train considered as a static point even if it keeps moving) was taken as the generalised standard for analytical and commercial applications (IEEE, 2004).

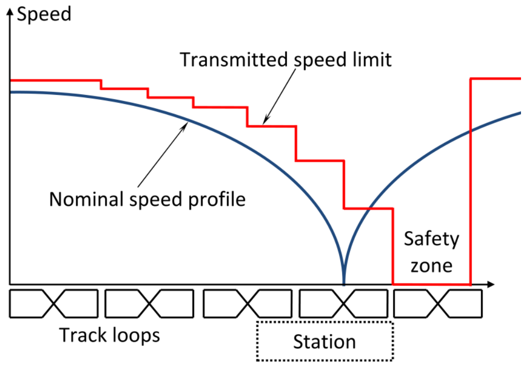


Figure 1-5. Loop speed limits approaching a station (Hill and Bond, 1995)

In modern railway systems the moving-block principle is implemented using bidirectional radio signals for train and wayside communications; this way of control is known as Communications-Based Train Control (CBTC). Railway signalling systems based on CBTC rely their safety on radio signals, wayside beacons transponders (balises) and minimum or null fallback wayside signals. In this signalling system a reliable train speed and position measurement as well as train integrity determination approach is also important to guarantee that two trains, or part of them, will not collide. The train speed, position and integrity measurements could be performed using redundant systems like tachometers, axle counters, radio signals and passive absolute position reference (APR) beacons, among others (IEEE, 2008, 2004; Pascoe and Eichorn, 2009). The quantity of equipment is reduced, and in the same way the likelihood of failure and maintenance costs are also reduced.

The IEEE has developed a guide for the calculation of braking distances for different railway applications (IEEE, 2009). The standard is intended to be comprehensive and include all commonly used considerations taken into account in designing braking curves. The specific application, driving technique (manual or automatic) and the railway administration will define if all of the model parameters and sections should be considered. A sample of a general model for rail transit applications is shown in Figure 1-6.

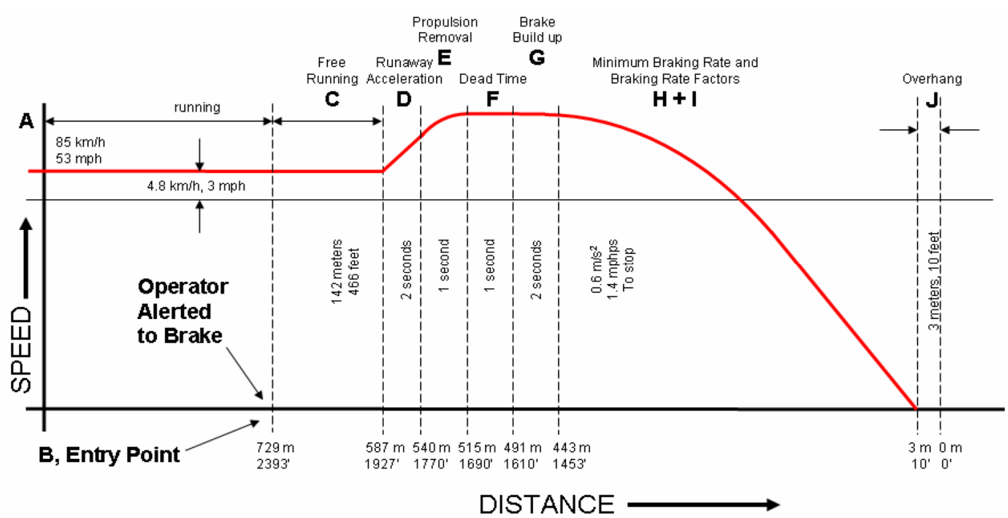


Figure 1-6. ATP emergency brake curve (IEEE, 2009)

CBTC system has the information about track speed limits, receives the LMA and calculates the target point (S_{target}), ATP emergency brake curve, ATP overspeed detection curve and ATP profile (see Figure 1-7). In this way, the ATP system provides safety margins and the ATO module will have the ATO authorised path as its maximum permitted curve (IEEE, 2004). The ATP emergency brake speed curve is a value that cannot be surpassed by the train because it immediately initiates an emergency brake procedure. The ATP overspeed detection curve is the maximum operative speed variation without intervention of the ATP system. Finally, the ATP profile is the authorised path or maximum speed curve profile which can be followed by the automatic driving system (ATO). The ATP part is the safety supervision level over the ATO layer of the CBTC equipment.

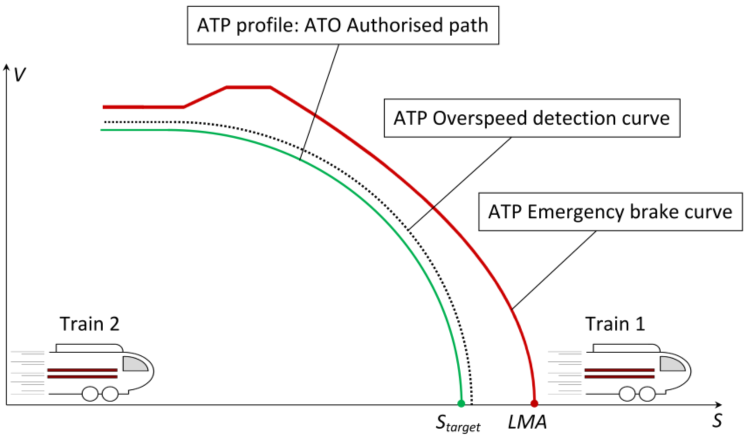


Figure 1-7. Braking curves model

The CBTC signalling system permits a close tracking between consecutive trains with the required safety margins. This capability yields a potential increase in the capacity because of the reduction of the headway. As previously mentioned, each manufacturer customises its products according to the needs of the transportation operator and constraints, the basic structure will keep the compliance with international standards and mandatory safety regulations to avoid accidents (He, 2011). This continuous communication feature could be exploited by the centralised traffic regulation system to perform more frequent and efficient traffic management. However, exploration of new energy-efficient regulation algorithms should be accomplished and implemented in the new CBTC lines (Chen, R. and Guo, J., 2010; Ding et al., 2009; Gu et al., 2011; S. Su et al., 2013b).

1.4. ENERGY EFFICIENCY IN RAILWAYS

The world transportation sector is responsible for nearly 23% of energy-based CO_2 total emissions, mainly due to road traffic. Transportation CO_2 worldwide emissions have constantly increased since 1990 and almost all transportation modes (except railways) have increased their green house gases emissions from fuel combustion. In 2009 the transportation sector was responsible for about 31% of total CO_2 emissions from fuel combustion in Europe, 1.5% of which were generated by rail (IEA and UIC, 2014, 2012). European trains are mainly propelled by electricity, and this fact makes railways a sustainable transportation mode.

Besides the care of environment, there is an increasing need of financial efficiency in the railways companies. The liberalisation process of railway markets to survive in a competitive atmosphere, have encouraged railways companies to test new technologies, developments or strategies to improve their performance without affecting the quality of the service they offer (Cantos et al., 2012; Douglas et al., 2015; González-Gil et al., 2014; Urdánoz and Vibes, 2012).

The energy-efficient operation of railways depends mainly on factors related to the rolling stock, infrastructure and traffic operation. Energy-saving strategies related to train technologies and infrastructure, are long term measures and involve heavy investment. Operation strategies are typically short- and medium-term measures along with low investment rates (Yang et al., 2016).

Energy saving during traffic operation can be reached by applying different techniques: the design of efficient timetables, the development of new traffic regulation algorithms and the ecodriving design (efficient driving profiles).

Timetable efficient design is a strategy to improve the energy performance of railways. In the design of timetables there are time margins or slack times that can be used to recover delays when necessary. This design consists in the optimisation of the distribution of the stopping time in the station (dwell time) and the running time for managing delays in the system (Wong and Ho, 2007). In addition, the optimal design of timetables could take into account the reduction in the energy consumption. Some interesting research considering this strategy can be found in the following references (Chevrier et al., 2013; Cucala et al., 2012b; Goverde et al., 2016; Scheepmaker and Goverde, 2015; S. Su et al., 2013a; Yang et al., 2009, 2014). Efficient timetabling design could also include regenerative energy management through the synchronisation of braking and starting trains at the stations (Nasri et al., 2010; Peña-Alcaraz et al., 2011; Tang et al., 2014; Yang et al., 2014; Zhou and Xu, 2012).

In normal operation, small or high delays can be present and incidences have to be solved in real-time. Trains may be delayed by different causes such as passenger accumulation at stations. These delays propagate through to the entire system and could cause instability of the service (Fernández et al., 2006; Hansen et al., 2010; Mao et al., 2007). There are two main trends to manage perturbations in the traffic operation. The first one is timetable rescheduling (Cacchiani et al., 2014; Corman et al., 2011; Jia and Zhang, 1994; Mazzarello and Ottaviani, 2007). Once a conflict is detected in real-time, the rescheduling algorithm proposes a new timetable to avoid or resolve the conflict, by means of the modification of dwell times, stop skipping, elimination of services, etc. (Abril et al., 2008; Cacchiani et al., 2014; Caimi et al., 2012; Corman et al., 2010; D'Ariano et al., 2007; Fay, 2000; Jia and Zhang, 1994; Tornquist, 2005; Wang et al., 2014b).

The second one is a centralised automatic traffic regulation system in ATO equipped lines. This system controls the departure of each train and the ATO driving commands sent to the train for adapting its individual running times (Gong et al., 2014; Gu et al., 2016, 2014; Ning et al., 2015; Takeuchi et al., 2003). In traffic regulation algorithms, running time and energy consumption are conflicting objectives, and thus, a balance must be found in real-time (Baranov et al., 2014; Rongwu, 2014; Sakowitz and Wendler, 2006). Adding the energy consumption requirement to the traffic regulation goals increases the complexity of the problem (Sheu and Lin, 2012, 2011).

Finally, ecodriving is one of the main operational strategies used to save energy and therefore reduce environmental impact and railway company's operational costs (Ceraolo and Lutzemberger, 2014; Conti et al., 2015; Fay, 2000; Feng et al., 2013a, 2013b; Zhang et al., 2005). The main goal of the energy-efficient driving (ecodriving) is to find the driving speed profile that minimises the energy consumption for a given target running time. The principle of energy efficiency by efficient driving is shown in Figure 1-8.

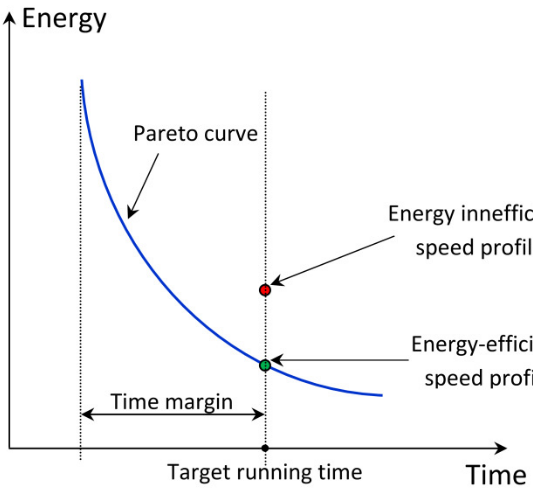


Figure 1-8. Energy-efficient driving principle

Each possible running time has an associated optimal speed profile located on the Pareto curve (see Figure 1-8). The lower the target time, the greater the associated energy consumption of the optimal speed profile. The target running time between consecutive stations is off-line designed in the timetable design phase. This running time is greater than the fastest possible (flat-out) as a margin time is necessary to recover delays that will appear during operation. If a delay occurs, the running time will be reduced to recover it, but if the train is punctual, the time margin can be used to execute an efficient driving, minimising this way the energy consumption.

Ecodriving is based on the utilisation of efficient driving strategies like coasting, holding speed at reduced values or coasting-remotoring cycles. Ecodriving principles could be applied in all levels of automation with their respective constraints. In manual driving, an ecodriving profile could be the result of the expertise of the driver or a set of driving commands suggested to the driver (Scheepmaker and Goverde, 2015; Sicre, C. et al., 2012). In automated metro lines using ATO equipment, it is possible to have strict control over speed profiles. The principal goal of ecodriving is based mainly on the use of the coast control command (null traction) (Açıkbaş and Söylemez, 2008; Chang and Sim, 1997; Chuang et al., 2009; Wong and Ho, 2004a, 2004b; Yang et al., 2016). The challenge consists in designing the proper switching points for the application of combined efficient driving modes to achieve the required running time minimising the energy consumption. Several methodologies for ecodriving have been proposed, from manual to automatic driving (Domínguez et al., 2008; Dong et al., 2010; Karvonen et al., 2011; Scheepmaker et al., 2016) and from metropolitan lines to high speed trains (Baranov et al., 2011; Domínguez et al., 2010; Ruelland and Al-Haddad, 2007; Sicre et al., 2014; Sicre, C. et al., 2012; S. Su et al., 2013c; Sun et al., 2012).

1.5. SAFE TRACKING OF TRAINS

A timetable is designed off-line to operate without disturbances considering time margins (buffer time) which can tolerate the normal minor delays. In that way, two consecutive trains can keep a headway without affecting the mutual scheduled performance (Martínez et al., 2007; Wong and Ho, 2007).

In metropolitan lines with a centralised traffic regulation system, a speed profile (ATO driving commands) is sent to the train in real-time before its departure from the station according to the target running time to the next station (Domínguez et al., 2014, 2010). These speed profiles are previously designed assuming that the train is not perturbed by proximity to the preceding one. However, if the buffer time is consumed and the train is perturbed during the running period, the designed speed profile cannot be executed and the tracking algorithm is triggered to maintain a safety distance to the preceding train. This algorithm has an impact not only on the tracking interval (capacity) but also on passenger comfort and energy consumption (Dong et al., 2016; Xu et al., 2014).

Current tracking algorithms are normally energy consuming, because of the application of braking/traction cycles to maintain safe separation. They affect also the passenger comfort during the trip due to the continuous speed commands changes.

The continuous communication of the CBTC signalling system can be used to improve not only the transportation capacity, but also the energy efficiency by means of new efficient tracking algorithms.

1.6. MOTIVATION AND SCOPE

It is expected that in the near future a high number of metro lines will be equipped with the CBTC signalling system. So far, some of the pioneers have installed CBTC, but its functionality is not being exploited completely; some of them are still operated without taking advantage of the wide operability of the new continuous system communications feature. In the literature revised, there is a need of improved algorithms for energy-efficient control of the railway operation.

This thesis is intended to contribute to improve the energy efficiency in CBTC lines.

As mentioned before, research has been conducted to the minimisation of the energy consumption in railway traffic operation. But, it is necessary to develop new specific models for CBTC which permit to take advantage of the better capacity of train control and continuous communication in order to obtain additional energy savings.

From the point of view of the ecodriving of ATO equipped trains, the CBTC permits to execute a wide variety of speed profiles due to its continuous control capabilities, and therefore it gives the chance to find more efficient ones. Hence, it is necessary to develop new optimisation models for the efficient design of speed profiles.

Also, CBTC system permits a better real-time control of the tracking of a leading train in a safe way, which improves capacity (that is the main goal of CBTC). This occurs more frequently in CBTC lines because they are exploited with a reduced headway compared to other signalling systems. Nevertheless, at present, there is no new research in CBTC tracking models including an additional aim to reduce the energy consumption.

Topics which could have some overlap with the main problems studied in this thesis, and also of interest in the analysis, were left aside to limit the research extent. These topics are mentioned below.

The effect of the catenary voltage variations in energy consumption estimation are not taken into account. The catenary voltage is considered as constant at its nominal value. The design process is an off-line task which produces speed profiles that will be executed in different scenarios, and the catenary voltage could be different to those considered during the design stage. In addition, the electrical power absorbed by modern metro trains will not be affected by pantograph voltage variations due to their input conditioning converter (Goodman et al., 1998)

The communication network is a key piece for the operation of the system, therefore the quality and stability of the signal communication used for transmitting the CBTC signals are the backbone of the signalling system. In this thesis it is assumed that the communication system is robust and reliable enough to withstand the required communications. When needed, a global delay time will be considered as the net effect of the influence of the communication system.

According to the previous analysis the main research question that must be addressed is:

How to control the motion of metropolitan trains with the CBTC signalling system in an energy-efficient way?

From this main research question a set of sub-questions arises:

Q1. How could be controlled each individual train to obtain the best energy performance for a target running time?

Q2. Which methodologies or algorithms could be implemented to control in real-time efficient tracking of trains in a metro line?

Q3. A simulation framework (software platform), including train and line models and interfaces for testing, has to be developed in order to validate the algorithms proposed in this thesis. Which simulation tools and software platforms should be used to validate them?

1.7. OBJECTIVES

CBTC, which is the last technology in signalling systems, is being installed nowadays in new metro lines and in upgraded existing ones. The main advantage of CBTC system is the reduction of headway between consecutive trains without compromising safety. This system permits continuous communication, thus besides improving capacity, this thesis states that it could also be used to improve energy efficiency.

Main objective:

The main objective of this thesis is to reduce the energy consumption in the operation of a metropolitan line equipped with CBTC signalling system.

Specific objectives:

• *To investigate new optimisation models for the design of ecodriving speed profiles that meet the running times required by the traffic regulation system with the minimum energy consumption in CBTC equipped trains.*

For this purpose, simulation-based evolutionary optimisation algorithms are investigated where each population individual is simulated to calculate its running time and energy consumption. The uncertainty associated with the mass of the train during the design process is modelled by means of a fuzzy model. With the goal of producing more even Pareto fronts for practical applications, methods for the approximated pseudo-Pareto front design are investigated.

• *To investigate new efficient tracking algorithms to be used in lines with CBTC signalling system*.

New tracking algorithms are investigated to improve the energy consumption by using coasting commands. These algorithms must keep a tracking interval with the leading train, but reducing the energy consumption.

The uncertainty associated with the speed of the leading train is included in the model. The proposed algorithms are assessed in terms of running time impact and energy consumption. The proposed algorithms are validated based on the simulation of two close consecutive trains.

• *To propose and develop simulation models of the train motion*.

A detailed simulator of the train motion is necessary to obtain reliable results of the optimal design of the speed profiles along with the new train tracking algorithm. The simulator includes models for train dynamics and traction/braking characteristics, track parameters, ATO and ATP functions. A two train simulation module is necessary to simulate the motion of two following trains with a safety distance.

1.8. THESIS DOCUMENT OUTLINE

The thesis is organised in 5 Chapters. In the first one an introduction to the problem and the motivations and objectives of the research work were exposed. In chapter 2, there is a description of the train model and the CBTC driving parameterisation proposed for this study. Chapter 3 deals with the development of the NSGA-II-F algorithm to calculate optimal speed profiles for CBTC operated trains. This chapter analyses as well the impact of the network receptivity to the energy regenerated by trains on the optimal design of speed profiles.

The next chapter, 4, deals with the proposal and validation of a new efficient tracking algorithm under disturbed conditions. A final chapter 5 of conclusions, contributions and future research work derived from this thesis is outlined.

Chapter 2

TRAIN SIMULATION MODEL

Simulation is the best approach to design and validate different strategies and algorithms and for the evaluation of railway related studies, considering the variability of the parameters involved in the problems. Railway design and operation analyses are based on good simulation platforms where realistic data and conditions can be reproduced. It is very important to build computer tools where each part of the railway system can be modelled with the necessary level of detail and accuracy, in such a way that there is an equilibrium between computational load, simulation time and precision of the solution obtained (Mao et al., 2007; Martin, 2010).

In this thesis, new algorithms for the design of efficient driving profiles (ecodriving) are investigated. The solutions for ecodriving design based on analytical models include simplifications which make them often inadequate for real cases (Albrecht et al., 2013; Franke et al., 2000; Khmelnitsky, 2000; Ko et al., 2004; Miyatake and Ko, 2010; S. Su et al., 2013c). To obtain the required level of accuracy, the algorithms proposed in this thesis are based on the detailed simulation of the train motion.

There are several approaches for railway operation analysis such as detailed simulation (time or space based simulation), event driven simulation, state-space analysis, and blended approaches (Bigharaz, et al., 2014).

Each of the methodologies has its own scope of application, accuracy levels and modellisation complexity (De Martinis and Gallo, 2013; Grube et al., 2011; Jaekel and Albrecht, 2014; Lin and Sheu, 2011; Lu et al., 2002; Xu et al., 2014).

If the purpose of the study is the design of a railway line in its initial stages or the study of the whole behavior of the system and the capacity, an event driven procedure with simplified models for track and speed profile is recommended (Goodman et al., 1998; Ho et al., 2002; Jong and Chang, 2005).

If the aim is the detailed simulation of running times and an analysis of energy consumption of trains, the time or space based procedure is advised (Bešinović et al., 2013; De Martinis and Gallo, 2013; J.P. Powell and Palacín, 2015).

A simulation model of metro lines equipped with CBTC ATO system is proposed in this thesis. Detailed simulation is a useful process to produce precise results in the study of energy consumption and running times, especially when constraints associated with actual train control equipment have to be taken into account (Mao et al., 2007).

It is necessary to design and develop a simulation model to be used in the optimisation algorithm to calculate the new efficient driving in CBTC (chapter 3 of this thesis). The simulation model will be used as well to test the new efficient tracking algorithm proposed in chapter 4.

In the present chapter a general description of a CBTC system structure and the main data flow paths among the system components is described. The description of the general model used for the simulation of the train motion, track details as well as traction motor characteristics are also included to provide a more precise simulation of the behavior of the train. The parameterisation of an individual CBTC driving for ATO applications is proposed.

2.1. THE CBTC SYSTEM

In moving-block system, the tracking of the trains depends on the braking distance plus a safety margin. The headway is variable because each LMA (limit of movement authority) is individualised according to the braking capacity of each train. It permits to increase the transportation capacity of the system. The main data known are position, direction of travel and speed of the trains. The position of each train is determined through earth located (along the track) transponders and onboard equipment. The information is transmitted wirelessly by the train to a wayside controller and then to a centralised control facility which coordinates all trains throughout the system. Instead of a fixed distance, the system has a variable safety buffer and has the capability of adjusting speed.

Figure 2-1 shows a basic configuration of a CBTC system (Pascoe and Eichorn, 2009; Wang et al., 2013). The CBTC system is based on the continuous communication via radio between trains and the control centre (Chen, R. and Guo, J., 2010; Pascoe and Eichorn, 2009). The speed and the position of each train within the coverage area are reported to the zone controller (ZC) along with the infrastructure configuration sent by the interlocking equipment. By using this data, the ZC calculates and transmits the LMA to each train within its zone of influence. As mentioned before, each train has its own mechanisms to measure and calculate position, speed, motion direction, and braking curves with the previous information about the LMA.

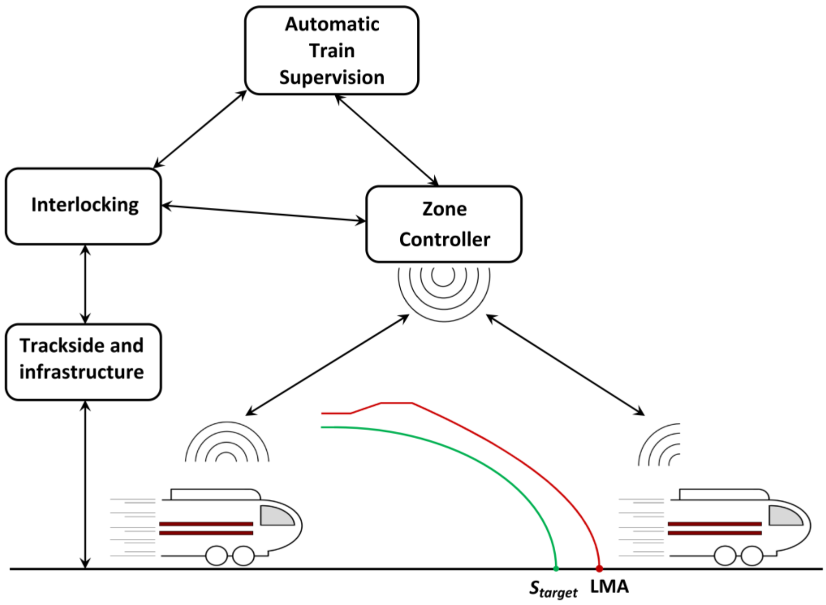


Figure 2-1. Configuration of a CBTC signalling system

In CBTC signalling system there are functions of automatic train protection ATP, automatic train supervision ATS and automatic driving (as part of the automatic train operation ATO) (IEEE, 2008, 2004).

It is possible to check almost in real-time the position, speed (and direction) of the preceding train and obstacles in the track (mainly switching points). This permits to supervise the braking curve and security distances to the leading train (IEEE, 2009). The speed and the position of the tail of each train are reported via radio to the zone controller which calculates and sends to each train its LMA. A 'brick wall' assumption is used to calculate the most restrictive braking distance considering that the preceding train is stopped at the LMA point, despite the train can be in motion. Railway signalling designers and manufactures use this concept as an extended practice (Takagi, 2012; Xu et al., 2012).

The CBTC signalling system can be implemented under pure moving-block or virtual-block systems. In a moving-block system, the portion of the track occupied by a train, which is used to calculate the LMA for the following train, is a continuous variable. However, the updating time period of the LMA depends on the architecture and design of the communication system, as well as on the admissible delay for latency of signals (Wang et al., 2015; Xun et al., 2013; Zhu et al., 2014a).

In a CBTC implemented as virtual-block system a set of parameterised logical short sections of the track are blocked while the train is passing, which introduces an additional delay in the LMA updating period (Barrow, 2010; Morar, 2012; Platt, 2010; Schaefer and Mortlock, 2001).

2.2. TRAIN SIMULATION MODEL

The train simulation is performed using a detailed simulation process with a time step basis.

In CBTC signalling systems, the ATP equipment has the information about fixed speed limits, receives the limit of movement authority (LMA) and calculates the target point S_{target} (see Figure 2-2).

The ATO authorised path calculated by the CBTC ATP equipment is the limit curve followed by the ATO system if it is reached by the train. The ATP part is the safety supervision level over the ATO layer of CBTC equipment.

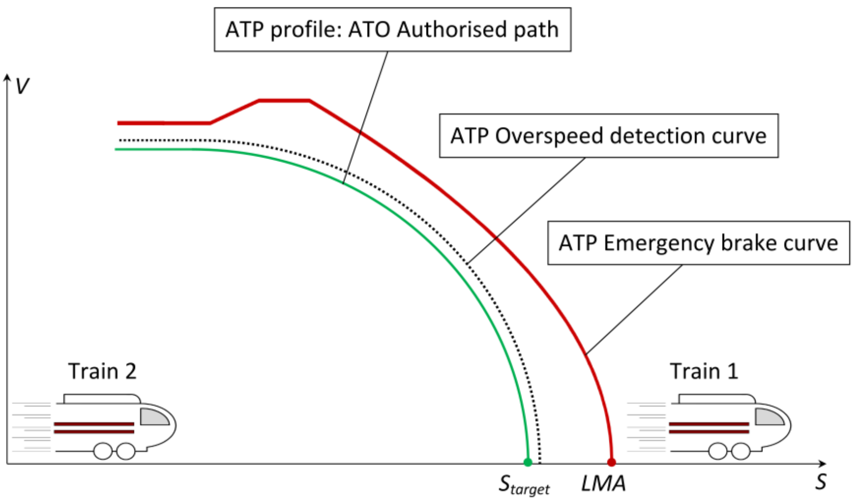


Figure 2-2. Braking curves model in CBTC

Hereafter, unless otherwise stated, it is understood that mention of the braking curve will refer to the ATO authorised path and it will be used for the most of the analysis in this thesis.

The CBTC continuous communication signalling system (Gill and Grostate, 2012) would permit to update the ATO commands along the interstations, providing new and, probably, more efficient speed profiles. In the driving model for CBTC lines, proposed in this thesis, a list of distance-based driving commands is defined from one station to the next (position, type of command, value). The types of command in the CBTC representation proposed here are:

- Traction: this command applies maximum traction force, which is a function of the train speed.
- Speed-holding: Consists in changing the traction value to maintain, if possible, a constant speed.
- Coasting-remotoring cycles: Defined by a speed band. When the coasting speed is reached, traction effort is null until the remotoring speed is reached and full traction effort is demanded.
- Coasting: the traction demanded is null and the train continues its motion along the track.

The transition points between each pair of commands are also called switching points.

The braking command is launched automatically depending on final stop process or safety requirements given by changes in the LMA from the ATP. A deceleration rate is supplied for the calculation of braking curves (Carvajal-Carreño et al., 2014).

The developed simulation model consists of three modules: train, line and ATO modules and considers all of the main variables that affect the train dynamics (Carvajal-Carreño et al., 2014).

The model of the train takes into account the length and mass of the train, running resistance, traction and braking maximum effort curves, variations of motor efficiency with respect to effort ratio, and rotary inertia.

The line characteristics included in the model are speed limits, tunnels, track slopes (and the effect along the train) and track bends (Carvajal-Carreño et al., 2015; Domínguez, M. et al., 2011).

The ATO module interprets and executes the driving commands that can be programmed in real ATO equipment and always observes the speed limitations provided by the ATP system (Allotta et al., 2013).

Under this representation the train has several operations regimes: traction (to reach or keep the maximum speed or flat-out), speed holding (to reach or keep a speed command value), coasting-remotoring cycles fluctuating between two predetermined speeds, coasting in a section of the route and braking. An illustrative speed profile with several of the possible driving regimes is shown in Figure 2-3.

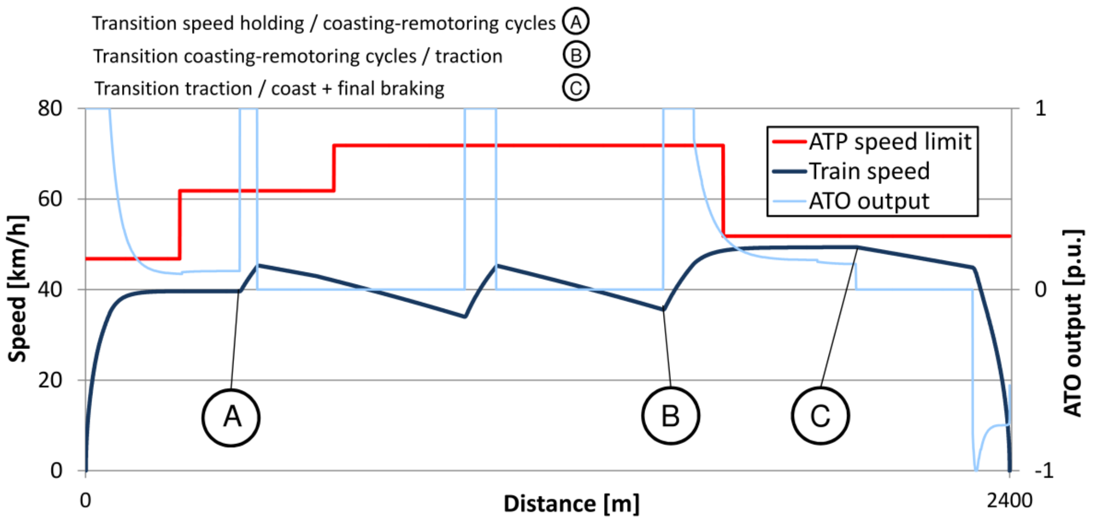


Figure 2-3. ATO driving commands in CBTC

The respective command matrix of the sample speed profile is shown in Table 2-1.

Distance [m]	Driving command	MinVal	MaxVal	Dec. Rate
0 - 400	Speed holding	40 km/h	-	0.8 m/s^2
400-1500	Coasting-remotoring cycles	45 km/h	34 km/h	
1500-2000	Traction	-	-	
2000-2500	Coasting	-	-	

Table 2-1. Example of descriptive parameters in CBTC ATO driving

The switching points A, B, and C in the diagram of Figure 2-3 represent the transitions between different driving modes: Speed holding, coasting-remotoring cycles, traction and coast up to the final braking curve. Initially, a speed holding command of 40km/h is applied, and at transition point A (400 m) the command is changed to coasting-remotoring cycles between 45 and 34 km/h. Then, a traction command is applied between 1500m (point B) and 2000m. A coast command is activated at point C (2000 m) up to intersecting the braking curve. A final braking process with deceleration rate of 0.8m/s^2 is executed to stop at the next station.

For undisturbed operation it is supposed that this sequence of commands is kept until the train reaches the next station. In case of disturbed operation analysis, a tracking algorithm is launched to control safely the train separation according to the applicable rules in the CBTC.

It is worth to notice that the flexibility in the operation of the ATO operated trains in a CBTC environment gives the possibility of applying new techniques and algorithms because of the improvement of communications bandwidth and the possibility of changing the driving command during the journey.

All the CBTC driving profiles presented in this thesis will be based on the parameterisation described before.

A scheme to represent the main parameters and the data flow in the train model is shown in Figure 2-4.

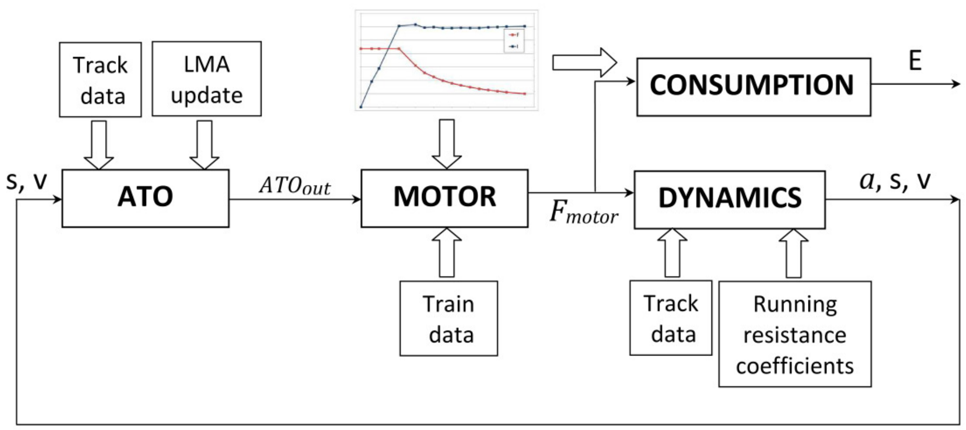


Figure 2-4. General structure of the train model (Adapted from (Domínguez et al., 2010))

One of the main components of the train simulation is the ATO equipment. This thesis models real ATO equipment widely used in Spanish metro lines. The output of the ATO system (ATO_{out}) is calculated as a speed change to reach the target speed, and corrected with the gradient (a_g) and it is bounded at 1 and -1 (see Eq.(2-1)). This calculation function is a proportional controller, where k ensures that the target speed is achieved in a certain period of time (Domínguez, M. et al., 2011). V_{target} and V are the target and current speed of the ATO at each simulation cycle considering the active driving command and the ATO authorised path received from the ATP system. The value a_g is a feedforward parameter of the controller to compensate the gradient of the track. This way, if the train is running with no error (that is V is equal to V_{target}) along a positive slope, the command calculated by the ATO is adequate to maintain the target speed. To adjust this feedforward parameter, it is considered that in real metro lines like Metro de Madrid, the acceleration rate at maximum traction effort is designed to be approximately 1 m/s^2. Thus, the command necessary to compensate the slope is a_g (dimensionless): $\frac{F_m}{F_{max}} = \frac{M \cdot a_g}{M \cdot 1} = a_g$

And a_g is calculated as 9,8*slope (in ‰), given the slope stored in the ATO configuration data (and that could be simplified compared to real data).

$$ATO_{out} = k \cdot \left(V_{target} - V\right) + a_g \qquad (2\text{-}1)$$

If the driving command is coast, then ATO_{out} = 0 (unless it is necessary to apply the brake to keep the maximal speed in a steep slope).

The output ATO_{out} of the ATO model is interpreted by the motor as the ratio between the required traction/brake force and the maximum traction/brake force corresponding to the speed at each simulation step (Eq.(2-2)).

$$F_m = ATO_{out} \cdot F_{max}(V) \qquad (2\text{-}2)$$

When the onboard ATO equipment receives the command, if the difference between the target speed and the current speed of the train is very high, the output ATO_{out} calculated by the ATO system is saturated to ±1. Thus, the effort applied by the motor is the maximum for the respective speed, F_{max}**.** Maximum traction/brake curves, corresponding to the maximum ATO values ±1, are shown in Figure 2-5.

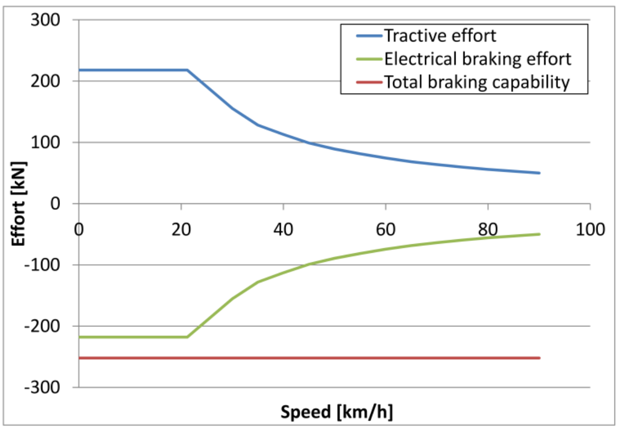


Figure 2-5. Traction/Braking curves

When the train brakes, electric brake is first applied, taking into account the maximum braking effort curve (Figure 2-5). Blending (electric and mechanical braking) actuates if the effort necessary to provide the deceleration rate required by the ATO system is higher than the maximum electrical braking effort (see the total braking effort in Figure 2-5)(Conti et al., 2015).

A function controls the jerk limit ($\Delta a/\Delta t$) (J. P. Powell and Palacín, 2015) at each simulation step, so uncomfortable speed profiles due to abrupt traction force changes are avoided. A sample of a speed profile traction effort for a jerk limit of 1m/s^3 is shown at Figure 2-6.

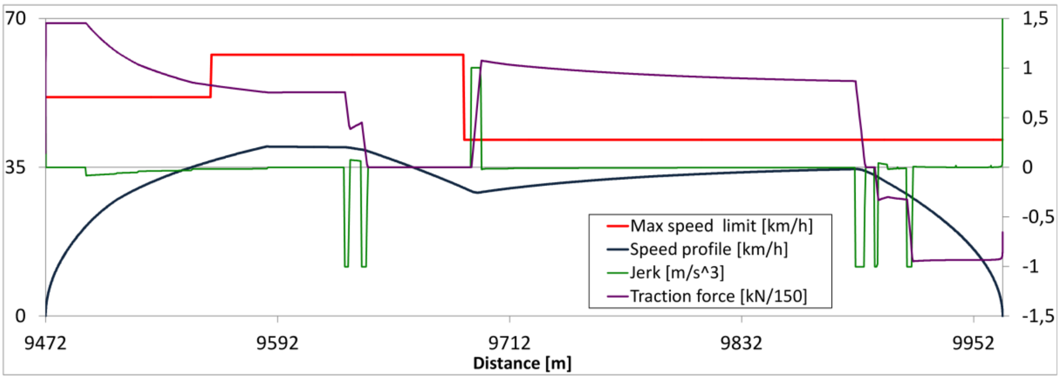


Figure 2-6. Jerk limitation

The track map included in the onboard memory is modelled considering the permanent speed restrictions given by the ATP. The simulator takes into account, the length of the train in the application of the speed limits. Speed limits apply until the whole length of the train is outside of the restricted zone (IEEE, 2004).

The time step-based simulation model calculates the train acceleration at each step from the balance of forces expressed in Eq.(2-3).

$$M_{eq} \cdot a = F_m - (F_r + F_g + F_c) \quad (2\text{-}3)$$

where the equivalent mass M_{eq} is the mass of the train plus the rotational inertial effect, a is the acceleration of the train, F_m is the motor force, F_r is the running resistance force, F_g is the force due to the track grades and F_c is the force due to curvature radius. Bends are modelled as equivalent grades. The equation of the running resistance is the Davis formula which is a function of train speed (v) as shown in Eq.(2-4) (Luckasewicz, 2001). The force due to the grades along the track is calculated as shown in Eq.(2-5) and the resistance due to curves is modelled as a equivalent grade depending of the curvature radius as is shown in Eq.(2-6).

$$F_r = A + B \cdot v + C \cdot v^2 \quad (2\text{-}4)$$

$$F_g = g \cdot m \cdot p \quad (2\text{-}5)$$

$$F_c = \frac{g}{1000} \frac{514}{R} m \quad (2\text{-}6)$$

where m is the mass of the train, g is the acceleration of gravity, and p is the average grade of the track affecting the length of the train at each simulation step and R is the curvature radius.

Once the train acceleration has been calculated, the new position of the train at each simulation step can be obtained from the uniformly accelerated motion equation.

The energy consumption of motors is calculated at each simulation step as the mechanical power ($F_m \cdot v$) multiplied by time step (Δt), divided by the efficiency of the motor (μ) (Domínguez et al., 2011).

$$\Delta E = F_m \cdot v \cdot \frac{1}{\mu} \cdot \Delta t \qquad (2\text{-}7)$$

To calculate the traction energy consumption (*EC)* associated with an interstation, these consumptions are integrated for all of the simulation steps (N) as is shown in Eq.(2-8)

$$EC = \sum_{i=1}^{N} \Delta E_i \qquad (2\text{-}8)$$

To validate the simulation model of the train, the model was configured to meet similar conditions to those in previous research, and simulation results were compared to previous work (Domínguez et al., 2011).

The simulator is developed in an object oriented environment using the C++/CLI programming language. It is composed by modules: train motion, track and CBTC/ATO modules. The main physical and dynamic variables that affect the train motion are considered in a high level of detail for each of the components. The data are taken from real data sources as infrastructure layouts and train data sheets.

Additional models for the design of off-line optimal speed profiles using a simulation-based optimisation approach named NSGA-II-F and a tracking algorithm applied to two consecutive trains will be explained in the next chapters.

A general scheme for the description of the available models and modules and the data flow interchange is depicted in the Figure 2-7. A detailed description of each algorithm and the scientific contributions related with each of them will be presented in the following chapters of the thesis.

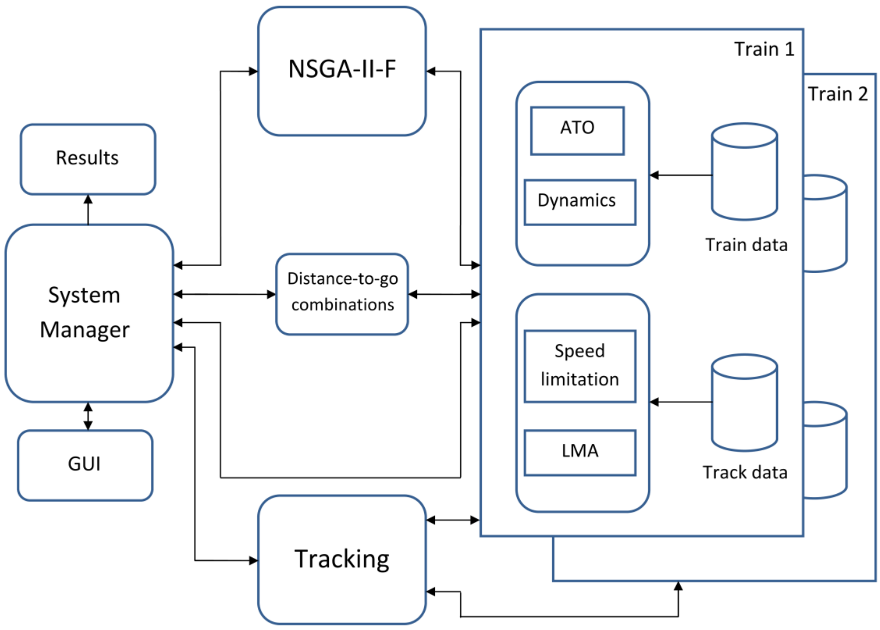


Figure 2-7. General structure of the simulation environment

2.3. CONCLUSIONS AND CONTRIBUTIONS

2.3.1. CONCLUSIONS

A simulation model of a train motion for metro lines with CBTC ATO system has been proposed.

The developed simulation model consists of three modules: train, line and ATO modules, and considers all of the main variables that affect the train dynamics.

The model of the train takes into account the length and mass of the train, running resistance, traction and braking maximum effort curves, motor efficiency, and rotary inertia. The line characteristics included in the model are speed limits, tunnels, track slopes (and the effect along the train) and track bends. The ATO module interprets and executes the driving commands that can be programmed in real ATO equipment. In the proposed driving model for CBTC lines, a list of distance-based driving commands is defined from one station to the next (position, type of command, value). The types of command in the CBTC representation proposed here are: traction, speed-holding, coasting-remotoring cycles (defined by a speed band) and coasting. The ATO module of the simulation model always observes the speed limitations provided by the ATP system, simulating the real behavior of ATO equipments.

This detailed simulation model will be used in the optimisation algorithm to calculate the new efficient driving in CBTC (chapter 3 of this thesis), as well as to test the new efficient tracking algorithm proposed in chapter 4.

2.3.2. CONTRIBUTIONS

The main contribution of this chapter is the development of a detailed simulation model for the motion of a train equipped with CBTC ATO system, including realistic characteristics of the train, the line and the ATO equipment.

Chapter 3

OPTIMAL DESIGN OF ATO SPEED PROFILES IN CBTC OPERATED TRAINS

This chapter is focused on the optimal design of CBTC ATO speed profiles. First, a state of the art in the design of efficient ATO speed profiles is presented. Next, a new model for CBTC is proposed based on a multi-objective NSGA-II algorithm with fuzzy parameters. This way, the model includes the uncertainty associated with the passengers load, and thus, with the mass of the train. A comparison among fixed-block speed profiles and CBTC ones is performed to compare the improvements in the energy saving level. The proposed model is refined to enhance the solutions with non-uniformly distributed Pareto fronts by a new gap-filling algorithm for the regions of the Pareto front without available solutions. An analysis for considering the effects of regenerated energy flow and net energy performance on the ecodriving design is carried out.

3.1. INTRODUCTION AND STATE OF THE ART

As previously indicated, the objective of ecodriving is to find the driving speed profile that minimises the energy consumption for a target running time.

The energy savings associated with the ecodriving design depend on the available time margins and the track and train characteristics. Previous research has shown that 14-20% of savings can be obtained through manual or automatic driving strategies that get the maximum exploitation of the system configuration (Fernández-Rodríguez et al., 2015; Mlinarić and Ponikvar, 2011; Rao et al., 2013; Sicre, C. et al., 2012; S. Su et al., 2013a).

In ecodriving design, different optimisation techniques have been used combined with simulation: Genetic algorithms (GA) (Bocharnikov et al., 2010, 2007; Brenna et al., 2016; Chang and Sim, 1997; Fu et al., 2009; Sandidzadeh and Alai, 2016; Sicre, C. et al., 2012; Wong and Ho, 2004a; Yang et al., 2012), Artificial neural networks (ANN) (Açıkbaş and Söylemez, 2008; Chuang et al., 2009, 2008), direct search methods (De Cuadra, F. et al., 1996; Wong and Ho, 2004a), Ant Colony Optimisation (ACO) (Lu et al., 2013; Sandidzadeh and Alai, 2016; Zhao et al., 2015), Particle Swarm Optimisation (PSO) (Domínguez et al., 2014; Hu, 2012; Meng et al., 2009; Sun et al., 2012). In (Ding et al., 2011) GA combined with simulation is applied for the ecodriving design and the distribution of recovery times along the line, designing the timetable.

For trains equipped with ATO, the design of ATO driving speed profiles has two main objectives: quality of service (punctuality, regularity and comfort of passengers), and energy consumption (Domínguez et al., 2011; Wang et al., 2011).

The optimal speed profile is a combination of train operation modes as acceleration, speed regulation, coast and braking (Chang and Sim, 1997; Ding et al., 2009; Domínguez et al., 2011, 2008; Gu et al., 2011; Miyatake and Ko, 2010).

Studies on the driving efficiency with ATO can be found in (Bocharnikov et al., 2007; Chang and Xu, 2000; Han et al., 1999; Khmelnitsky, 2000; Kim et al., 2013; Lu et al., 2013; Wong and Ho, 2004a; Zhao et al., 2014; Zhou et al., 2011). However they do not meet realistic features and constraints of the ATO equipment, or the ATO model is simplified (De Cuadra, F. et al., 1996). Actual characteristics of ATO equipment are considered in (Domínguez et al., 2011; Fernández-Rodríguez et al., 2015; Ke et al., 2009) but their analysis are just suitable for fixed-block signalling systems.

The continuous communication feature in CBTC systems can be exploited by the centralised traffic regulation system to perform more regular and efficient traffic management. However, new energy-efficient traffic regulation algorithms have not been developed and implemented in current CBTC lines (Ding et al., 2009; Gu et al., 2011; S. Su et al., 2013b).

CBTC continuous communication allows for updating ATO driving commands at any point of the interstation, in contrast with the former fixed-block signalling system, where ATO commands are loaded onboard the train only at the station and it is not possible to update them until the train reaches the next station. This way, new types of speed profiles can be executed by CBTC, and in general it will be possible to obtain more efficient profiles for each running time. The aim of the algorithm presented in this chapter is to calculate the optimal ATO speed profiles (Pareto curve) for the two objectives: running time and energy consumption. The designed Pareto curve will be the input configuration data for the traffic regulation system that will select, in real-time, the optimal speed profile.

An ACO max-min ant (MMA) algorithm is proposed in (Ke et al., 2012) on the framework of moving-block systems, for the single objective problem. In (Domínguez et al., 2014) the multi-objective problem was stated for energy consumption and running time, based on a Multi-Objective Particle Swarm Optimisation (MOPSO) algorithm, but it does not take advantage of the CBTC communication capability to update ATO commands.

In (Chevrier, 2010), the multi-objective design problem was stated for minimising energy consumption and the travel duration, based on an evolutionary algorithm called the Indicator Based Evolutionary Algorithm (IBEA), but the driving model used was too simplistic (traction, speed regulation, coasting and braking).

A multi-population genetic algorithm (MPGA) is used to calculate efficient driving profiles for multiple interstations in (Huang et al., 2015). A bi-level problem is solved: the high level part aims to optimise the trip time and dwell time distribution and the low level part is intended to the design of an efficient driving regime sequence (combination of maximum acceleration, coasting and maximum braking).

In this chapter, a multi-objective evolutionary algorithm NSGA-II-F is proposed to obtain the consumption-running time Pareto front based on the detailed simulation of a train equipped with a real ATO system, in a CBTC metro line.

In order to obtain a smooth functioning of the traffic regulation system, it is preferred to obtain a Pareto curve in which time distance between consecutive points is small enough, thus, specific algorithms for gap-filling are necessary. These algorithms include the one based on crowding distance measure (Kukkonen and Deb, 2006), the solution proposed in (Patnaik and Behera, 2011) by means of pseudo-inverse functions and Artificial Neural Networks (ANN) techniques, the Pareto front interpolation method proposed in (Hartikainen et al., 2012), and other gradient-dependent methods (Schütze et al., 2010).

However, all these methods fill gaps with dominant points, so the gap is not filled if there are no dominating points. When the energy consumption difference is negligible, filling the gaps with dominated points is necessary to avoid broad separation between points (a few seconds is a large distance for traffic regulation purposes). The method proposed in (Burachik et al., 2013; Dutta and Kaya, 2011), called Tchebychev Scalarization Along Rays, deals especially with disconnected Pareto fronts. Dominated points are discarded, but this procedure could be applied to obtain dominated points. One of the main drawbacks of the process consists of the adequate determination of the weights of the algorithm. A new procedure for gap detection and filling is proposed in this chapter to obtain a pseudo-Pareto curve with dominated points when necessary.

The uncertainty associated with the mass of the train, that is, the passengers load, should be taken into account due to the important impact on the running time and the energy consumption. However, most of the papers in the literature focused on ecodriving design do not consider the uncertainty associated with this parameter.

Frequently the uncertainty in parameters is better represented by fuzzy knowledge modelling. Uncertainty modelled as fuzzy knowledge (Bellman and Zadeh, 1970) has been applied to different railway applications as in (Bai et al., 2014; Chang and Thia, 1996; Corriere et al., 2013; Fay, 2000; Hanaoka and Kunadhamraks, 2009; Isaai et al., 2011; Jia and Zhang, 1994; Tsang and Ho, 2004; Wang et al., 2012; Yang et al., 2009).

In (Bocharnikov et al., 2007), a model for an optimal driving strategy is proposed based on a single objective GA with energy consumption and running time included as the fuzzy parameters. However, the uncertainty associated with the mass of the train is not modelled. The proposed model in (Cucala et al., 2012b) permits the joint design of timetable and efficient driving, taking into account a fuzzy model of delays and fuzzy punctuality constraints. In (Sicre et al., 2014) the manual driving is modelled by means of fuzzy parameters and a GA with fuzzy parameters is proposed for the driving regulation algorithm of a high-speed train.

In the present chapter an algorithm for the design of efficient speed profiles is developed. The proposed method is an evolutionary algorithm based on the detailed simulation of the train motion. The Pareto curve running time-energy consumption is calculated by means of the multi-objective NSGA-II-F algorithm (Carvajal-Carreño et al., 2014). The mass of the train is modelled as a fuzzy number, thus a hybrid technique (Vasant, 2010; Vasant et al., 2012a) is proposed: a multi-objective NSGA-II with fuzzy parameters (NSGA-II-F). The method to solve the optimisation model with fuzzy parameters is based on α-cut arithmetic of the fuzzy numbers (Chanas et al., 1984) combined with the NSGA-II optimisation. For this purpose, new definitions of fuzzy weak and strong dominance are proposed. In addition, the algorithm permits the inclusion of dominated solutions to obtain a pseudo-Pareto curve, filling running time gaps.

In the following section the design of efficient ATO speed profiles in distance-to-go fixed-block signalling system is described in detail as an introduction to the model proposed in this thesis for CBTC ATO systems.

3.2. DESIGN OF EFFICIENT SPEED PROFILES IN DISTANCE-TO-GO FIXED-BLOCK SYSTEM

In automatic driving, the possible speed profiles depend on the combination of the speed profile parameters available at the ATO equipment. The set of parameters sent to the ATO equipment through the balises varies according to the manufacturers (Cucala et al., 2012a; Domínguez et al., 2008) and could involve for example, speed holding (cruise speed), coasting-remotoring cycles and a deceleration rate for reductions and final braking processes (Domínguez et al., 2008). The purpose of having these different choices of speed profiles with different running times for the same interstation is to have a wide regulation control to manage delays and different traffic conditions during an operation day. An example of possible speed profiles for coasting-remotoring cycles and holding speed commands can be observed in Figure 3-1 a) and b).

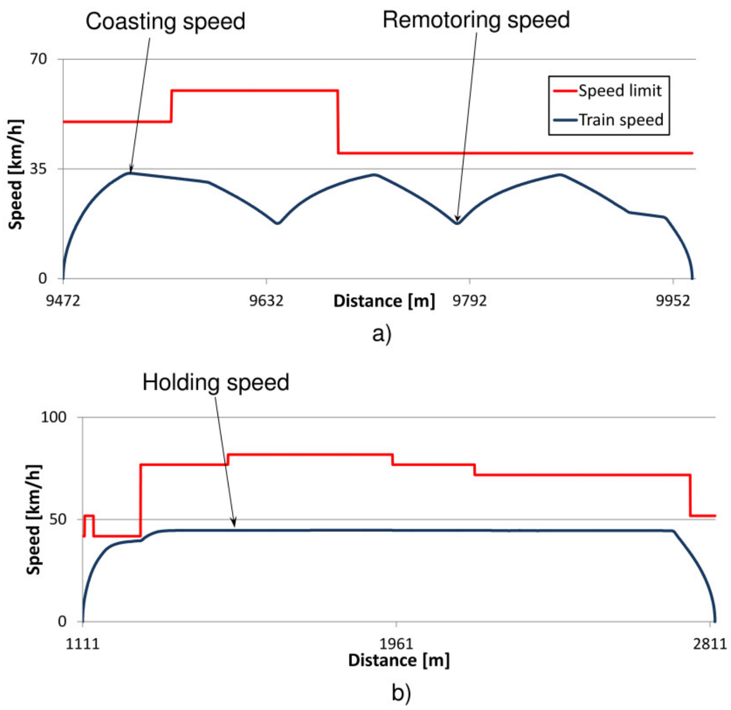


Figure 3-1. Different speed profiles: a) Coasting-remotoring, b) Holding speed

An example of the possible cloud of points or feasible driving profiles for the ATO parameters is shown in Figure 3-2. The driving profiles are selected taking into account different criteria as optimality, sensitivity, time separation distribution and comfort (defined by the railway administrator). Feasible solutions (possible profiles) located along the same vertical line correspond to speed profiles which spend the same running time with different energy consumption. The optimal or best possible solution should be located in the Pareto frontier of the solution space.

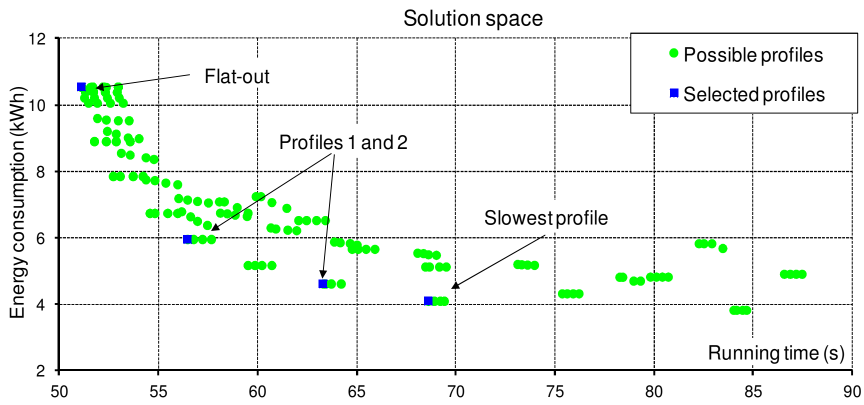


Figure 3-2. Solution space for distance-to-go ATO (Domínguez, M. et al., 2011)

As an illustrative example, Figure 3-3 shows two different speed profiles: the actual profile in the interstation and a proposed speed profile to obtain energy saving within the admissible journey time limits.

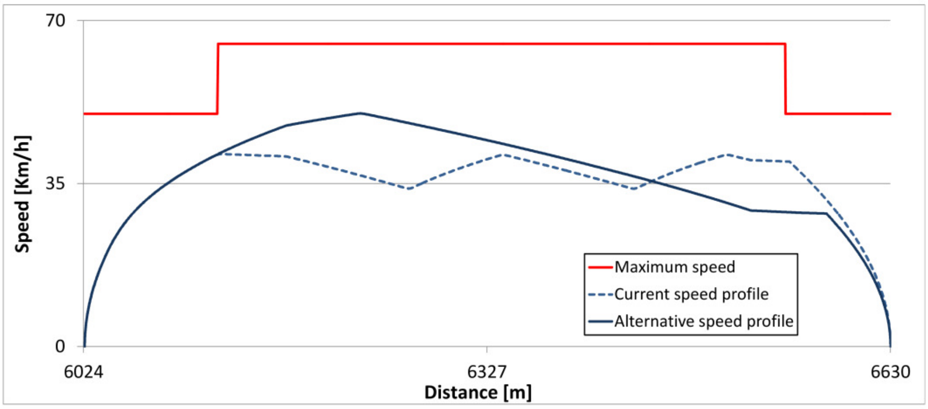


Figure 3-3. Actual and proposed speed profiles

In the work presented in (Domínguez et al., 2011, 2008) a cloud of points was evaluated. Then four different optimal speed profiles were selected off-line and supplied to be programmed in the railway traffic regulation system. This system selects the most suitable speed profile (among these four solutions) in real-time according to the actual operational requirements of the network. Figure 3-2 shows the four selected speed profiles: the fastest one (or flat-out), the slowest admissible according to the operator criterion, and two intermediate speed profiles. In the work done in (Domínguez et al., 2011) a detailed simulator was built to design off-line speed profiles for distance-to-go signalling systems.

These speed profiles are transmitted to the train through fixed antennas (balises) located at the departure point of the stations to perform the selected driving profile in the next interstation. Therefore, the set of parameters sent before departing is unique and does not permit changes at intermediate points. Besides, the communication system has a low bandwidth and hence the values taken for the parameters are discrete and limited.

The finite space of solutions was explored exhaustively simulating all the possible combinations of the ATO configuration parameters and then, by using decision techniques, a set of energy-efficient driving profiles was selected. The above mentioned methodology will be used in the case example of this chapter to compare the achievable improvement level in energy saving comparing the distance-to-go and CBTC signalling systems.

The following sections present the proposed fuzzy NSGA-II algorithm (NSGA-II-F) for the optimal design of CBTC ATO speed profiles. To overcome the design and operations constraints, a time-gap detection and gap-filling algorithm is added to obtain an evenly spaced pseudo-Pareto frontier.

3.3. UNCERTAINTY IN THE TRAIN MASS

The mass of the train is an influencing factor in the performance of the train from the energy point of view. The transported mass is a function of the passenger load. The mass can vary according to the time of the day and the day, and this uncertainty has been modelled as a fuzzy number.

Figure 3-4 shows the influence of the train mass in the running time and energy consumption. Different speed profiles using different percentages of the train load have been simulated (from 10% to 100% of train load). The empty train mass is 159,697 t and the full loaded train mass is 237,697 t. The figure shows the effects of the mass variation in the running time and mainly in the energy consumption.

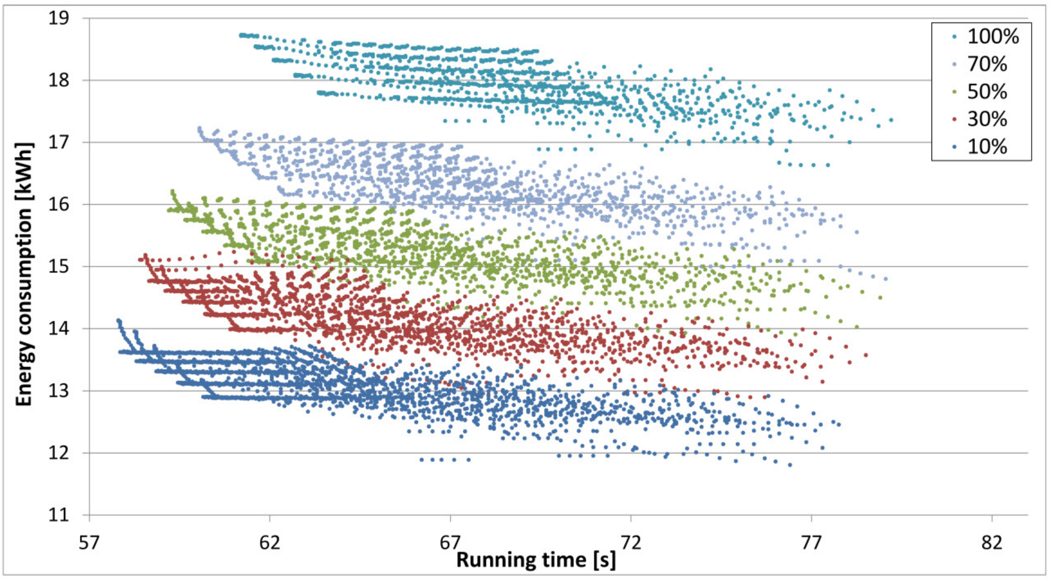


Figure 3-4. Influence of passengers mass (percentage of load) in the running time and energy consumption

A triangular fuzzy number is used to model the mass of the train as shown in Figure 3-5. Other choices of fuzzy membership functions could be used as the exponential, hyperbolic, piece-wise linear (Xiao et al., 2012) and the S-shaped membership (Chang, 2010; Vasant et al., 2012b).

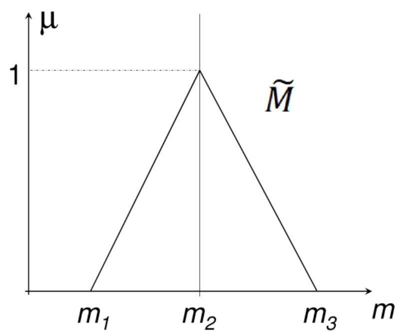


Figure 3-5. Fuzzy mass model

The mathematical representation of the membership function is shown in the Eq.(3-1), where m_3 is the maximum train mass and m_1 is the minimal train mass taken for the considered period of time.

$$\mu_{\widetilde{M}}(m) = \begin{cases} 0 & \text{if } m < m_1 \\ \frac{m-m_1}{m_2-m_1} & \text{if } m_1 \leq m \leq m_2 \\ \frac{m_3-m}{m_3-m_2} & \text{if } m_2 \leq m \leq m_3 \\ 0 & \text{if } m > m_3 \end{cases} \tag{3-1}$$

Fuzzy numbers and probability distributions play a similar role in possibility and probability theories, respectively. In possibility theory, a fuzzy number could be understood as a sequence of nested confidence intervals called α–cuts ($x^{\alpha_k} = [x^{\underline{\alpha_k}}, x^{\overline{\alpha_k}}]$) in Figure 3-6, with the confidence degree indicating the level of belief that the concerned uncertain magnitude belongs to the corresponding interval (Klir and Yuan, 1995). This belief measure, called Necessity (*N*) is maximum for x^0, *N*(x^0) = 1 and decreases as alpha increases *N*(x^α) = 1- α. Necessity is defined for any set of real numbers, not only α-cut, using a related fuzzy measure called Possibility (Π). For any given set A, where, A^c is the complement of set A. Π(A) = 1-*N*(A^c) and N(A) = 1-Π (A^c). The possibility that the mentioned magnitudes belong to a set of points increases, as the necessity of being outside this set decreases (Romero et al., 2008).

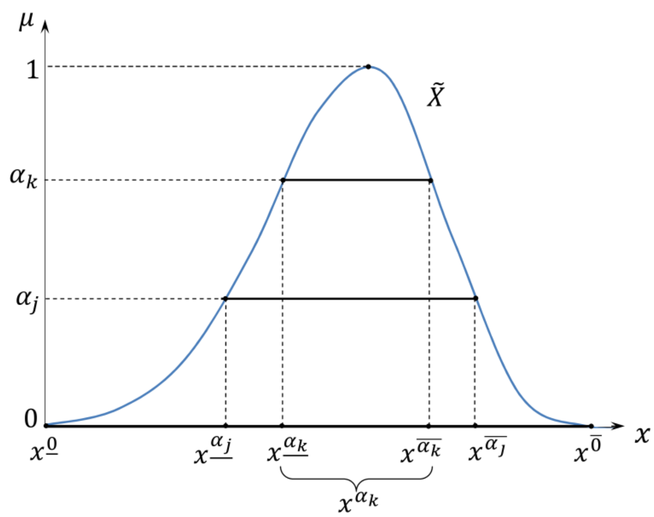


Figure 3-6. Fuzzy number and alpha cuts

3.4. NSGA-II-F ALGORITHM FOR THE DESIGN OF OPTIMAL SPEED PROFILES

Once the fuzzy model of the train mass has been defined, this chapter describes the proposed multi-objective optimisation model.

The optimisation problem can be stated as Eq.(3-2).

$$\text{minimise}\, J(x) = \big(T(x), E(x)\big) \tag{3-2}$$

Where $J(x)$ is the objective function, and $T(x)$ and $E(x)$ are the running time and energy consumption associated to an evaluated solution x (the set of parameters that configures the speed profile). The optimisation process is subject to the constraints given by the train dynamics, the track and the operation constraints. The multi-objective minimisation problem that should be solved is the minimisation of two conflicting objectives, the energy consumption and the running time. The algorithm is refined with a time-gap detection and function for filling with dominated points, to obtain a pseudo-Pareto curve.

A multi-objective crisp NSGA-II algorithm classifies the solution space in terms of dominance and crowding distance (CD). The crowding distance is used to guarantee a more spread set of solutions along the Pareto curve (Deb et al., 2002) although other diversity and distribution measures can be found in the literature (Yan et al., 2007).

Figure 3-7 shows a schematic representation of the dominance concept for a bi-objective optimisation problem. An index denoting the quantity of solutions that dominate each point is the basis to determine the levels of dominated fronts. The solutions in the level zero of domination (non-dominated) correspond to the optimal Pareto front (Veldhuizen and Lamont, 1998).

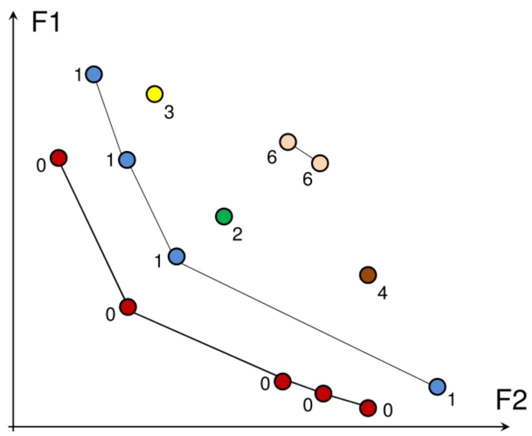


Figure 3-7. Dominance levels (different fronts classified by dominance index)

A solution *A* is said to dominate *B* denoted by $\prec B$, if and only if $A_i \leq B_i$ for every *i* (being *i* each of the objective functions) and $A_i < B_i$ at least for one objective function. If it is equal in one of the objectives then B is called a weak Pareto point (See Figure 3-

8). The objective functions in this research are the energy consumption (F1) and the running time (F2).

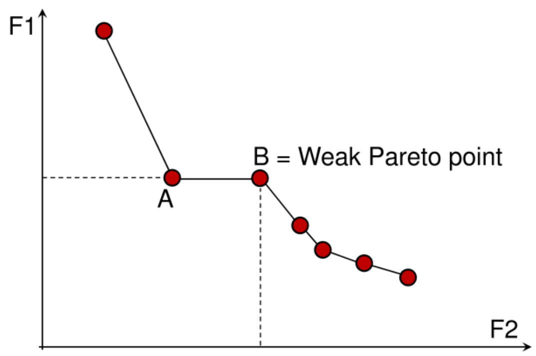


Figure 3-8. Example of weak Pareto point

3.4.1. NSGA-II-F ALGORITHM FLOWCHART

The flowchart of the proposed NSGA-II-F algorithm is shown in Figure 3-9. In the first step, a random population of crisp driving command matrices (real number coded genes (Herrera et al., 1998)) is generated. The set of CBTC commands that configures one individual of the population is a set of crisp commands. Then they are simulated and the unfeasible and uncomfortable speed profiles are discarded.

An individual of the population is a speed profile and is composed of: a matrix of distance based commands, and the associated running time and energy consumption.

For each individual, the simulation with the fuzzy mass $\widetilde{M}$ of the train provides a fuzzy running time $\widetilde{T}$ and a fuzzy energy consumption $\widetilde{E}$.

In the following, the rest of the diagram is described: fuzzy-dominance, fuzzy crowding distance, mutation and crossover and the gap-filling algorithm.

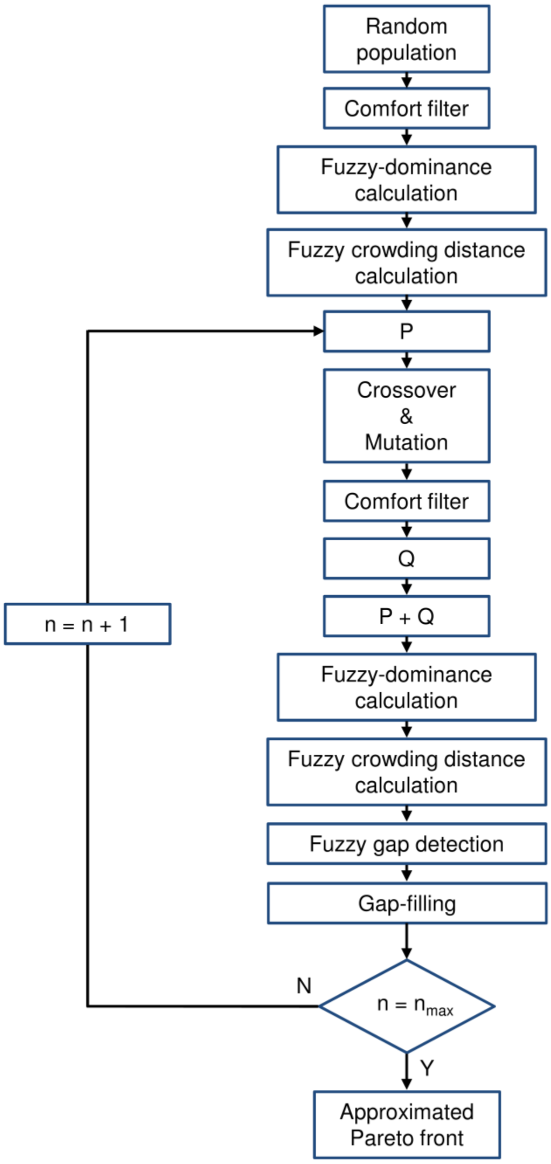


Figure 3-9. Flowchart of the NSGA-II-F algorithm

The feasibility of each speed profile could be detected by evaluating during the simulation or after its finalisation if the operational or comfort conditions are met or violated.

3.4.2. FUZZY-DOMINANCE

Fuzzy-dominance is defined by (He et al., 2013) as an indicator to measure the level of domination in each objective when there is a multi-objective problem and most of the population becomes non-dominated at early stages of the procedure. The authors stated that the dominance of an individual *A* over another one *B* can be hardly fulfilled in high dimensional problems. Therefore, a fuzzy Pareto dominance relation is proposed by the authors applying a left Gaussian function to transform the performance of an individual with respect to the other into a measure in the interval [0,1]. After doing that, a fuzzy product is used to aggregate the individual fuzzy contributions for each single objective obtaining the total fuzzy-dominance value.

In the reference (Farina and Amato, 2004), the fuzzy-dominance is defined using the fuzzy definition of 'equal to', 'greater than' and 'less than' as fuzzy sets. A numerical interpretation can be derived from this linguistic concepts and give the definition of fuzzy-dominance and fuzzy-optimality levels to permit the classification of a set of solutions in a multi-objective optimisation problem in a more understandable way for the decision maker.

In (Koduru et al., 2008), the authors presented a fuzzy Pareto dominance concept to compare two solutions. An individual *A* fuzzy-dominates another *B* if it fuzzy-dominates for each objective *i.* The corresponding level of fuzzy-dominance is calculated by means of the fuzzy intersection of each objective (see Eq.(3-3). The intersection is a t-norm function (Gupta and Qi, 1991; Nasir et al., 2011; Panigrahi et al., 2010; Sengupta et al., 2012)

$$\mu^{dom} = \left(\tilde{A} \prec_i^F \tilde{B}\right) = \cap \mu_i^{dom}\left(\tilde{A} \prec_i^F \tilde{B}\right) \tag{3-3}$$

Where the fuzzy-*i* dominance (μ_i^{dom}) is defined as a function (monotonically non-decreasing) which transforms and objective *i* into a measure in [0,1].

The design of CBTC speed profiles is a two-dimensional problem with running time and energy consumption as objectives. In this case, as the mass of the train is modelled as a fuzzy number, the energy and running time are also fuzzy numbers. Thus, the classical crisp dominance relationship can be rewritten for the fuzzy domain as shown in Eq.(3-4)

$$\tilde{A} \prec \widetilde{B} = \cap \tilde{A} \prec_i \widetilde{B} \tag{3-4}$$

Where *i*=1,2 and the two objectives are running time and energy consumption.

Therefore the proposed fuzzy-dominance of *A* over *B* can be defined as the intersection of these two objectives as: $\widetilde{T_B} > \widetilde{T_A}$ and $\widetilde{E_B} > \widetilde{E_A}$.

The calculation of the fuzzy-dominance proposed in this chapter is carried out by the use of the *min* t-norm and the fuzzy numbers $\widetilde{T_B}, \widetilde{T_A}, \widetilde{E_B}, \widetilde{E_A}$, are compared in terms of possibility and necessity measures (Dubois and Prade, 1983).

<u>Weak fuzzy-dominance</u>

A definition of weak fuzzy-dominance is proposed in this thesis by means of the possibility measure. The individual *A* fuzzy weakly dominates *B* if $\Pi\left(\widetilde{T_B} > \widetilde{T_A}\right) \geq \alpha^{wd}$ and $\Pi\left(\widetilde{E_B} > \widetilde{E_A}\right) \geq \alpha^{wd}$ and applying the *min* t-norm for the intersection operator we have:

$$\min\left(\Pi\left(\widetilde{T_B} > \widetilde{T_A}\right), \Pi\left(\widetilde{E_B} > \widetilde{E_A}\right)\right) \geq \alpha^{wd} \tag{3-5}$$

Where α^{wd} is the required level of possibility for the comparison. A graphic representation when $\Pi(T_A < T_B) = \alpha^{wd}$ is shown in Figure 3-10.

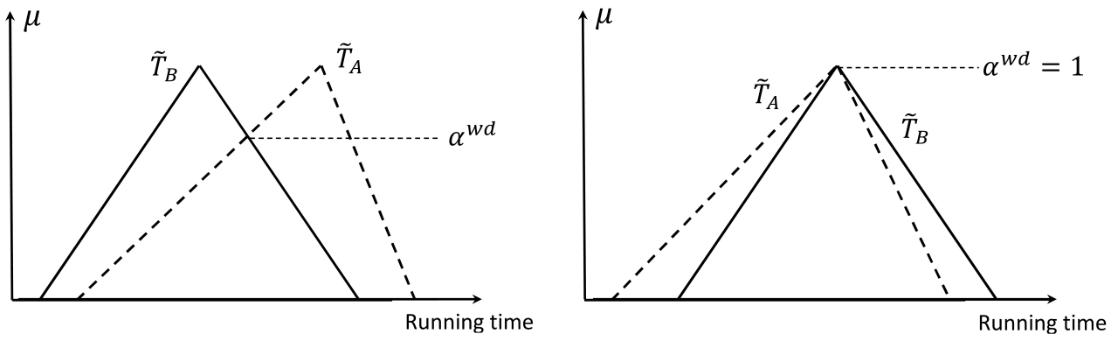


Figure 3-10. Weak fuzzy-dominance (*wd*)

<u>Strong fuzzy-dominance</u>

A definition of strong fuzzy-dominance is proposed by means of the necessity measure. The individual *A* fuzzy strongly dominates *B* if $N(\widetilde{T_B} > \widetilde{T_A}) \geq n^{SD}$ and $(\widetilde{E_B} > \widetilde{E_A}) \geq n^{SD}$, and applying the min t-norm for the intersection operator:

$$\min\left(N(\widetilde{T_B} > \widetilde{T_A}), N(\widetilde{E_B} > \widetilde{E_A})\right) \geq n^{SD} \tag{3-6}$$

The necessity measure of $\widetilde{T_B} > \widetilde{T_A}$ is equal to one minus the possibility of $\widetilde{T_B} < \widetilde{T_A}$ as is written in Eq.(3-7).

$$N(\widetilde{T_B} > \widetilde{T_A}) = 1 - \Pi(\widetilde{T_B} < \widetilde{T_A}) \tag{3-7}$$

The relationship shown in Eq.(3-7) is depicted graphically in Figure 3-11.

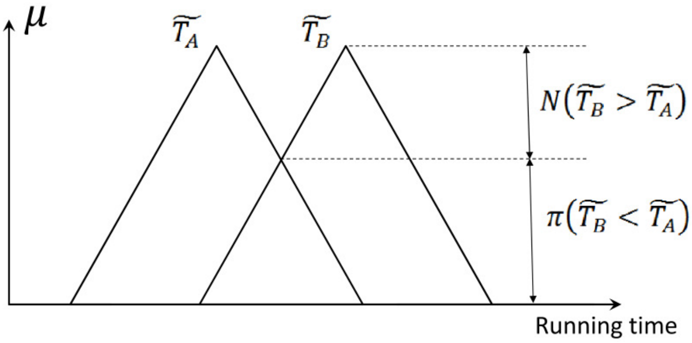


Figure 3-11. Representation of strong fuzzy-dominance (*SD*)

3.4.3. FUZZY CROWDING DISTANCE

When the Pareto front and its successive dominated fronts are calculated and identified, the crowding distance (CD) is calculated for each of the fronts. In crisp terms, the CD is defined as (Kukkonen and Deb, 2006):

$$CD(x_k) = \frac{T_{k+1} - T_{k-1}}{T_{max} - T_{min}} + \frac{E_{k+1} - E_{k-1}}{E_{max} - E_{min}} \tag{3-8}$$

Figure 3-12 shows the concept of CD. The CD for each front is calculated as the normalised sum of the cuboid edge lengths formed by the solutions that surround a specific point in the solution space.

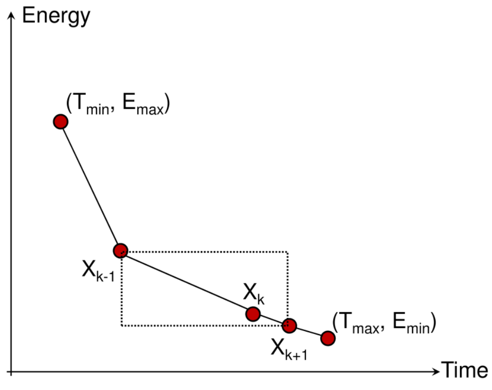


Figure 3-12. Crowding distance

As in the current research, the mass has been considered as a fuzzy quantity, the running time and energy consumption are also fuzzy numbers. The fuzzy crowding distance for a solution x_k is defined in Eq.(3-9) by summing the fuzzy crowding distance for each of the objectives (Eqs. (3-10) and (3-11)).

$$\widetilde{CD}(x_k) = \widetilde{CD}_{Time}(x_k) + \widetilde{CD}_{Energy}(x_k) \tag{3-9}$$

$$\widetilde{CD}_{Time}(x_k) = \frac{\tilde{T}_{k+1} - \tilde{T}_{k-1}}{T_{max} - T_{min}} \tag{3-10}$$

$$\widetilde{CD}_{Energy}(x_k) = \frac{\tilde{E}_{k+1} - \tilde{E}_{k-1}}{E_{max} - E_{min}} \tag{3-11}$$

Where $\tilde{T}_{k+1}$, $\tilde{T}_{k-1}$ are the fuzzy running times and $\tilde{E}_{k+1}$, $\tilde{E}_{k-1}$ are the fuzzy energy consumptions of the adjacent solutions to x_k. $T_{max} - T_{min}$, $E_{max} - E_{min}$ are the crisp normalisation values (see Eqs. (3-10) and (3-11)) for the running time and energy consumption.

By successively applying the procedures of fuzzy-dominance and crowding distance, the population P mentioned in the flowchart of Figure 3-9 is obtained.

3.4.4. CROSSOVER AND MUTATION

For each dominance level, the fuzzy crowding distance is used as a criterion for assigning the mutation and crossing probabilities. The higher the crowding distance measure, the higher the probability of the selection for the mutations and crossover processes.

A crossover is defined between two roulette-based selected parents (driving profile set of parameters) by randomly selecting and interchanging the switching point distance. The mutation operator is also based on the roulette random selection of one of the driving commands or the switching point and applies a random change in the selected value according to the admissible limits.

Given that the parents' chromosomes are of the same length and the commands are interchangeable, the crossing operator is based on the exchange of genetic information between two parents. There are constraints about interchangeability of the driving commands, as for example, the first command cannot be a coasting command. The parents are selected based on the probabilities given by the roulette selection according to the dominance level and crowding distance values. The offspring is formed by parts of the information of its parents. A graphic representation of a crossing process is shown in Figure 3-13 for a simplified version of two switching points.

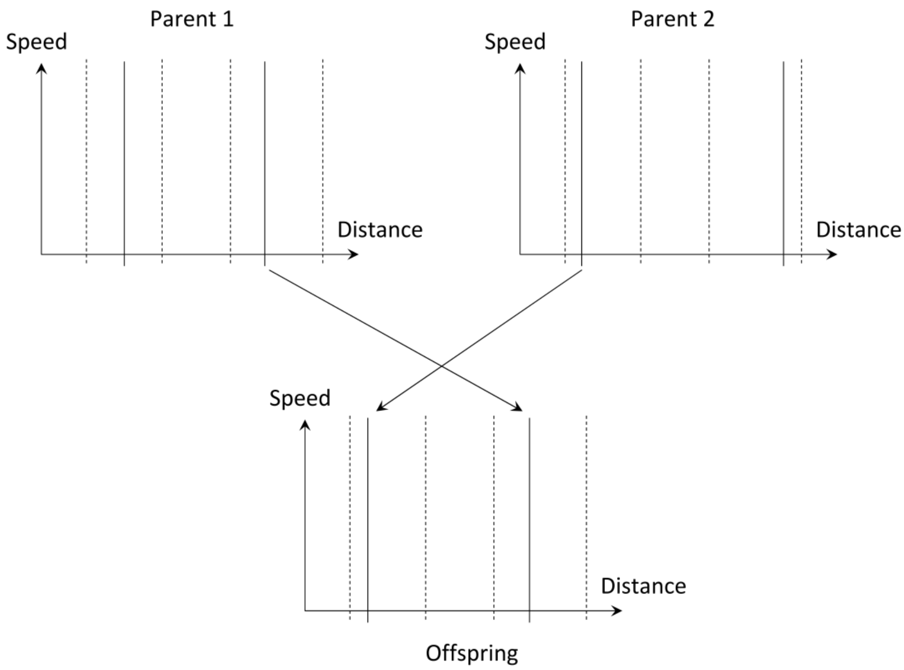


Figure 3-13. Representation of the crossing process

The crossover and mutation algorithms used in this research are based in the concept of differential evolution (Chang et al., 1999; Chang and Xu, 2000; Kwan et al., 2007; Kwan and Chang, 2005) which is based on the creation of new individuals by the application of scaling factors to the randomly selected parameter vectors.

The population Q (Figure 3-9) is created from the P population by the application of crossing and mutation. Then, merging the populations P and Q the population for the next iteration is created.

3.4.5. CALCULATION OF THE PSEUDO-PARETO FRONT

An evenly distributed Pareto front is desirable for the proper operation of a centralised traffic regulation system. This aim could be partially fulfilled with the Pareto front, but regions without optimal points can produce time gaps which can make difficult the availability of suitable speed profiles. These gaps are originated by the presence of non-convexities in the solution space or the elimination of non-comfortable or operationally inadequate speed profiles. The use of speed profiles located out of the optimal curve could be considered to fill in the running time gaps if the energy consumption is under a prefixed tolerance limit (see Figure 3-14).

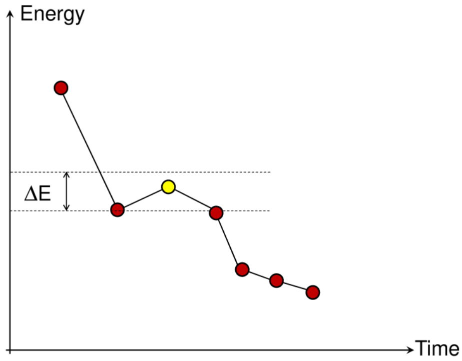


Figure 3-14. Region for the acceptance of dominated solutions

Speed profiles matching the required time but located out of the optimal curve must be kept for further analysis. Considering optimisation criteria, it is a dominated solution, but from the point of view of traffic regulation goals it could have practical usefulness. In this sense, a procedure for obtaining the filling points is proposed to calculate the pseudo-Pareto curve.

The algorithm for the gap detection and calculation of the pseudo-Pareto curve is described in fuzzy terms, as the running time is a fuzzy variable. A threshold is established to determine if the time distance between two consecutive solutions could be considered as big enough to fill it with dominated solutions. This is mathematically formulated as:

$$\widetilde{T_B} - \widetilde{T_A} > K \qquad (3\text{-}12)$$

Where *K* is a crisp constant.

This expression can be written as a necessity measure that a fuzzy gap would be selected:

$$N\left(\widetilde{T_A} + K < \widetilde{T_B}\right) \geq n_{GAP} \qquad (3\text{-}13)$$

If the necessity measure is greater than n_{GAP} a gap has been identified and the procedure for filling it with dominated point starts. An analysis is performed to the subsequent front until reaching (if there exists) some dominated point that matches the running time within the specified bound ΔE (Figure 3-14).

A sequence to depict the steps of the algorithm is shown in the Figure 3-15.

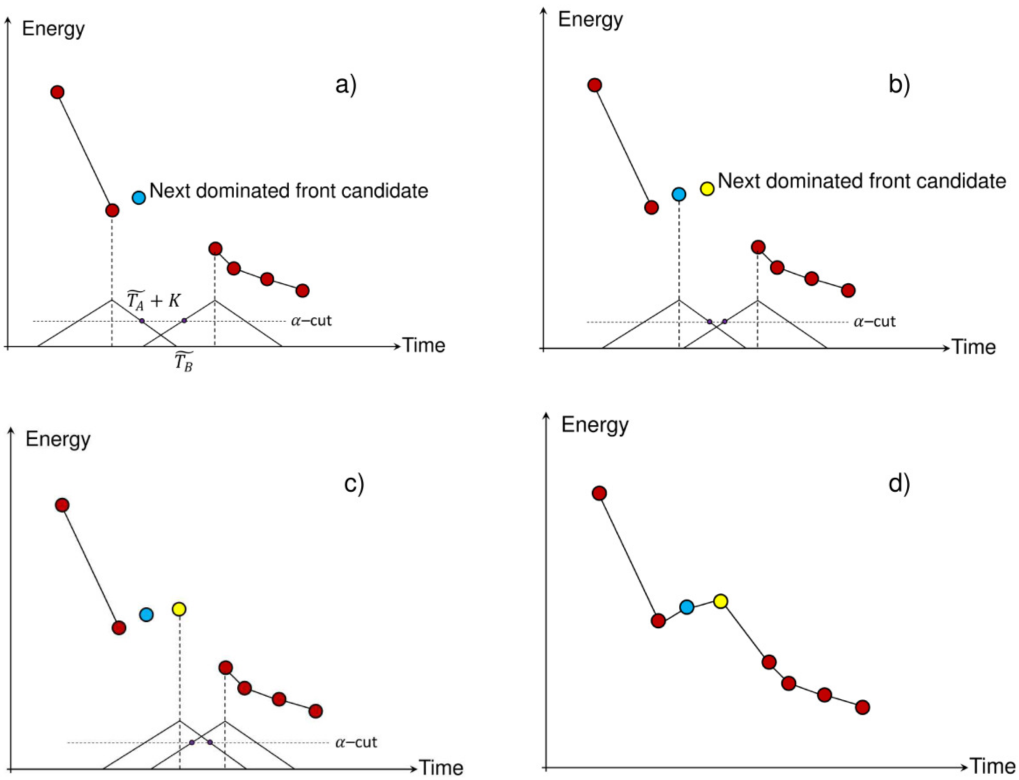


Figure 3-15. Fuzzy gap-filling algorithm operation

3.4.6. THE α–CUT FORMULATION

The proposed NSGA-II-F algorithm can be expressed in terms of the α–cuts of the fuzzy mass of the train. As shown in Figures 3-10, 3-11 and 3-15 the upper and the lower limits of the α–cuts of the fuzzy running times are needed to calculate the fuzzy-dominance (weak or strong), and to detect the gap in the Pareto curve. As the running time increases with the mass of the train, the upper $t^{\overline{\alpha}}$ (or lower $t^{\underline{\alpha}}$) limit of the α–cut of the fuzzy running time can be calculated simulating the train motion with the upper (or lower) limit of the α–cut of the fuzzy mass. In a similar manner, as the energy consumption increases with the mass value, this can also be used to calculate the upper $e^{\overline{\alpha}}$ (or lower $e^{\underline{\alpha}}$) limit of the α–cut of the fuzzy energy consumption. See Eqs. (3-14) through (3-17).

$$e^{\overline{\alpha}} = F(m^{\overline{\alpha}}) \tag{3-14}$$

$$e^{\underline{\alpha}} = F(m^{\underline{\alpha}}) \tag{3-15}$$

$$t^{\overline{\alpha}} = F(m^{\overline{\alpha}}) \tag{3-16}$$

$$t^{\underline{\alpha}} = F(m^{\underline{\alpha}}) \tag{3-17}$$

Where *F* is the simulation function of the train motion, $m^{\overline{\alpha}}$ is the upper limit of the α–cut of the fuzzy mass, and $m^{\underline{\alpha}}$ is the lower limit of the α–cut of the fuzzy mass. This situation can be better understood by checking the correspondence in the Figure 3-16 which explains the extension principle.

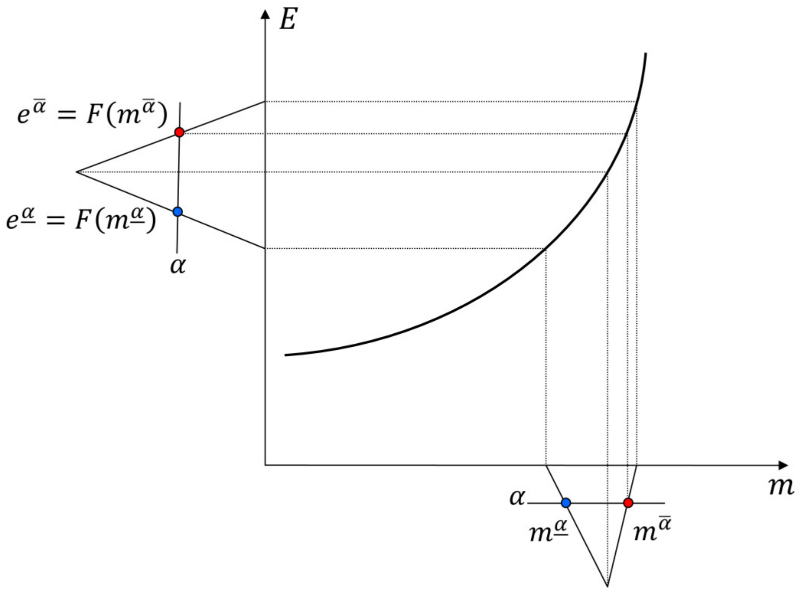


Figure 3-16. Extension principle to calculate upper and lower limits of α-cuts

3.4.7. ALGORITHM RESOLUTION

The resolution of the NSGA-II-F based on α-cut arithmetic is described in the following paragraphs:

1. Generation of the random initial population. The initial population of CBTC commands is generated and each driving profile is simulated for the upper limit of the α–cut for an initial value of α = 0 (maximum allowable passenger load). Using this consideration, it is assured that all the speed profiles obtained at this stage will be valid also for lower load levels and no additional tests are required. Load profiles valid for a low load level could turn into unfeasible under higher load conditions, for example, for higher loads the train could decrease its speed during the coasting periods under the minimum operating speed or even stop before reaching the next station.

2. Fuzzy-dominance. To analyse weak/strong dominance for α^{wd}/n^{SD}, each individual of the initial population is simulated as described in the following. Given two solutions *A* and *B*, to determine if *A* dominates *B*, different α–cuts have to be calculated depending on the application of weak or strong dominance.

Weak dominance

Point *B* is simulated with the value of the upper limit of the α–cut α^{wd} ($\overline{\alpha^{wd}}$) of the fuzzy mass $\widetilde{M}$

Point *A* is simulated with the value corresponding to the lower limit of the α–cut α^{wd} ($\underline{\alpha^{wd}}$) of the fuzzy mass $\widetilde{M}$

A weakly dominated *B* if $t_A^{\underline{\alpha^{wd}}} < t_B^{\overline{\alpha^{wd}}}$, and $e_A^{\underline{\alpha^{wd}}} < e_B^{\overline{\alpha^{wd}}}$

Strong dominance

Point A is simulated with the mass value corresponding to the upper limit of the α–cut of $\alpha^{SD} = 1 - n^{SD}$

Point B is simulated with the mass value corresponding to the lower limit of the α–cut of $\alpha^{SD} = 1 - n^{SD}$.

A strongly dominates *B* if $t_A^{\overline{\alpha^{SD}}} < t_B^{\underline{\alpha^{SD}}}$, and $e_A^{\overline{\alpha^{SD}}} < e_B^{\underline{\alpha^{SD}}}$

3. Fuzzy crowding distance. The crowding distance (CD) is calculated for the running times and energy consumption obtained for α = 1 and solutions are sorted

$$\widetilde{CD}_1 > \widetilde{CD}_2 \text{ if } \Pi\left(\widetilde{CD}_1 > \widetilde{CD}_2\right) = 1$$

4. Calculate population P by taking the best classified elements of the determined population size

5. Crossover and mutation procedures are applied to obtain new individuals. Each new individual is simulated for mass value of the upper limit of the α–cut, with α = 0 and the unfeasible individuals are discarded. After this reorganisation and pruning process, the population Q is obtained.

6. The populations P and Q are aggregated.

7. Calculation of fuzzy-dominance (as described in step 2).

8. Calculation of the fuzzy crowding distance (as described in step 3).

9. Calculation of the pseudo-Pareto front. If the detection algorithm identifies a time gap in the Pareto curve, new candidates are added to the pseudo-Pareto front.

The rule to detect a gap between consecutive solutions *A* and *B,* is a fuzzy comparison between the associated running times and a crisp threshold time K(Eq.(3-18)).

$$\widetilde{T_A} + K < \widetilde{T_B} \qquad (3\text{-}18)$$

And expressed in terms of a necessity measure (Eq.(3-13))

The detection of the fuzzy gap by means of the α–cut calculation is described as follows.

Point A is simulated with the mass value corresponding to the upper limit of the α -cut of $\alpha^{GAP} = 1 - n_{GAP}$

Point B is simulated with the mass value corresponding to the lower limit of the α –cut of $\alpha^{GAP} = 1 - n_{GAP}$

If $t_A^{\overline{\alpha^{GAP}}} + K < t_B^{\underline{\alpha^{GAP}}}$, a gap is flagged and a new candidate for filling it is taken from the next dominated front, taking care not to exceed a predefined band. In that sense the gap is filled with speed profiles which better match the required running times with still efficient but not optimal speed profiles. The gap-filling algorithm is repeated at each detected gap until $t_A^{\overline{\alpha^{GAP}}} + K \geq t_{\overline{B}}^{\alpha^{GAP}}$ (see Figure 3-15).

Stopping criteria: The stopping condition of the main algorithm is the maximum number of generations. The iterative process is repeated from step 4 in case the generation limit is lower that the bound. The final solution of the optimal design is the pseudo-Pareto front with the non-dominated points and the dominated points used to fill in the gaps. In real world problems it is always an issue to terminate the search because there is no clue about where are the optimal values (Veldhuizen and Lamont, 1998) this is the reason why a maximum number of generations together with an evaluation of the hypervolume indicator have been used here.

3.5. CASE STUDY

A Metro de Madrid interstation has been selected for the design of ATO CBTC speed profiles by means of the application of the proposed NSGA-II-F algorithm. The interstation of Line 3 between 'Delicias' and 'Palos de la Frontera' stations has an associated length of 495m. This length is around the average interstation length in the studied metro line.

The train data are summarised in Table 3-1, where *A*, *B* and *C* are the coefficients of the train running resistance. The maximum traction/braking efforts are modelled as curves and their maximum values are indicated in Table 3-1.

Property	Value
Train type	SERIE 3000 3M3R3S CAF
Mass	159.697 t
Rotary mass	8.186 %
Max passenger load	78 t
Train length	89.16 m
A	1.8810 daN/t
B	0.02 daN/t* h/km
C	0.00042 daN/t* h^2/km^2
Max traction force	218 kN
Max braking force	252 kN

Table 3-1. Train data

To deal with the uncertainty associated with the passenger load, the mass of the train has been modelled as a triangular fuzzy number (m1; m2; m3) = (190.897 t; 214.297 t; 237.697 t). The value range selected for the support of the fuzzy mass model is the interval between the tare of the train plus 40% of the passenger load (lower limit), and the full load (upper limit). The core of the fuzzy mass model corresponds to 70% of the passenger load.

The parameters of the fuzzy algorithm are α^{wd} =1 for the fuzzy weak dominance and α=1 for crowding distance procedures, n_{GAP} = 0.1 and K = 2 s for the fuzzy gap-filling algorithm. The size of the initial population of the NSGA-II-F is 50 individuals and the stopping criterion is 50 generations.

As a frame of reference, the exhaustive simulation of the full possible combinations of the distance-to-go ATO parameters was executed (the results are shown in Figure 3-17). Each command can only take discrete values according to an increment value, from the minimum to the maximum limits, due to communication constraints. These values are presented in Table 3-2. In this case study much smaller increments than D2G ATO real systems have been considered as in (Domínguez et al., 2014).In total there are 16040 possible solutions represented as blue dots.

	Deceleration rate(m/s^2)	Speed holding (km/h)	Coasting speed (km/h)	Remotoring speed (km/h)
Minimum	0.6	30	30	5
Maximum	0.8	80	80	75
Increment	0.05	0.25	0.5	1

Table 3-2. ATO parameter values combination in distance-to-go ATO system

The proposed NSGA-II-F algorithm is executed for the same interstation and ATO CBTC commands, generating a pseudo-Pareto front (Figure 3-17). A comparison between both D2G and CBTC solutions is shown. According to this figure, savings up to 7.3 % and 8.5 % could be obtained for non-dominated and dominated speed profiles respectively.

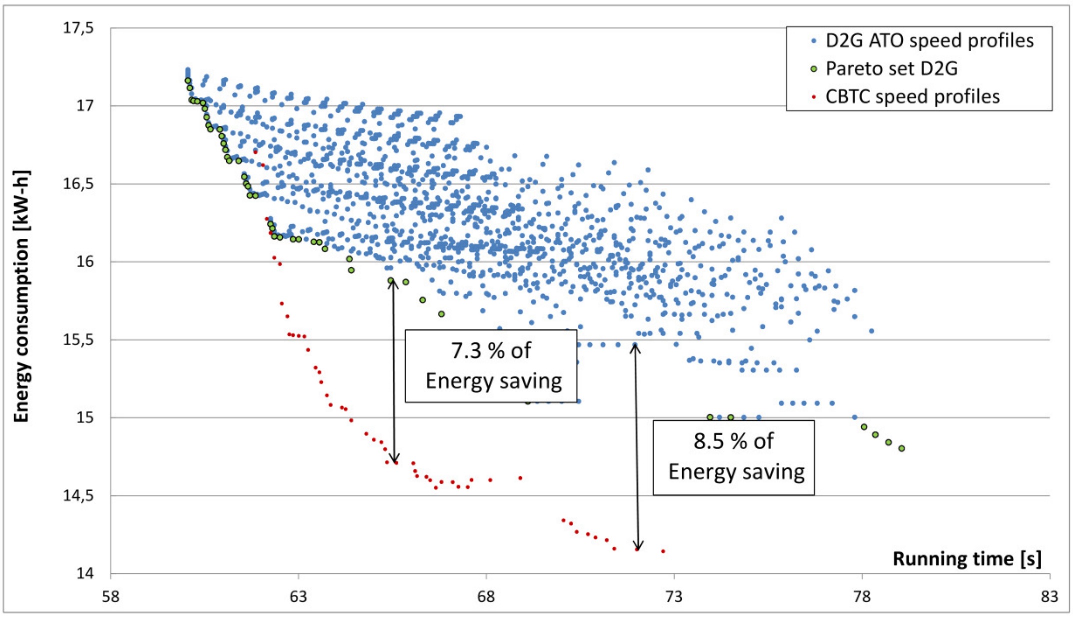


Figure 3-17. Improvement in the savings with speed profiles designed for CBTC-ATO

A comparison between the D2G and CBTC speed profiles (corresponding to the 7.3% of energy savings in the Figure 3-17) are shown in Figure 3-18, and the associated ATO driving commands are described in Tables 3-3 and 3-4.

Speed holding (km/h)	Coasting speed (km/h)	Remotoring speed (km/h)	Deceleration rate (m/s^2)
-	37.5	30	0.6

Table 3-3. D2G ATO driving command

Distance [m]	Command	Dec. Rate
9472 - 9613.08	Traction	0.683 m/s^2
9613.08 - 9675.13	Coast	
9675.13 - 9841.13	Traction	
9841.13 - 9967	Coast	

Table 3-4. List of ATO CBTC driving commands

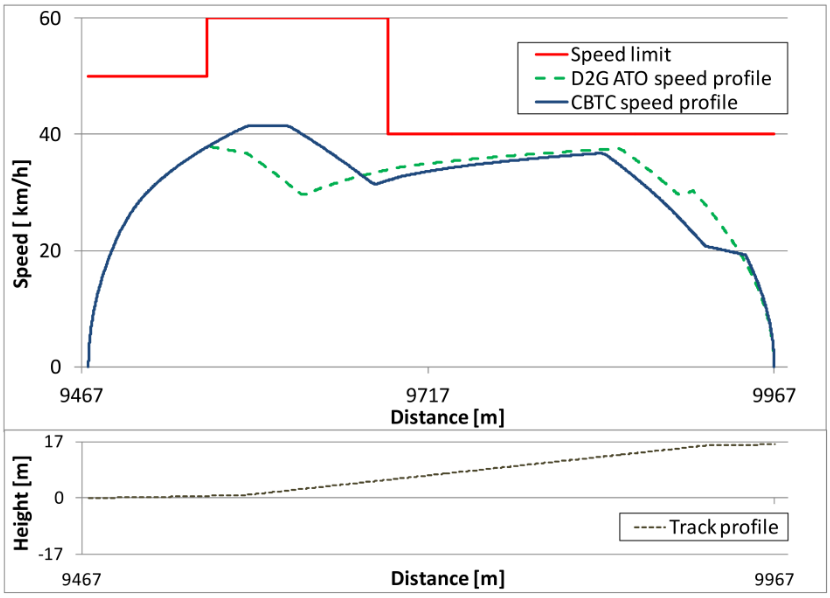


Figure 3-18. Comparison of speed profiles for D2G and CBTC for the same running time

The CBTC solution given in Table 3-4 was simulated with full passenger load and compared with the Pareto front generated for full passenger load. Figure 3-19 shows that the difference between the CBTC optimal solution provided by the NSGA-II-F for α=1, and the optimal solution that would be obtained for the maximum train load is only 0.98%.

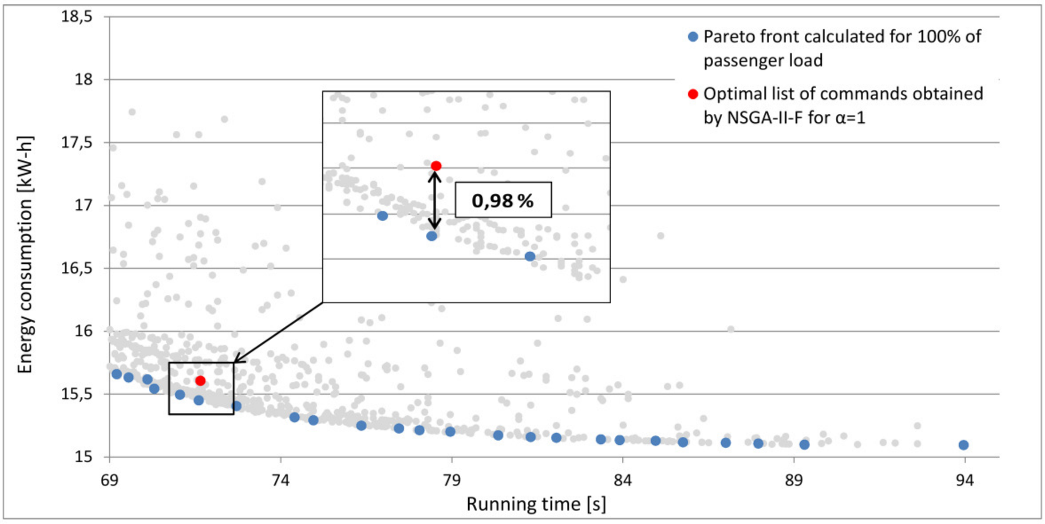


Figure 3-19 Comparison of optimal speed profiles

The gap-filling or smoothing algorithm was applied to an example of the same interstation obtaining the approximated Pareto front shown in the Figure 3-20.

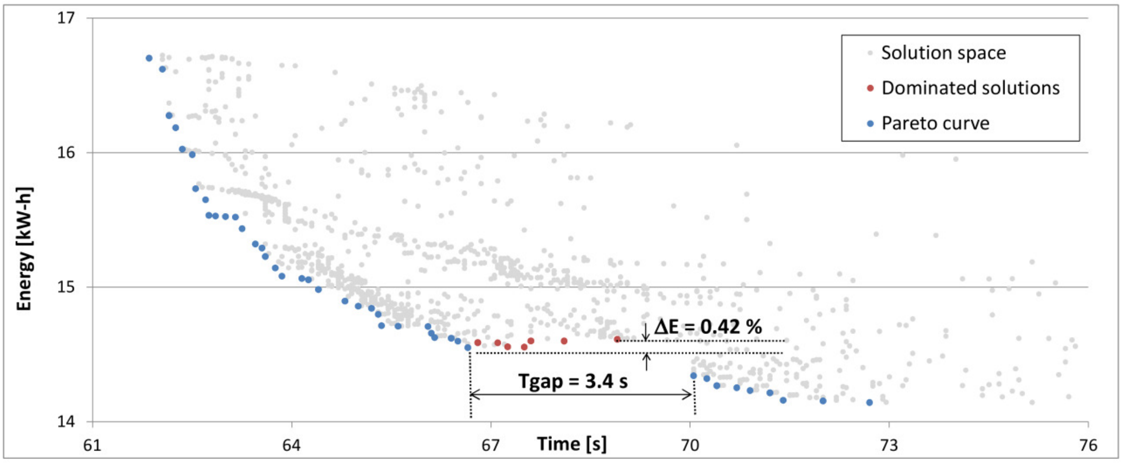


Figure 3-20. Pseudo-Pareto front obtained using the NSGA-II-F algorithm

In the Figure 3-20 there is a complete solution, where the dominated and non-dominated solutions are marked in different colors. The ‘gap width’ and the ‘inefficiency’ band percentage with respect to the last Pareto point are shown.

The resulting pseudo-Pareto front is shown, where a time gap (Tgap) of 3.4 seconds was detected by the algorithm and filled with the best dominated solutions available. The value of energy consumption of the fillers is less than 0.5% greater than the reference point (the energy of the solution at the left of the gap). The result was obtained for an initial population of 50 individuals, 50 generations, and the simulation time was 24.55 seconds. As a reference the computation time for the D2G ATO solution space exhaustive generation was 46.3 seconds. By applying the NSAG-II-F algorithm, from a theoretically infinite space of solutions, a population of 50 individuals is initially selected. During 50 generations, the utilization of the genetic operators permits the exploration of different regions of the solution space. The number of speed profiles evaluated and accepted in this case were 1949, but this quantity is variable depending on the proportion of rejected speed profiles during the process, the width of the time gap detected and the number of valid solutions found for filling it. The final pseudo-Pareto front is composed by a set of 57 solutions. The simulations were performed in a desktop computer Intel core i7-2600 CPU@3.4 GHz, 8GB RAM and 64 bits.

It is worth mentioning that each of the points in the solution space involves a complete simulation of the commands proposed included an evaluation of the comfort criteria evaluated and safety conditions met. In that sense a complete evaluation of the solution space for the CBTC case is not possible and the need of using the proposed optimisation algorithm is enforced.

Convergence

The maximum number of generations is the finalisation criterion for finishing the iterations. The number of individuals and generations is a tradeoff between accuracy of the results and simulation time. In the Figure 3-21 there is an example of the pseudo-Pareto front obtained for different population sizes running the algorithm for 50 generations in all cases. The issue of finding the proper number of individuals, generations, crossover and mutation rates is a matter of trial and error and is also problem dependent.

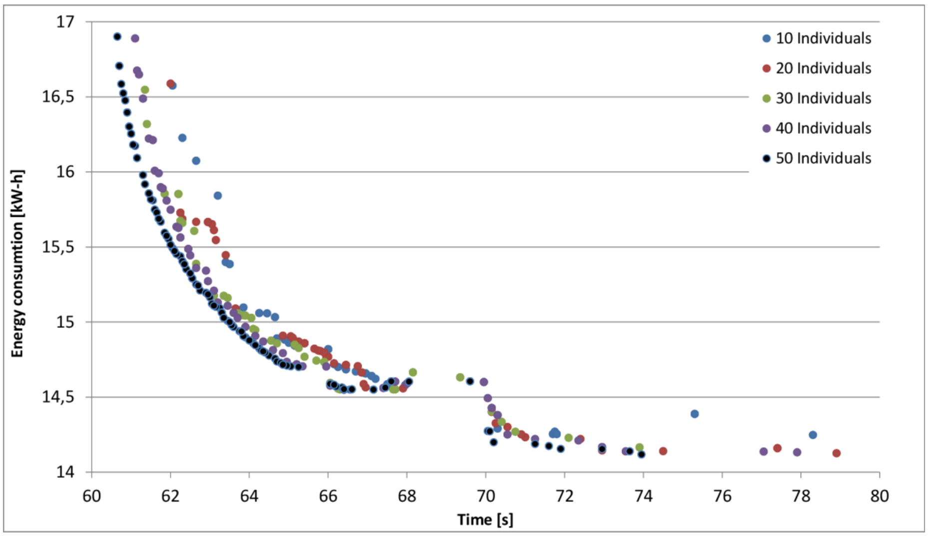


Figure 3-21. Convergence for different population size

A measure to evaluate the convergence of a multi-objective algorithm is the hypervolume (Knowles and Corne, 2002; Yan et al., 2007) given by the Eq.(3-19).

$$hv = 1 - \frac{\sum_{i=1}^{NI}\left[\left(f_{no}^{max} - f_{no}^{i}\right)\prod_{j=1}^{no-1}\left(f_j^{sup_j^i} - f_j^i\right)\right]}{\prod_{j=1}^{no}\left(f_j^{max} - f_j^{min}\right)} \tag{3-19}$$

where f_j^i is the value of the objective *j* for the individual *i*, *no* is the number of objectives and *NI* the number of individuals of the efficient front obtained with the algorithm. f_j^{max} and f_j^{min} are the limit values for the j^{th} objective when the objective space is bounded. If the objective space is not bounded these are the values that satisfy $f_j^{max} > f_j^i$ and $f_j^{min} < f_j^i$ for each individual *i*. $f_j^{sup_j^i}$ is the value of the objective j^{th} for the individual higher adjacent in the j^{th} objective to individual *i*.

A test for convergence comparisons using a high number of individuals (500) and generations (400) is used as a reference for comparisons. The evolution of the hypervolume indicator for different population sizes is shown in Figure 3-22.

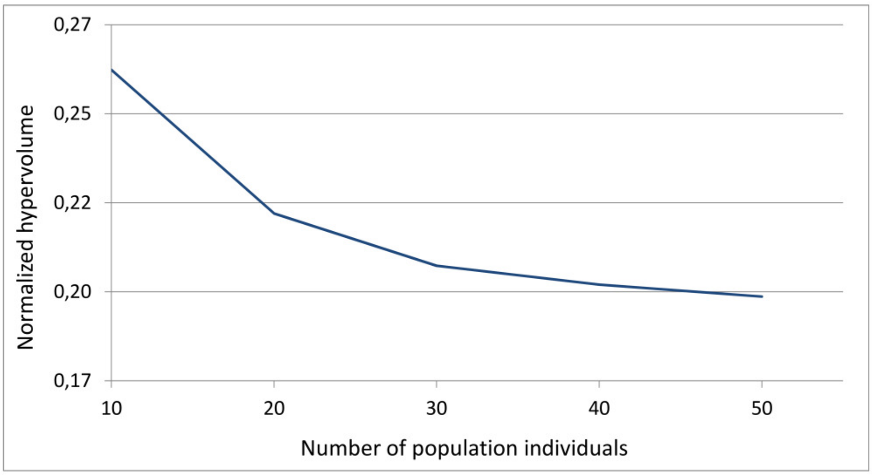


Figure 3-22. Convergence of the algorithm as a function of population size

The evolution of the hypervolume measure as a function of the number of generations is shown in Figure 3-23. According to the figure, from the 50th generation the slope converges to a horizontal value which means that a set of stable (solutions) values were found.

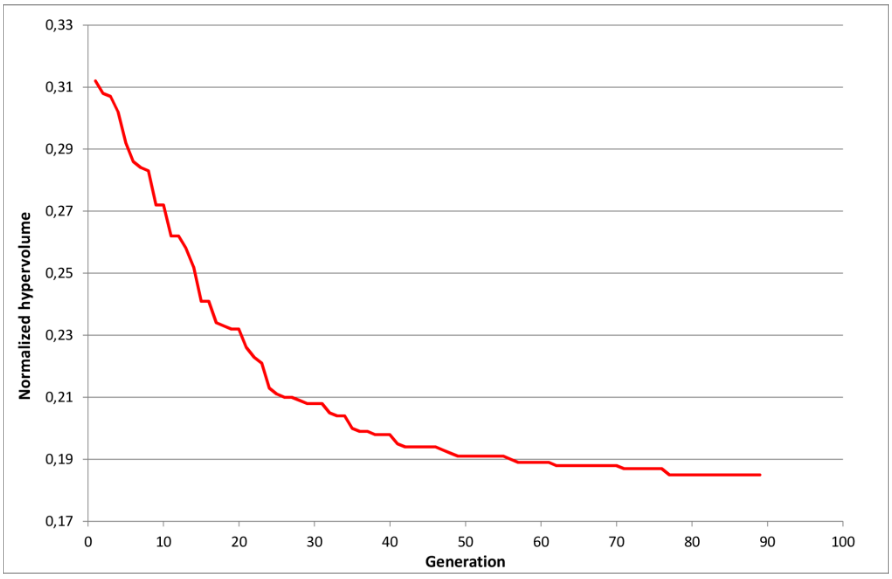


Figure 3-23. Normalised hypervolume value during the evolution of the NSGA-II-F

Diversity of the solution

For traffic regulation purposes it is worth having a diverse and uniform distribution of the solutions in the pseudo-Pareto front. It could be necessary to have a speed profile for each possible running time. This diversity is reached by the application of the crowding distance procedure along the successive generations, and also using the gap-filling algorithm with dominated solutions providing a pseudo-Pareto front (Figure 3-20).

3.6. CONSIDERATIONS OF THE REGENERATED ENERGY CAPABILITY

Until now, only traction energy has been considered in the calculation of the energy consumption of the train. But, taking into account that the braking energy can take different pathways, an analysis of the effect of the regenerated energy flow in the design of the efficient speed profile will be performed in this section.

Regenerated energy management is another strategy for energy-efficient operation of railways. Several approaches could be used for these methods. Braking energy recovery by synchronising the timetables are mentioned in (Albrecht, 2004; Chen et al., 2014; Gordon and Lehrer, 1998; Nasri et al., 2010; Oettich et al., 2004; Peña-Alcaraz et al., 2011; Scheepmaker et al., 2016; Shuai Su et al., 2013; Su et al., 2015; Tang et al., 2015; Yang et al., 2016). The storage of regenerated energy in wayside or onboard devices is studied in (Barrero et al., 2010; Calderaro et al., 2014; Ceraolo and Lutzemberger, 2014; Conti et al., 2015; Domínguez et al., 2012, 2010; Douglas et al., 2015; González-Gil et al., 2014; Hong et al., 2007; Iannuzzi and Tricoli, 2010; Kondo, 2010; Miyatake et al., 2009; Xia et al., 2015).

More complex schemes as the utilisation of inverting substations in DC networks (Domínguez et al., 2012; Douglas et al., 2015; Falvo et al., 2016; López-López et al., 2014) or combined approaches considering energy injected back to the system through substations and energy storage systems interacting together could have higher levels of global energy efficiency but the costs involved in such infrastructure investment require detailed evaluation of the cost-benefit ratio to justify and assure the recovery of the investment (Cornic, 2010; Domínguez et al., 2012; Douglas et al., 2015; Falvo et al., 2011; Feng et al., 2013b; González-Gil et al., 2013; Miyatake and Ko, 2010; Su et al., 2016).

To take into account the use of regenerative braking, a complete analysis of the structure and operation of the system should be done. Depending on the type of supply system (AC/DC), type of substation (single or bi-directional flow capability), the distribution of electrical sections of the line, the presence of accumulation devices on track or onboard and the timetable structure. All these factors work together and different scenarios should be studied considering different levels of interaction in presence of all or some of them. (Buscema et al., 2010; Chen et al., 2014; Miyatake et al., 2009; Miyatake and Ko, 2007; Peña-Alcaraz et al., 2011; Watanabe and Koseki, 2014; Yang et al., 2016).

The objective of this section is to analyse the impact of regenerated energy in the design of optimal ATO speed profiles in CBTC lines. For that purpose, the net energy consumed by a train, measured at substation will be calculated and minimised.

According to previous studies, the influence of the system and nearby trains could be considered by using factors which relate the energy flow in the train itself and among the system components (Chu, 1983; Domínguez et al., 2012; Yang et al., 2014).

Under normal operation, the braking energy could have one or more of the following paths:

-To feed the auxiliary equipment in the train.

-To be injected to the catenary and be consumed by nearby powering trains.

-To recharge onboard storage devices. This option which at first glance could seem profitable should be evaluated against the additional weight and space occupied in the train and the initial investment and other lifecycle costs and safety considerations.

-To be injected from the DC to the AC power network using bidirectional substations (rectifier-inverter). It should be taken into account that all these energy flows have associated losses and they should be considered in the calculation of general benefits of the regenerative energy redirection.

-To be dissipated in onboard braking resistors if the voltage of the catenary is too high.

A diagram to summarise the regenerated energy flows and interaction with the electrical network considered for this analysis is depicted in Figure 3-24. A portion of the system has been represented to describe the possible energy flows in this part of the system.

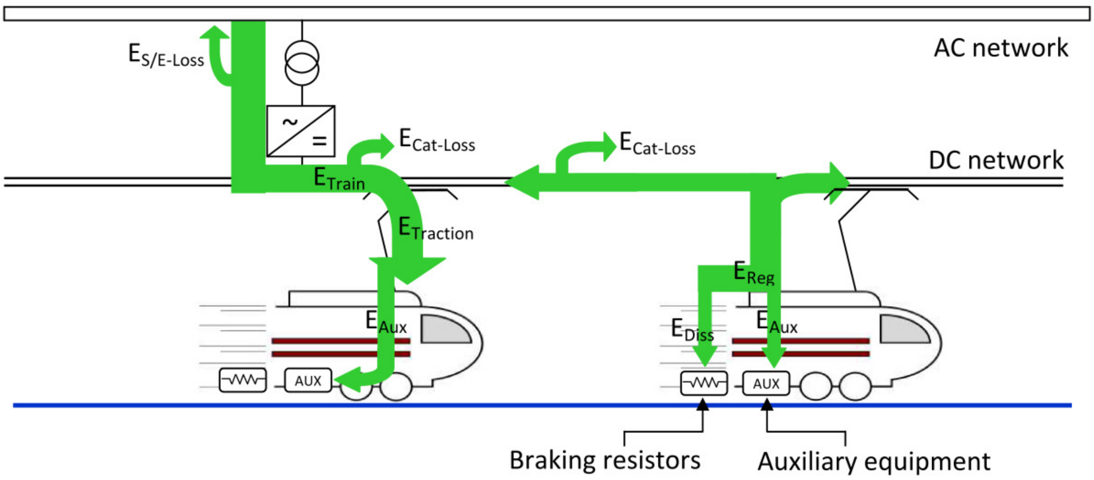


Figure 3-24. Regenerated energy flow and interaction with the DC network

This section applies the procedure proposed in (Domínguez et al., 2012), where two coefficients are defined to model the average receptivity and electrical losses of the traction network, calculating the net energy consumption at substations and pantograph of each train. This is calculated by means of an electrical simulation model of the network, considering all the elements and devices (energy accumulation devices, reversible substations) and a traffic scenario along a period of time.

Then, the net energy consumed by a train, measured at substation, can be calculated by means of these two coefficients that model the whole electric network and its average receptivity.

In the following the Recovery coefficient and Energy losses coefficient are described.

Recovery coefficient (RC)

Because of the regenerated energy flow, the energy required from substations decreases. The recovery coefficient is defined as the energy saving at substations due to regeneration related to the total amount of regenerated energy available at pantograph. A base case is considered for comparison, where the receptivity of the network is null.

$$RC = \frac{\sum_t E^t_{cons_{sub},b} - \left(\sum_t E^t_{cons_{sub}} - \sum_t E^t_{reg_{sub}}\right)}{\sum_t E^t_{reg}} \qquad (3\text{-}20)$$

For any train t,

Where $E^t_{cons_{sub},b}$ is the energy consumption supplied by substations in the base case, $E^t_{cons_{sub}}$ is the energy consumption supplied by substations, $E^t_{reg_{sub}}$ is the regenerative energy back to substation (in case of reversible substations) and E^t_{reg} is the energy regenerated by the train t not used by the auxiliary systems.

Energy losses coefficient (LC)

It characterises the losses along the lines and in substation by considering the total demand of energy in pantograph. The (recovery coefficient) *RC* and (losses coefficient) *LC* coefficients are scenario-dependent and should be calculated for a whole railway line during a period of time. So the results analysed here are for a specific picture (freeze frame) of the system.

$$LC = \frac{\sum_t E_{cons}^t}{\sum_t E_{cons_{sub},b}^t} \quad (3\text{-}21)$$

Where E_{cons}^t is the energy consumed by the train t.

Once these two coefficients are calculated by simulation, they can be used to calculate the net energy consumption of a single train, measured at substations, taking into account the receptivity of the network as indicated in the following.

Energy consumption in substation of a train (ECS)

$$ECS^t = \frac{E_{cons}^t}{LC} - E_{reg}^t.RC \quad (3\text{-}22)$$

Where ECS^t is the net energy consumption of a train t in substations, which is used in this thesis for designing optimal ATO speed profiles taking into account its regenerated energy.

Calculation of the energy of a train measured at pantograph

To calculate the energy demand for a train and the regenerated energy available for reutilisation measured in pantograph, a simulation process is performed. The auxiliary energy consumption is considered along with the traction energy to make a global balance of the energy flow in the train. Also the traction and braking current curves as a function of the speed are considered in the model, along with a constant value of voltage of the motor.

For the correct consideration of the regeneration capability it is very important to take into account the auxiliary energy consumption. Upon considering the auxiliary energy consumption and the possibility of consuming the braking energy, the algorithm for the calculation of the energy at each time step is depicted in the diagram of the Figure 3-25.

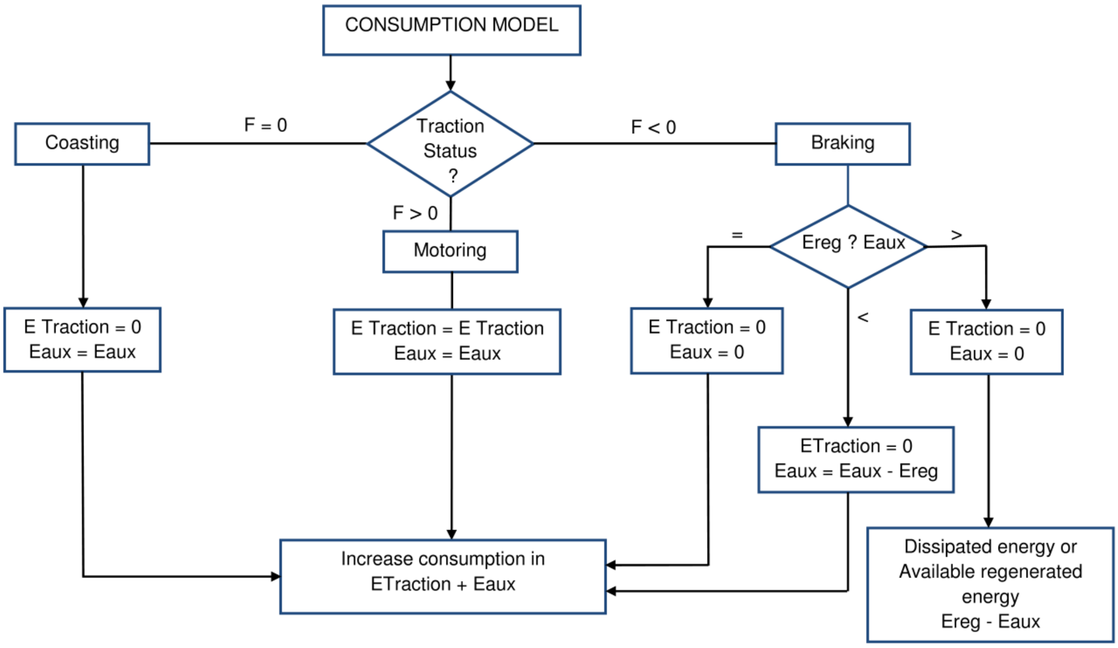


Figure 3-25. Consumption model

According to the figure, the consumption model first checks the traction status (coasting, motoring or braking) and depending on the force value, a path is followed. If the path to follow is coasting, no traction energy is considered and the energy consumption of this simulation time step is the auxiliary equipment energy. If the path is motoring, the traction and the auxiliary energies are taken from the electrical network. The last choice is the braking energy path. Three cases are derived from the comparison between the regenerated energy and the energy consumed by the auxiliary equipment. In all the cases the traction energy consumed by the traction equipment is zero. The auxiliary equipment energy taken from the network is accounted by evaluating if the braking energy is enough to cover the auxiliary equipment demand or if this energy should be used as part of the required energy. The remainder energy should be taken from the electrical network. If the regenerated energy is higher than the auxiliary demand, the surplus energy is assumed to be directed for feeding up back to the network in presence of close trains to the braking one. Other option, if there are no available trains to consume the energy, is to direct the energy towards the braking resistors, depending on the catenary voltage.

The net energy consumption calculation will be affected by the network and equipment efficiencies. The estimation model for the interaction of the railway network components over a single train is taken from (Domínguez et al., 2012). Different scenarios were considered in the reference (Domínguez et al., 2012) involving peak hours and traffic conditions, also braking resistors, onboard storage devices, inverting substations, regenerative energy taken by other trains were considered in different proportions and combinations to extract coefficients (recovery and energy losses) which model the interaction of the different components of the railway system.

As mentioned, for the specific case considered in this research, the influence of the nearby trains will be taken along with the auxiliary energy consumption and, the losses and system efficiencies to calculate the pantograph energy under regeneration.

Case study considering regenerated energy flow and interaction with the network.

The case considered for the study is an interstation in the L3 of Metro de Madrid.

Line 3 has 17 interstations and 13.5 km per direction, and the gradient profiles are up to 50mm/m. The whole round trip has been considered which takes about one hour. The electrical network is made up of rigid overhead, electrified with 1500V DC supply and 6 substations.

The headway between trains is 15 min (off-peak hour).

There are 3 scenarios considered: the base case where the receptivity of the network is null (all the available energy regenerated after feeding auxiliary equipments is consumed in rheostats), another scenario (scenario 2) where regenerated energy can be consumed by other trains in the network, and a third scenario where reversible substations are considered and energy consumption by other trains.

The base case scenario gave as a result the following coefficients (Domínguez et al., 2012): *RC*=0, *LC*=0.9886.

The second scenario gave as a result *RC*=0.6983, *LC*=0.9886.

The third scenario gave as a result *RC*=0.9674, *LC*=0.9886.

The interstation 'Palos de la Frontera'–'Embajadores', track 1 is analysed, now considering the interaction with the electrical network, to optimise the speed profile minimising the net energy consumption of a train measured at substations.

Figure 3-26 shows the solution spaces and Pareto curves resulting from the sample scenarios. The values of the coefficients used are shown in the legend.

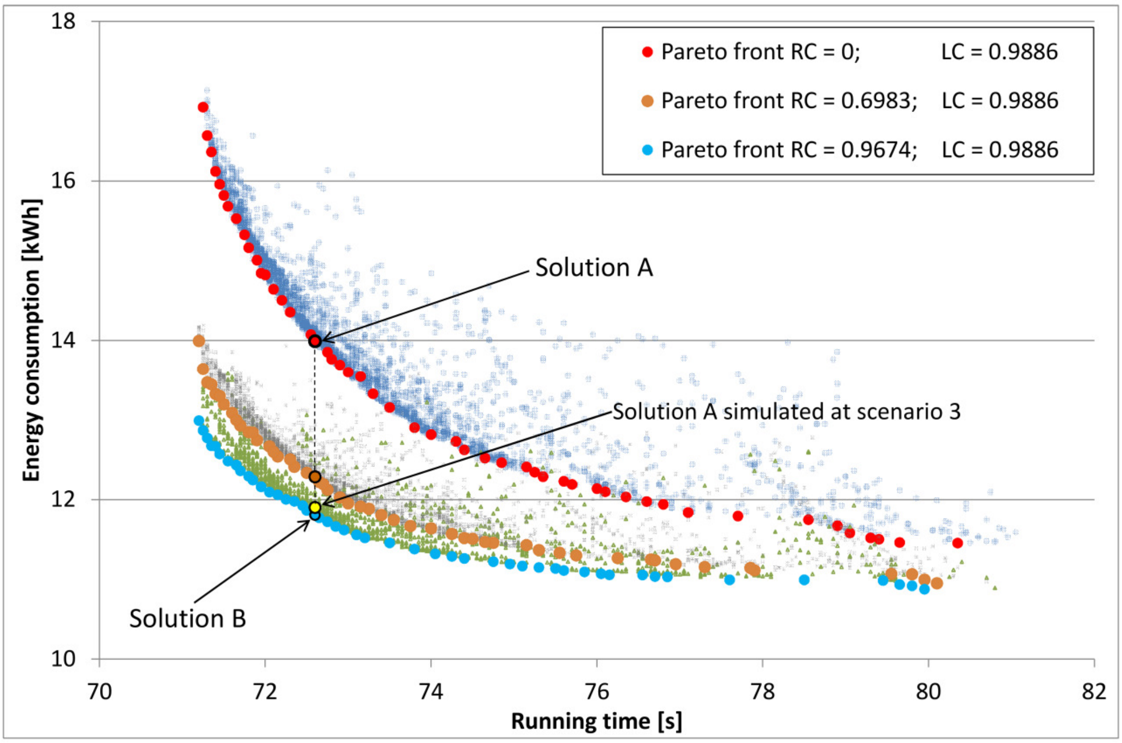


Figure 3-26. Solution space and Pareto fronts for regeneration scenarios

In Figure 3-26 are marked, in bold circles, the solutions for the speed profiles with a constant running time of 72.6s. The optimal solution obtained for the base case (*RC*=0; *LC*=0.9886) where the receptivity of the network is null is shown in Figure 3-26 (solution A), and its configuration parameters are the following (see Table 3-5):

Distance [m]	Driving command	Dec. Rate
9967 – 10141.30	Traction	0.788 m/s^2
10141.30 - 10436.91	Coasting	
10436.91 - 10582.58	Traction	
10582.58 - 10753.62	Coasting	

Table 3-5. Sets of parameters of solution A

The speed profile corresponding to this solution A is shown in Figure 3-27.

It should be noted that the speed profile shown is the same speed profile for the different scenarios because of the recovery and losses coefficients are considered independent of the operation of the ATO and traction motors.

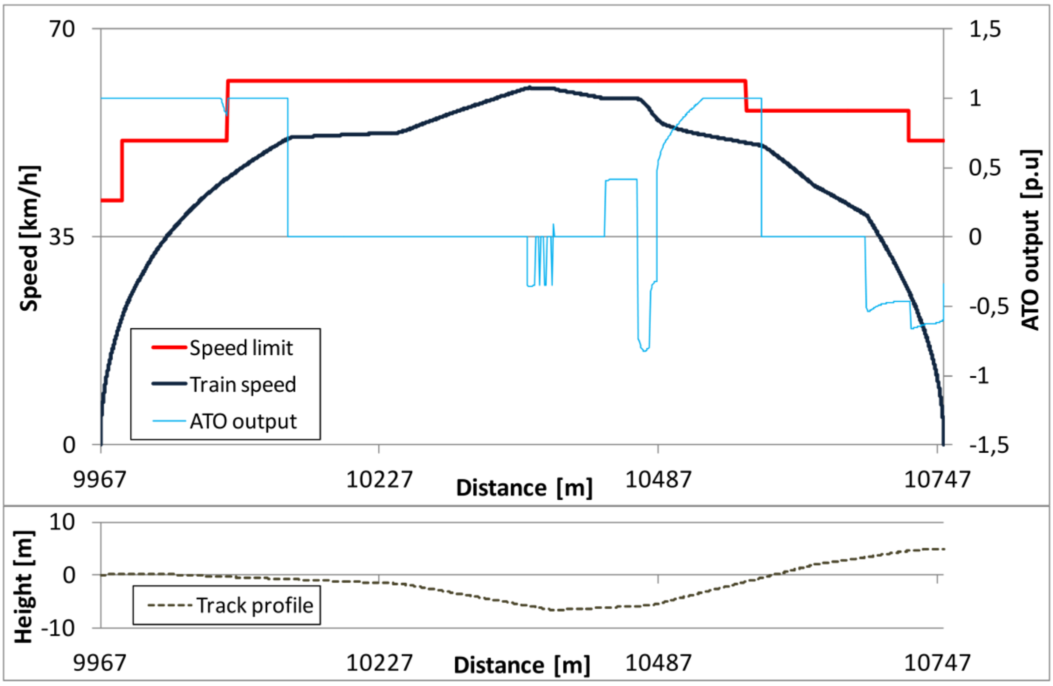


Figure 3-27. Speed profile for parameters of Table 3-5 (solution A)

When the optimisation algorithm is applied to minimise the energy consumption measured at substations, scenarios 2 and 3 are analysed and new Pareto fronts are calculated as shown in Figure 3-26.

After analysing the net energy consumption of each speed profile generated by the set of parameters at Table 3-5 one can conclude that the studied speed profiles lie close to the Pareto solutions given by the optimisation algorithm.

For the second scenario with *RC*=0.6983 and *LC*=0.9886, the optimal speed profile coincides (within the precision limits) in running time and energy consumption with the generated for the optimisation algorithm (Table 3-5).

In the third scenario (coefficients *RC*=0.9674 and *LC*=0.9886), the optimal solution (solution B in Figure 3-26) is a different profile and its parameters are shown in Table 3-6.

Distance [m]	Driving command	Dec. Rate
9967 – 10131.573	Traction	0.797 m/s^2
10131.573 – 10438.751	Coasting	
10438.751 – 10591.6	Traction	
10591.6 – 10753.62	Coasting	

Table 3-6. Sets of parameters for the Pareto front speed profile (solution B)

The speed profile generated by the parameters in Table 3-6 is shown in Figure 3-28.

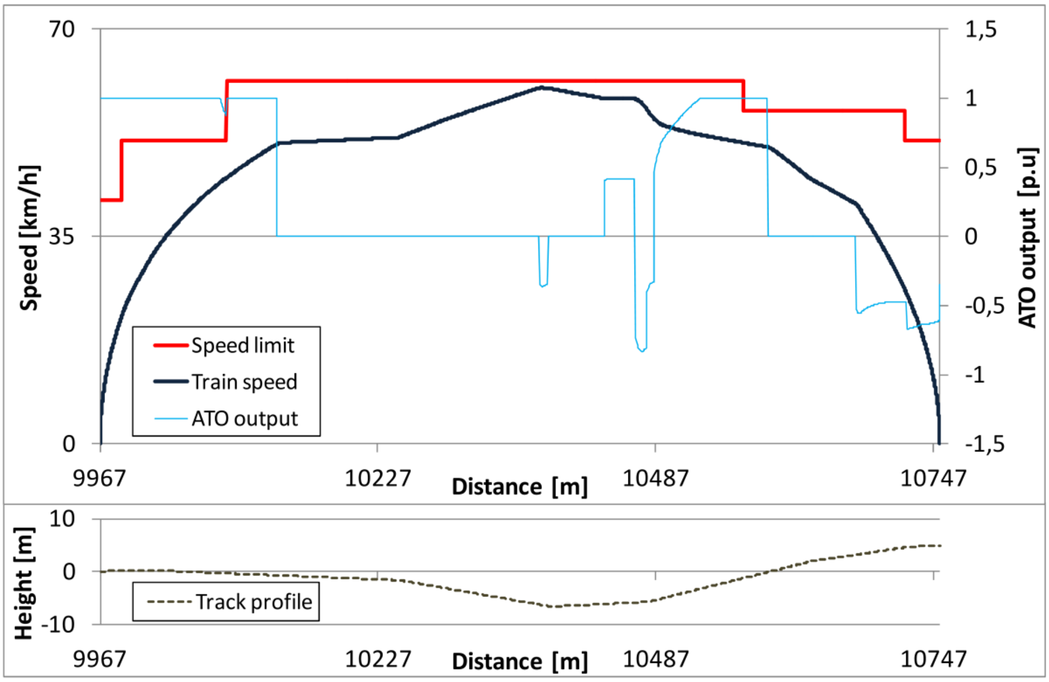


Figure 3-28. Speed profile for parameters of Table 3-6 (solution B)

The previous solution A (configuration parameters of Table 3-5) is now simulated considering the *RC* and *LC* of scenario 3, and as shown in Figure 3-26 there is a difference in energy consumption with the new optimal solution B. The difference in energy consumption between both profiles is 0.51%.

The knowledge that can be drawn of the previous analysis is that the CBTC parameters of the optimal speed profiles are approximately kept for the scenarios considering the interaction with the DC network and nearby trains.

The results found in this section confirm the conclusions presented in (Domínguez, 2013; Domínguez et al., 2012) for the design of efficient profiles in distance-to-go systems and extend the applicability to the design of efficient speed profiles in the CBTC signalling system.

3.7. CONCLUSIONS AND CONTRIBUTIONS

3.7.1. CONCLUSIONS

In this chapter, an algorithm is proposed for the design of these new ATO CBTC drivings in order to minimise the energy consumption. The running time-energy consumption Pareto front is pre-calculated and then, the centralised traffic regulation system will select an efficient driving profile in real-time according to the required running time of the train.

The proposed algorithm is a multi-objective NSGA-II with fuzzy parameters (called NSGA-II-F) where the uncertainty associated with the mass of the train (load of passengers) is included as a fuzzy number. In addition, a method is proposed to fill running time gaps with dominated points providing a pseudo-Pareto curve.

The NSGA-II-F is based on detailed simulation of the train motion, where ATO CBTC driving is modelled as a list of distance-based commands to be executed along the interstation. For the resolution of the NSGA-II-F, the weak and strong fuzzy-dominances have been defined as well as the fuzzy crowding distance by means of the possibility and necessity measures, and a procedure based on alpha-cut arithmetic has been proposed.

This algorithm has been applied for the design of ATO speed profiles of a real interstation in Metro de Madrid, showing that important energy savings can be obtained by the re-design of ATO speed profiles, taking advantage of the CBTC features (7-8%), and providing a well distributed pseudo-Pareto front. This way, it has been shown the important impact that the new CBTC signalling system can have not only in transportation capacity but also in reducing the energy consumption of traffic operation.

Finally, the impact of the use of regenerative energy on the optimal design of ATO speed profiles has been studied. It has been concluded that the optimal solution designed for a null receptivity case remains as optimal or quasi-optimal in other scenarios with associated high receptivity of the traction network.

3.7.2. CONTRIBUTIONS

The contributions of this chapter are listed in the following:

- A multi-objective optimisation algorithm, NSGA-II-F, for the off-line design of CBTC speed profiles based on detailed simulation of the train motion has been proposed. This multi-objective genetic algorithm includes the uncertainty associated to the mass of the train modelled as a fuzzy number.
- An improvement to the NSGA-II-F has been added to fill the gaps in the Pareto front and a pseudo-Pareto front is calculated to provide solutions well distributed in running time terms.
- An analysis of the effect of the regenerated energy flow in the design of CBTC ATO speed profiles has been developed to show that solution provided remains as optimal or quasi-optimal in different receptivity scenarios.

Chapter 4

ENERGY-EFFICIENT FUZZY TRAIN TRACKING ALGORITHM

In this chapter, algorithms for the tracking of trains are investigated and it is proposed an efficient tracking algorithm for two consecutive trains under disturbed conditions. The algorithm is based on the application of coasting commands, considering the uncertainty in the leading train speed as a fuzzy variable. Cases for test and validation of the proposed algorithm are shown and quantitative results are drawn.

4.1. INTRODUCTION AND STATE OF THE ART

The utilisation of new technologies in signalling communications has conducted to the reduction of headways in metro lines. In CBTC, the LMA (limit of movement authority) is the critical value to control the separation of trains. The updating period of the LMA is dependent of the installation architecture and the additional delays given by the communication network (Xun et al., 2013; Zhu et al., 2014b).

Because of the increase in the operation frequency, disruptions caused by train proximity are more likely in new installations. These disruptions must be managed to keep the timetable and to maintain a minimum headway between consecutive trains.

As it was stated in the introductory chapter, if an optimal speed profile (designed off-line) cannot be executed by the ATO equipment because of a perturbation in the motion of the leading train, a tracking algorithm must supervise the minimum headway to avoid the activation of the emergency braking system. This algorithm has impact not only on the tracking interval (capacity) but also on passenger comfort and energy consumption. The continuous communication of the CBTC signalling system can be used to improve transportation capacity, quality of service, and furthermore, the energy efficiency of train driving.

Figure 4-1 shows the speed profiles for the leading and following trains for a minor disturbance. The leading train (Train 1) has an initial full speed (flat-out) command and the following train follows it with the same command. Then, the leading train suffers an unscheduled speed reduction and because of the short headway, the next train (Train 2) is affected. The tracking algorithm adapts the speed profile of the following train to the new condition with a basic tracking algorithm. A final braking process with different accelerations for both trains can be observed in the superimposed figures. The basic tracking process is performed for maintaining a safe distance, energy efficiency criteria are not generally taken in to account in the tracking process.

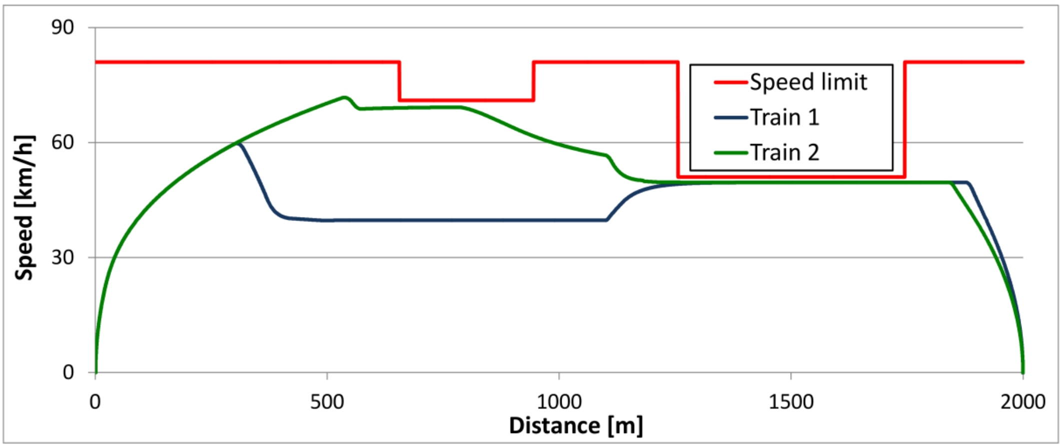


Figure 4-1. Speed profile for two consecutive trains with a minor disturbance

A method for controlling the separation of trains with moving-block signalling is proposed in (Gao et al., 2015a, 2015b; Takagi, 2012) with the application of neural adaptive, observer-based or direct control. In (Baek, 2009; Baek and Lee, 2007; Pan and Zheng, 2014) train separation calculations are made for long distance high speed trains. All these methods disregard the energy efficiency in their analyses.

A GA approach has been used by (Fu et al., 2009) to investigate the energy saving of train operation in the condition of disturbance by other trains with target running time. The optimisation problem is used to determine the critical switching points of control modes, but variable speed limits and track geometry were not modelled.

(Lu and Feng, 2013) propose a tracking algorithm but considering a fixed-block signalling system. In (Gu et al., 2011) the proposed tracking algorithm is based on a quadratic programming method. However, the algorithm contains some simplifications, such as not considering track slopes, train aerodynamics or the saturation of the traction effort curve. In (Ding et al., 2009) a heuristic algorithm is proposed for the train control under moving-block system (MBS) to reduce energy consumption and in (Wang et al., 2014a) the speed profile of the train is optimised for fixed-block system (FBS) and MBS using a MILP (mixed integer linear programming) formulation. Nevertheless, these algorithms do not include a realistic model of actual ATO equipment.

In (Chen et al., 2013), a time optimal tracking problem is investigated using the Pontryagin's maximum principle to follow the leading train with the minimal traveling time keeping the distance greater that the safety distance. No energy saving criteria was used in the definition of the switching rules and a more realistic and detailed model of the train is necessary to quantify the real effects of the control.

In (Albrecht et al., 2015a, 2015b), a safe separation scheme considering energy efficiency is performed for fixed-block signalling systems. These works present initial results for energy-efficient driving strategies for a leading and a following train using a prescribed intermediate section clearance. These preliminary results are the basis for a future extension to a fleet of trains running in the same direction and corridor considering speed limits and grades.

In (Gu et al., 2014) and (Gu et al., 2016), the tracking process in moving-block is studied and formulated as a switching process according to the leading train operation status (running or stopped) and considering the scheduled time. Several energy-efficient operation scenarios are presented and optimised by non-linear programming models, but they do not have a realistic model of actual ATO onboard equipment.

This chapter proposes a new energy-efficient tracking algorithm which controls the approaching of two consecutive trains with the CBTC signalling system. The proposed algorithm takes into account the characteristics of actual ATO equipment. The coast command or null traction is used to reduce the energy consumption taking into account the uncertainty associated with the speed of the leading train. This uncertainty is modelled as a fuzzy quantity. So, the proposed method is a fuzzy tracking algorithm.

4.2. CBTC BASIC TRACKING ALGORITHM

The proposed algorithm performs a detection of the proximity to the preceding train service braking curve (calculated from the LMA information) and the tracking control between two consecutive trains. The structure of the simulation tool is shown in the diagram of the Figure 4-2.

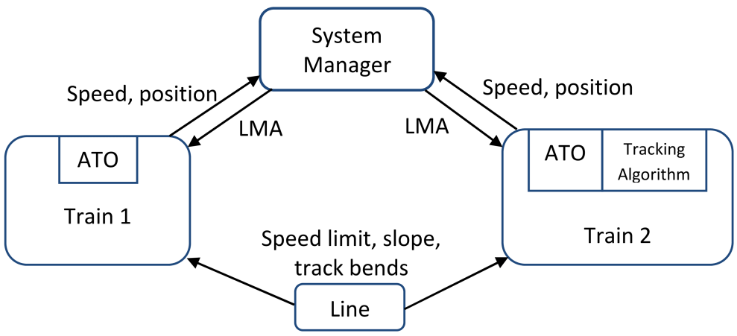


Figure 4-2. Tracking algorithm within the simulator structure

The diagram depicts a description of the functionality of the simulation tool and its algorithms. The data flow direction and communication between modules are also indicated in the diagram. The system manager module is in charge of the simulation of the zone controller (ZC) functionality. The ZC receives the position and speed of each train and with this data it calculates and transmits via radio to the trains in its influence zone the maximum safe distance to run or the LMA. The ATO module simulates the automatic driving, according to the individual active commands, and fulfilling the speed limitations and other safety constraints. When two trains are far enough, the driving follows the single ATO command of each train. But the tracking algorithm is launched under disturbed conditions when the train is tracking the ATO authorised path braking curve due to its proximity to the preceding train (see Figure 4-3).

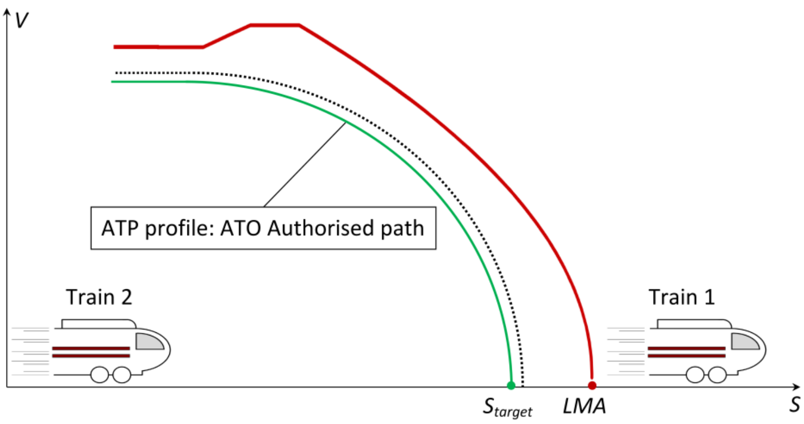


Figure 4-3. ATO authorised path

Figure 4-4, shows the undisturbed speed profiles and the distance and time diagrams show a normal operation. The preceding train (Train 1) has a flat-out (maximum permitted speed) command and the second train (Train 2) has a constant speed command of 60km/h.

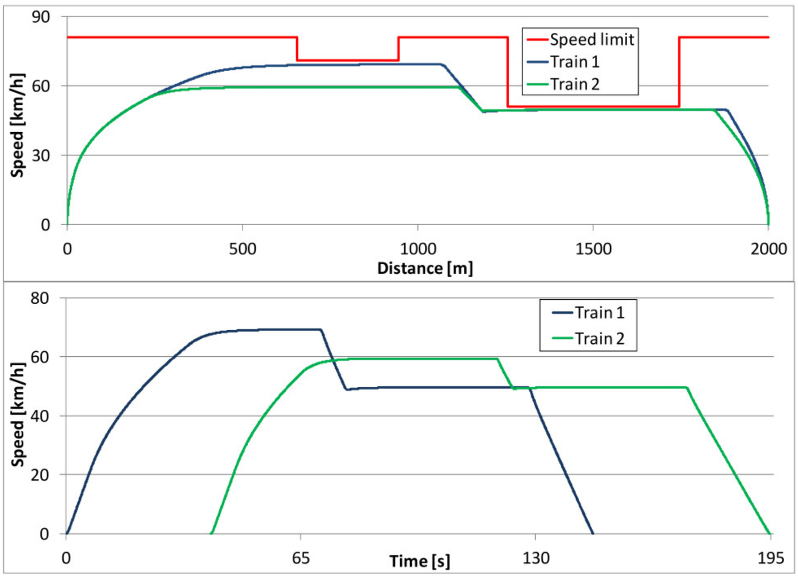


Figure 4-4. Speed vs. distance and speed vs. time profiles for two undisturbed consecutive trains

Under disturbed conditions there is a transient period between the perturbation and the final steady state of the train. This situation is illustrated in the diagram of the Figure 4-5, which displays separation time interval between the two trains.

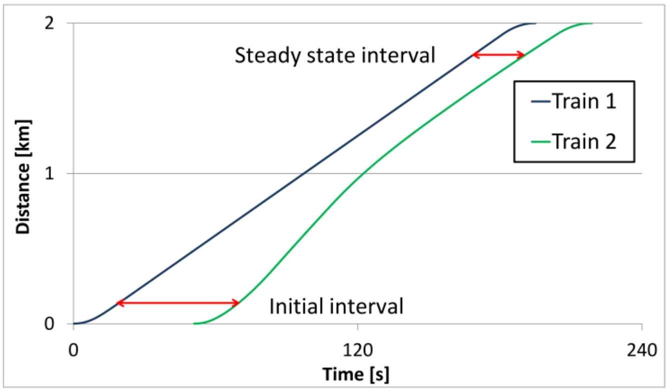


Figure 4-5. Distance vs. time chart showing the tracking interval

An example of the main variables taken for the analysis of the tracking algorithm and to set the reference framework is shown in Figure 4-6. This Figure shows the leading train (Train 1) speed profile (running at 40 km/h), the following train speed profile (Train 2), the speed limits in this interstation and the ATO reference speed for Train 2, which is the variable taken as the control variable of the tracking algorithm. Initially, the ATO driving command received by Train 2 is 'speed holding to 60 km/h'. When the following train is perturbed by the leading train motion, the basic tracking algorithm is triggered and the reference speed of the ATO is changed by the braking curve reference speed calculated from the LMA (the ATO authorised path).

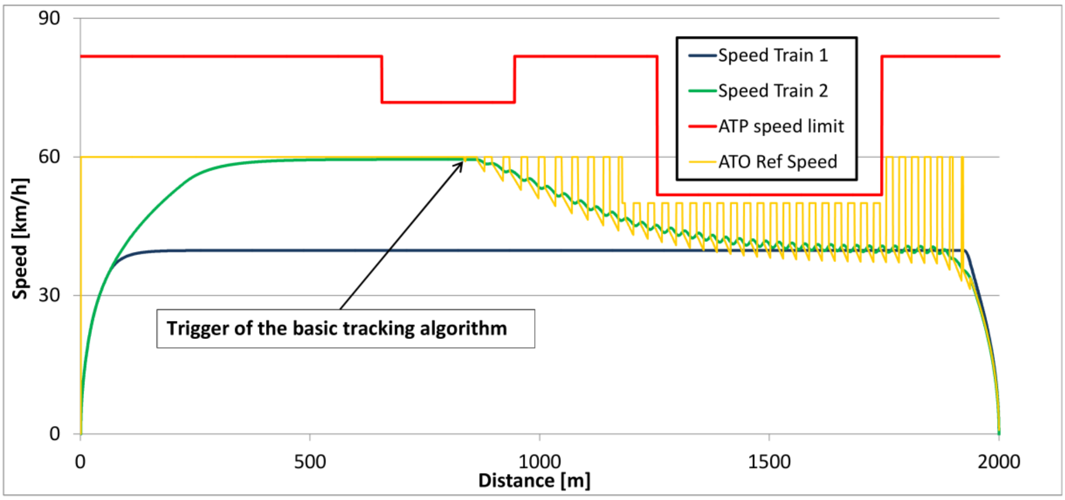


Figure 4-6. Basic tracking algorithm

As the preceding train moves, the LMA changes, but it will be detected in the next control cycle. Meanwhile, the train is driven considering the braking curve calculated from the last LMA, braking effort is applied and speed decreases. When the LMA is updated, the reference speed is the ATO driving command (60 km/h) again, and the train can apply traction effort until the braking curve from the new LMA is reached.

This behavior is repeated until the final braking curve is reached and the train stops at the station.

As described in Chapter 2, the LMA updating cycle could be variable depending on the CBTC implementation if it is moving-block or virtual fixed-block.

When the CBTC is implemented as a moving-block, the LMA updating cycle is shorter and corresponds to the communication delay. According to Annex C of (IEEE, 2004), Typical CBTC parameters, the wayside-to-train message communication delays are limited to 2s (nominal). In case of virtual-block (VB) implementation, the control cycle is longer and depends on the length of the virtual circuits configured in the system. For example, for virtual circuit length of 25m and the train travelling at 35km/h, the new LMA update will be every 2.5 seconds. Figure 4-6 shows the VB implementation for a better description of the control cycle.

The traction/braking cycles of the basic tracking algorithm are highly energy consuming (Gu et al., 2016; Xu et al., 2014) and a new algorithm is proposed to perform a more efficient and comfortable tracking of two perturbed trains.

4.3. FUZZY EFFICENT TRACKING ALGORITHM

The tracking algorithm proposed makes a detection of the train's proximity to the braking curve of the ATO authorised speed and, by means of coasting commands, performs a slower approach to the leading disturbed train.

Three probable scenarios will be analysed and will be the base for the formulation of the algorithm. First, when the following train (Train 2) is close enough to the leading train (Train 1), it reaches the braking curve (ATO authorised path) and starts braking (Eq.(4-1)). Second, if the time interval between the Train 2 and the braking curve is less than a reference interval, and it has not reached the braking curve, then a coast command is applied (Eq.(4-2)). And last, if the measured interval to the braking curve is greater than the reference interval the original pre-stated ATO command will be applied (Eq.4-3)).

If $(I_M = 0)$; brake ; else (4-1)

If $(I_M \tilde{<} \tilde{I_C})$; then coast (4-2)

If $(I_M \tilde{>} \tilde{I_C})$; then apply the active ATO command (4-3)

Where I_M is the measured time interval of Train 2 to the braking curve and $\widetilde{I_C}$ is the fuzzy reference interval.

In the rest of the section, a detailed description of the algorithm is given. The measured interval is defined, then fuzzy models of the leading train speed and the fuzzy reference interval are presented, a flow diagram describing the fuzzy tracking algorithm is depicted and finally the possibility and necessity measures are used to propose a fuzzy comparison operation.

Measured time interval to the braking curve I_M

This measured interval I_M is the time that the train would spend up to the LMA braking curve if the travelling speed remains constant and assuming that the position of the braking curve stays fixed. The situation is illustrated in the Figure 4-7 where the following train speed is V_2 and its position is S_2. This interval is calculated as the trip time at constant speed V_2 from the point S_2 up to S_b.

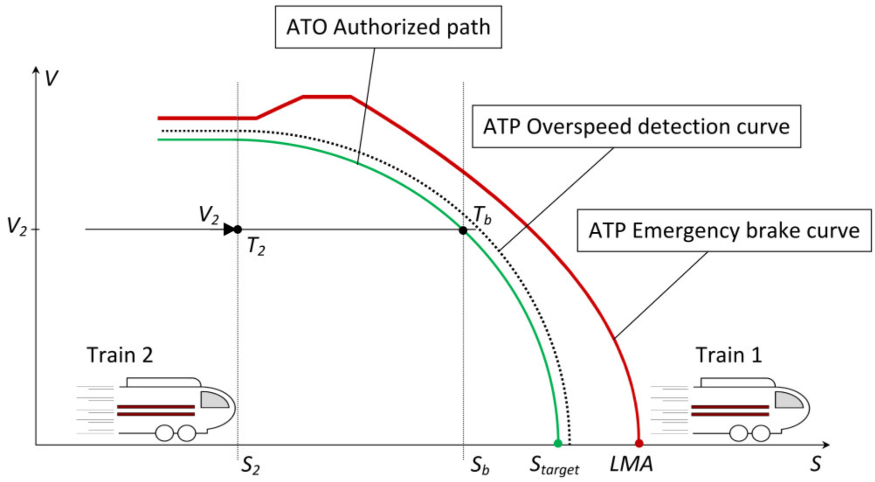


Figure 4-7. Schematic diagram of the proposed measured interval

The measured time interval is calculated in the following way:

$$I_M = \frac{S_b - S_2}{V_2} \qquad (4\text{-}4)$$

Where:

I_M = Measured time interval between the train and its preceding braking curve [s].
S_2 = Instantaneous position of the following train [m].
V_2 = Instantaneous speed of the following train [m/s].
S_b = Position of the point with speed V_2 in the braking curve.

Position S_b can be calculated from the equation of the uniform decelerated motion as:

$$S_b = S_{target} - \frac{V_2{}^2}{2d} \qquad (4\text{-}5)$$

Where:

d = Deceleration rate of the braking curve [m/s^2].

S_{target} = Position of the target point [m].

Uncertainty model of the speed of the leading train

Although the bidirectional communication feature of the CBTC system permits to know the current speed of the leading train, the transmission is affected by a communication delay and thus, the real-time value of the speed is uncertain. The speed can suffer variations or stay constant. To take into account the mentioned uncertainty, the speed of the leading train during the control cycle is modelled as a triangular fuzzy number (Dubois et al., 2004), where the maximum possibility is given to the known value V_1, that is the last speed measurement taken. Figure 4-8 shows the fuzzy model for the leading train speed.

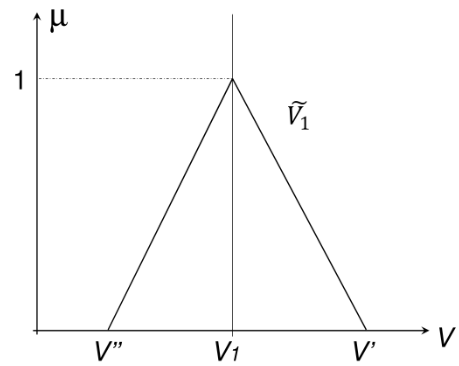


Figure 4-8. Schematic diagram of the proposed measured interval

The triangular membership function is described through the following expression (Eq.(4-6)):

$$\mu_{\widetilde{V_1}}(V) = \begin{cases} 0; & \text{if } V < V'' \\ \frac{V - V''}{V_1 - V''}; & \text{if } V'' \leq V \leq V_1 \\ \frac{V' - V}{V' - V_1}; & \text{if } V_1 \leq V \leq V' \\ 0; & \text{if } V > V' \end{cases} \tag{4-6}$$

where V', V'' are calculated under the assumption of a constant acceleration/ deceleration rate during a pre-established time interval.

That is, V'' = V_1 - LMA_update_period • acceleration.
And V' = V_1 + LMA_update_period • acceleration.

Fuzzy reference Interval $\widetilde{I_C}$

The reference interval has been defined as a function of the speed difference between the two consecutive trains. When the speed of both trains is equal, or V_2 is lower than V_1, the tendency will be that the separation distance is hold or increases. On the other hand, if V_2 is greater than V_1, Train 2 will approach rapidly to Train 1. In the last case the proposed reference interval is increased to start coasting earlier, reduce the approaching speed and in that way save energy.

Thus, when V_2 is greater than V_1 in the Eq.(4-7), a base interval (Io) is scaled in a proportional way to the speeds difference, and the following train starts coasting earlier. For equal speeds or for negative differences of speed, the reference interval for the application of coast command will be I_0.

As the speed of the leading train is a fuzzy number, the reference coast interval $\widetilde{I_C}$ is also a fuzzy number. These concepts are summarised in the mathematical expression:

$$\widetilde{I_C} = \begin{cases} I_0\,; & if\ V_2 \leq \widetilde{V_1} \\ I_0\left(1 + \frac{V_2 - \widetilde{V_1}}{V_2}\right); & otherwise \end{cases} \tag{4-7}$$

Where:

I_0 = Base reference interval [s].
V_2= Speed of the following train [m/s].
$\widetilde{V_1}$= Fuzzy speed of the leading train [m/s].

With this consideration in mind, the tracking algorithm could be redefined in fuzzy terms as indicated in Eqs. (4-1), (4-2) and (4-3).

Flow diagram of the fuzzy tracking algorithm

A flow diagram of the proposed tracking algorithm is shown in Figure 4-9. The variables of the leading train (Train 1) and the braking curve affecting Train 2 are calculated by the simulation model. In real world applications these variables are available from the traffic control manager, and they have an updating period according to the design and operation characteristics of the railway system.

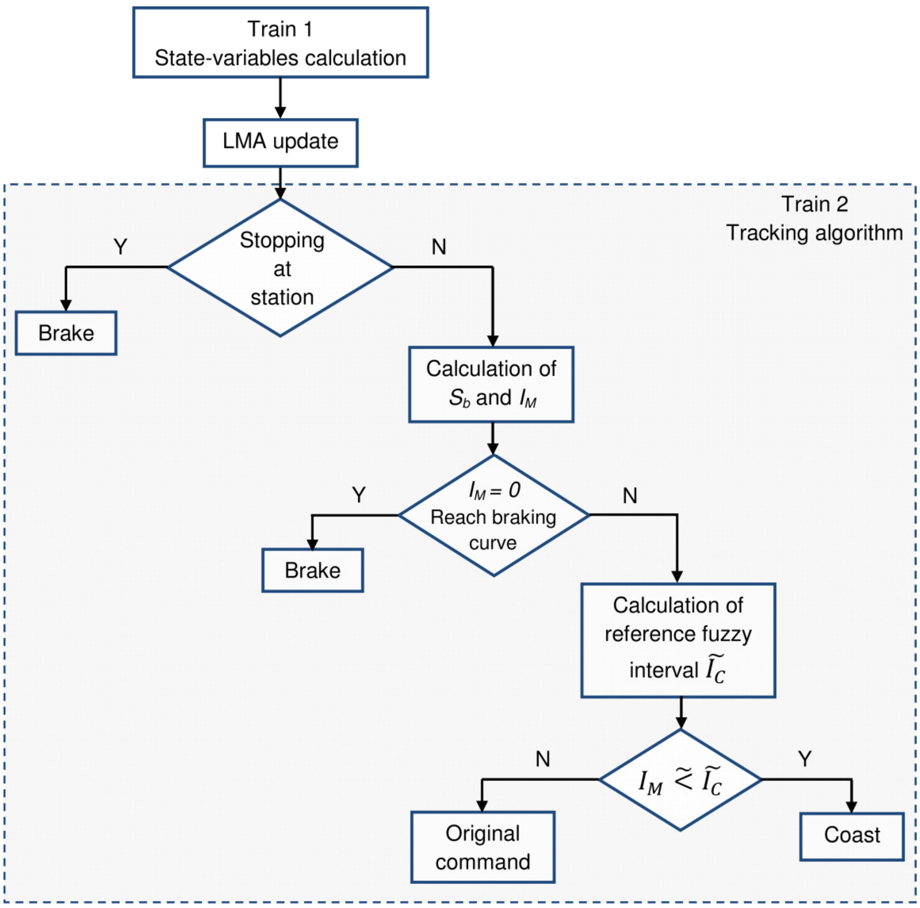


Figure 4-9. Block diagram of the fuzzy tracking algorithm

The tracking algorithm initiates by checking if the following train (Train 2) has to stop at the station. If the motion of the train is not interrupted, the measured time interval to the braking curve I_M is calculated according to the Eq.(4-4). If the interval is null, it means that the train has reached the braking curve. Under this fact the train starts braking. If it is not the case, the reference fuzzy interval is calculated using the expression proposed in Eq.(4-7). Next, a fuzzy comparison (using necessity or possibility measures) gives as a result the next command to be applied by the train. It could be a coasting command or the active command of the ATO.

Fuzzy comparison using possibility measures

The fuzzy comparison $I_M \lessapprox \widetilde{I_C}$ of Eq.(4-2) (if the measured interval is less than the reference interval, then coast) can be expressed using the possibility measure as:

$$\Pi\left(I_M \lessapprox \widetilde{I_C}\right) \geq \alpha_m \tag{4-8}$$

That is, the coast command will be applied if the possibility that *the measured interval I_M is less than the fuzzy reference interval $\widetilde{I_C}$* ($\Pi\left(I_M \lessapprox \widetilde{I_C}\right)$) is greater than or equal to α_m (the level of possibility required) (Eq.(4-8)).

The possibility measure can be used to rewrite the Eq.(4-8) in an equivalent form:

$$\text{If } \Pi\left(I_M \lessapprox \widetilde{I_C}\right) \geq \alpha_m\text{; then coast} \tag{4-9}$$

Eq.(4-9) can be expressed in terms of α-cuts (Chanas et al., 1984) as follows:

$$\text{If } I_M \leq I_C^{\overline{\alpha_m}}\text{ ; then coast} \tag{4-10}$$

where $I_C^{\overline{\alpha_m}}$ is the upper limit of the α_m–cut of $\widetilde{I_C}$.

That is, the possibility that the measured interval I_M is less than the fuzzy reference interval $\widetilde{I_C}$ is greater than or equal to α_m is equivalent to fulfill that I_M is less than or equal to the upper limit of the α_m-cut of $\widetilde{I_C}$. The fuzzy comparison considering possibility measures between the measured and reference interval is represented in the Figure 4-10.

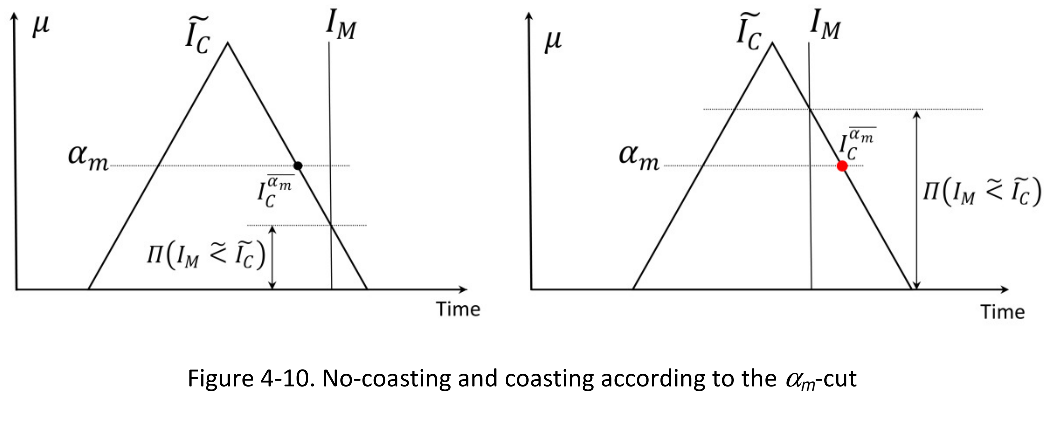


Figure 4-10. No-coasting and coasting according to the α_m-cut

At the left side of the Figure 4-10, Eq.(4-9) is not fulfilled because the possibility $\Pi(I_M \precsim \widetilde{I_C})$ is less than α_m . In terms of α–cuts (Eq.(4-10)) the same figure shows that I_M is not less than or equal to the upper limit of the α_m–cut of $\widetilde{I_C}$, thus coast is not applied, and the active ATO command will be enabled instead. At the right side of Figure 4-10, I_M is less that the upper limit of α_m–cut of $\widetilde{I_C}$, thus Eq.(4-10) is fulfilled and a coast command is applied by Train 2.

The upper limit of the α_m–cut of $\widetilde{I_C}$ ($I_C^{\overline{\alpha_m}}$) can be calculated from the α_m–cut values of $\widetilde{V_1}$. As the fuzzy reference interval is decreasing with the speed of the leading train (Eq.(4-7)), the upper limit of the α_m-cut of the fuzzy reference interval $I_C^{\overline{\alpha_m}}$ can be calculated from the lower limit of the α_m–cut of the leading train speed $V_1^{\underline{\alpha_m}}$ and vice versa. Eqs.(4-11) and (4-12) (Buckley and Qu, 1990; Chanas et al., 1984; Ross, 2010). The situation described is depicted in Figure 4-11.

$$I_C^{\overline{\alpha_m}} = F\left(V_1^{\underline{\alpha_m}}\right) \quad (4\text{-}11)$$

$$I_C^{\underline{\alpha_m}} = F\left(V_1^{\overline{\alpha_m}}\right) \quad (4\text{-}12)$$

Where *F* is the crisp expression of Eq.(4-7), shown in Eq.(4-13)

$$I_C = I_0\left(1 + \frac{V_2 - V_1}{V_2}\right) \quad (4\text{-}13)$$

Thus the reference interval $I_C^{\overline{\alpha_m}}$ in Eq.(4-10) can be calculated as:

$$I_C^{\overline{\alpha_m}} = I_0\left(1 + \frac{V_2 - V_1^{\underline{\alpha_m}}}{V_2}\right) \quad (4\text{-}14)$$

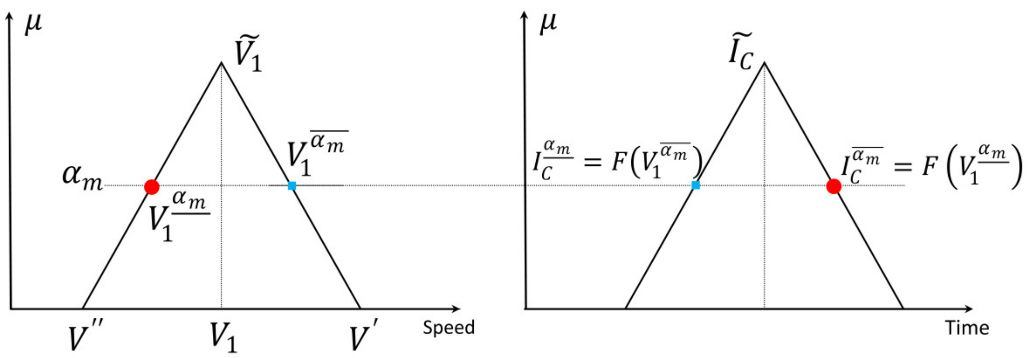


Figure 4-11. Calculation of the α-cut of $\widetilde{I_C}$ from the α-cut of $\widetilde{V_1}$

Fuzzy comparison using necessity measures

The fuzzy comparison $I_M \precsim \widetilde{I_C}$ of Eq.(4-2) (if the measured interval is less than the reference interval, then coast) can be expressed using the necessity measure as:

$$N\left(I_M \precsim \widetilde{I_C}\right) \geq n \quad (4\text{-}15)$$

That is, the necessity that I_M is less than $\widetilde{I_C}$ must be greater than or equal to n to apply the coast command.

This necessity measure can be expressed using the possibility measure as follows:

$$N\left(I_M \lessapprox \widetilde{I_C}\right) = 1 - \Pi\left(I_M \gtrapprox \widetilde{I_C}\right) \tag{4-16}$$

The previous equation means that the necessity that I_M is less than $\widetilde{I_C}$ can be calculated as 1 minus the possibility that I_M is greater than or equal to $\widetilde{I_C}$.

Thus the condition to apply the coasting command is:

$$\text{If } \Pi\left(I_M \gtrapprox \widetilde{I_C}\right) \leq 1 - n\text{; then coast} \tag{4-17}$$

Or the expression:

$$\text{If } \Pi\left(I_M \gtrapprox \widetilde{I_C}\right) \leq \alpha_n\text{; then coast} \tag{4-18}$$

where: $\alpha_n = 1 - n$

The Eq.(4-18) can be expressed in terms of α–cuts (Chanas et al., 1984). To calculate the possibility that the measured interval I_M is greater than or equal to the reference interval, the lower limit of the α_n–cut of $\widetilde{I_C}$, ($I_{\underline{C}}^{\alpha_n}$) has to be obtained where $\alpha_n = 1 - n$ (see Figure 4-12).

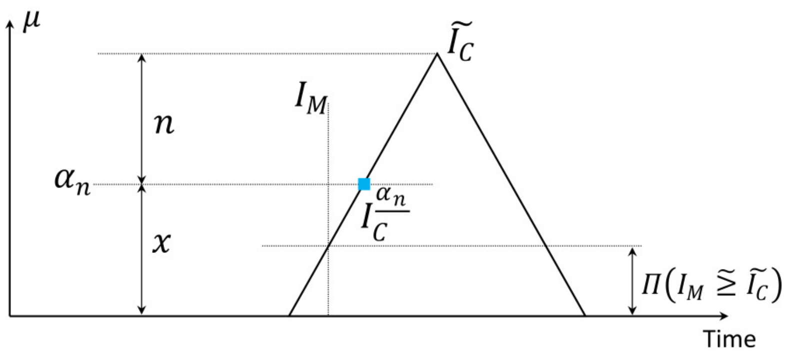


Figure 4-12. Coasting condition according to the necessity measure

If $I_{\underline{C}}^{\alpha_n}$ is greater than or equal to I_M then a coast command is applied, in that way Eq.(4-10) can be rewritten as:

$$\text{If } I_{\underline{C}}^{\alpha_n} \geq I_M\text{; then coast} \tag{4-19}$$

The lower limit of the α_n–cut of $\widetilde{I_C}$ ($I_{\underline{C}}^{\alpha_n}$) can be calculated from the upper limit of the α_n–cut of $\widetilde{V_1}$ ($V_1^{\overline{\alpha_n}}$) as previously indicated (see Figure 4-11).

$$I_{\underline{C}}^{\alpha_n} = F\left(V_1^{\overline{\alpha_n}}\right) \tag{4-20}$$

$$I_{\underline{C}}^{\alpha_n} = I_0\left(1 + \frac{V_2 - V_1^{\overline{\alpha_n}}}{V_2}\right) \tag{4-21}$$

In Figure 4-12 the possibility that I_M is greater than or equal to $\widetilde{I_C}$, is less than α_n. In terms of α–cuts (Eq.(4-13)), the figure shows that I_M is less than the lower limit of the α_n–cut of $\widetilde{I_C}$, thus, the coast command would be applied.

Next, the proposed algorithm is tested and compared with the typical basic tracking algorithm. The comparison is made in terms of energy consumption, running time and tracking interval.

4.4. CASE STUDY AND RESULTS

First, the case of a sustained disruption in the operation of the train is analysed, next the algorithm will be tested for perturbations in three real metro interstations. All the scenarios are analysed in terms of running time, energy consumption and tracking interval.

The train used for the case studies is a class-300 CAF, and its data are summarised in the Table 3-1.

The first case presented in this section consists of an interstation of 2km and the speed limitations are in the range of 50 and 80 km/h as shown in Figure 4-13. The leading train is disturbed and it has to reduce its speed twice, first it is driven at 50 km/h and then at 35 km/h. The ATO command received by the following train is 75 km/h.

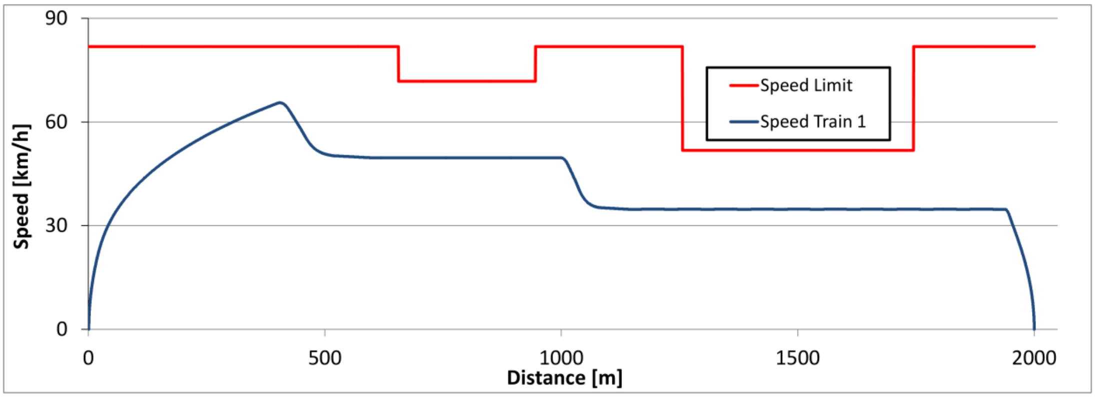


Figure 4-13. Speed profile of the disturbed leading train

The comparison is performed between the basic tracking and the proposed fuzzy tracking algorithms.

Firstly, Figure 4-14 shows the speed profile of the following train when the basic tracking algorithm is applied. The train behind starts with the ATO command received (in this example speed holding at 75 km/h). The train separation is checked until the tracking algorithm is launched when Train 2 is close to Train 1.

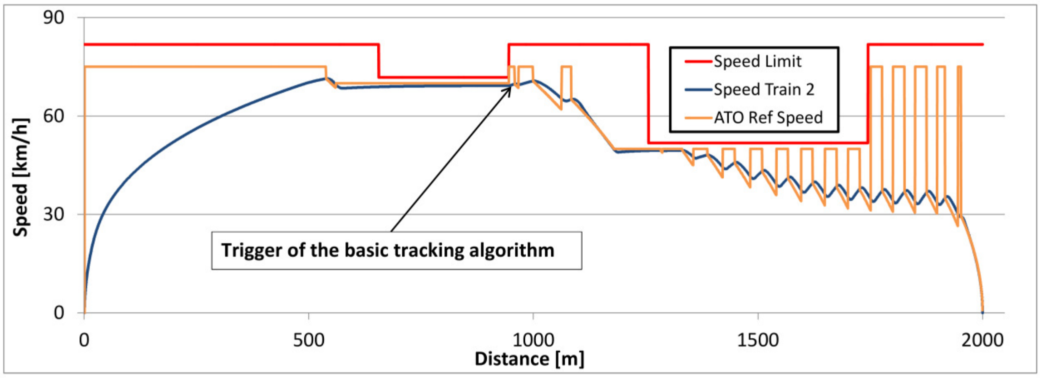


Figure 4-14. Speed profile of the disturbed leading train

A time updating period of 5 seconds is simulated to make more noticeable the changes in the graph. The speed limits, the speed profile and the ATO reference speed are shown in Figure 4-14. The reference speed of the ATO alternates between the ATO holding speed command (75 km/h) and the braking curve as the train advances. When the headway between the two trains is large enough (at the beginning of the trip), the reference speed is the current ATO command in this case 75 km/h, and traction is applied to reach the target speed. So, train driving is not affected either by the leading train nor by the delay in the LMA updating.

After several updating cycles, if the perturbation remains, the train approaches the preceding train. At this point the reference speed changes to the braking curve. The braking process starts, reducing the train speed. As a consequence of the mentioned behavior, the train executes traction/braking cycles which produce an oscillatory effect in the train speed around the final tracking value (35 km/h in this case) when the train is tracking the preceding one with the same speed. The amplitude of the speed oscillation decreases as the LMA updating period is reduced.

Figure 4-14 shows a virtual-block implementation with a large LMA updating period for a better description of the control cycle.

Different LMA updating periods have been used in simulations 100ms, 500ms, 2.5s and 5s and the effect in the running time, energy consumption and steady state tracking interval are compared for each scenario with respect to the base case o basic tracking algorithm.

Next, the proposed fuzzy tracking algorithm is simulated. The base reference interval I_0 is 5s. The fuzzy model of the leading train speed is set according to the definition given at section 4.3 with acceleration and deceleration rates of 1m/s^2 during a time period equals to the LMA updating period. Simulations were performed for 100ms, 500ms and 2.5s and 5s of LMA updating period.

The fuzzy speed of Train 1 is defined: V_1 = 35km/h and V'' and $V'$are calculated as:

V'' = V_1 - LMA_update_period $\cdot$acceleration ; and

V' = V_1 + LMA_update_period $\cdot$ acceleration.

for 100ms, *V''*= 34.54km/h and *V'*=35.36 km/h;

for 500ms, *V''*= 33.2 km/h and *V'*=36.8 km/h;

for 2.5 s, *V''*= 26 km/h and *V'*=44 km/h; and

for 5s, *V''*= 17 km/h and *V'*=53 km/h.

Shorter LMA updating periods correspond to the moving-block implementation of the CBTC signalling system (communication delay), and larger updating periods correspond to virtual-block implementation (and depend mainly on the length of the virtual circuits).

The parameters for the possibility and necessity levels in the fuzzy model are α_m=0.8; n=0.7. The mass passenger load is considered as 70%, a common value in the time operations range considered.

The speed profile of the following train (Train 2) and its reference speed are shown in Figure 4-15. The time updating period is 5 seconds. The reference speed during coasting periods is marked as zero value for ease the visualisation of the regions.

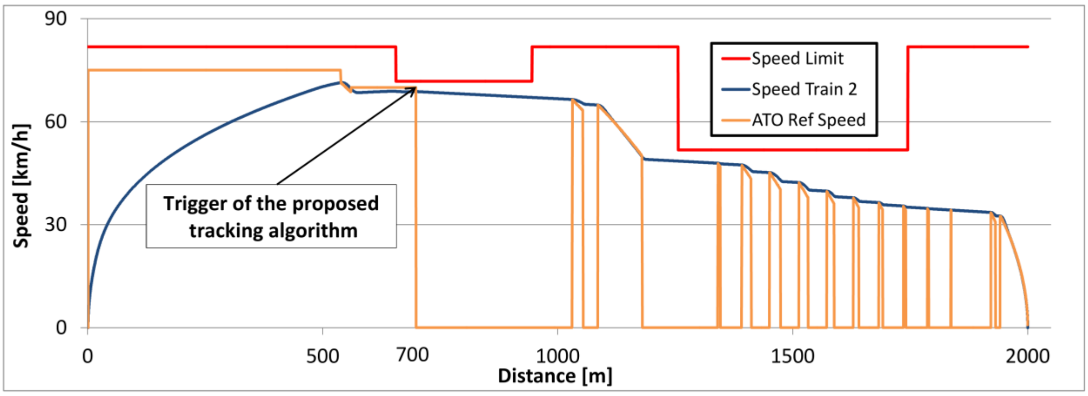


Figure 4-15. Speed profile of the disturbed following train

The traction energy consumption during the coasting periods is zero, nevertheless the safety requirements as speed reduction, train separation and final stop braking are kept. The net effect of this technique is that the energy consumption of the following train is reduced by anticipating a coast command according to the proximity to the leading train. When the train's nose of the following train is around 5 seconds far from the braking curve (700m from the departure station in Figure 4-15), the coasting process starts providing an energy-efficient slower approach. Figure 4-15 shows three main regions of coasting (700-1031m, 1180-1336m and 1837-1916m), additional small coasting regions alternated with braking periods can also be observed. At the end of the transient period, the following train speed is stabilised in a cyclic operation around 35 km/h (the speed of the preceding train) through the application of coast/braking cycles instead of traction/braking cycles. Figure 4-16 shows the comparison between the speed profiles for Train 2, generated by the basic tracking algorithm and the proposed fuzzy tracking algorithm. The time updating period is 5 seconds.

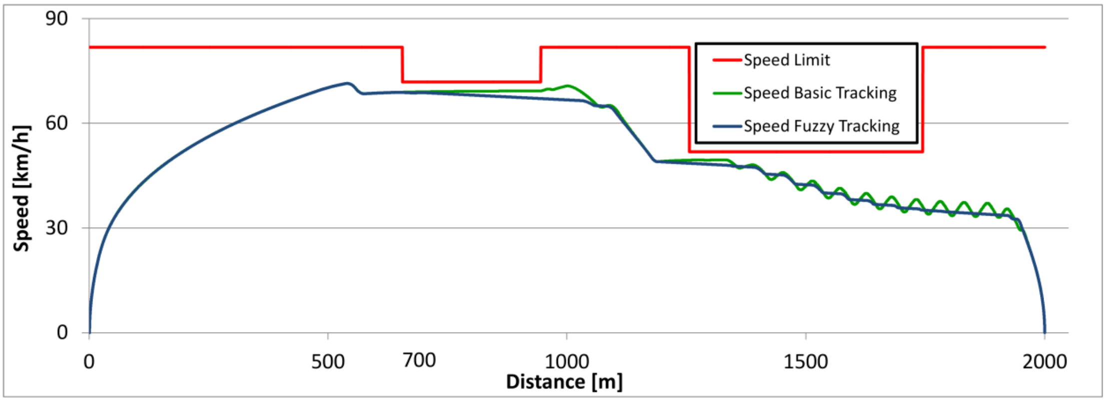


Figure 4-16. Comparison of speed profiles for Train 2 for the basic and fuzzy tracking algorithms

The summary of the simulation tests designed to assess the performance of the proposed algorithm is written at Table 4-1. The simulations were performed by comparing the basic tracking algorithm with the proposed algorithm using possibility and necessity measures. The table 4-1 contains the compilation of the results and comparisons.

	Update period of LMA	Running time [s]	% Running time increase	Steady state tracking interval [s]	Energy consumption [kW-h]	% Saving
Basic tracking algorithm	100ms	154.75	Base case	18.85	20.18	Base case
	500ms	154.95	Base case	19.05	20.37	Base case
	2.5s	155.95	Base case	20.05	24.34	Base case
	5s	157.65	Base case	21.75	27.81	Base case
Fuzzy tracking algorithm. Possibility α_m=0.8	100ms	154.85	0.06%	18.95	17.32	14.16%
	500ms	155.10	0.10%	19.20	17.30	15.04%
	2.5s	156.70	0.48%	20.80	17.23	29.22%
	5s	159.20	0.98%	23.30	17.13	38.41%
Fuzzy tracking algorithm. Necessity n=0.7	100ms	154.85	0.06%	18.97	17.49	13.33%
	500ms	155.10	0.10%	19.45	17.48	14.19%
	2.5s	156.70	0.48%	20.93	17.41	28.47%
	5s	159.20	0.98%	23.65	17.34	37.68%

Table 4-1: Comparative results of the different scenarios

From the table, the LMA updating times analysed are 100ms, 500ms, 2,5s and 5s. For each scenario the running time, percentage of running time increase given by the proposed algorithm with respect to the base case (basic tracking), steady state tracking interval, energy consumption and percentage of energy saving are calculated.

From the results, the energy consumption in the basic case increases as the updating period is higher, because higher updating periods produce larger speed oscillations. In contrast for the fuzzy algorithm, the energy consumption is not affected by the increase of the updating period due to the utilisation of coasting commands.

The running time is only slightly increased by the application of the fuzzy algorithm when the two algorithms are compared for the same LMA updating period (0.98% increase in the worst case, 0.06% in the best case). Therefore, it can be concluded that the application of the fuzzy coasting algorithm has no marked influence over the running time.

Respect to the steady state tracking interval, it should be noticed that there is a slight increase as the LMA updating time increases. This happens because the train speed follows the braking curve for longer periods while the LMA is updated again. For example, in the base case the steady state tracking interval varies from 18.85s for the shortest LMA updating period, to 21.75 s for the longest one. When the fuzzy tracking algorithm is compared to the basic algorithm with the same LMA updating period, the increments of the steady state tracking interval are ranged from 0.1s to 1.9s. Hence, the influence on transportation capacity is minimal.

Lastly, the energy savings shown in the table provided by the fuzzy tracking algorithm are in the range of 14.16% (for 100ms of LMA updating period) and 38.41% (for the 5s LMA updating period) for the possibility measure and between 13.33% and 37.68%, for the necessity measure. Therefore, the presented fuzzy tracking algorithm provides an efficient behavior with a minor influence in the running time.

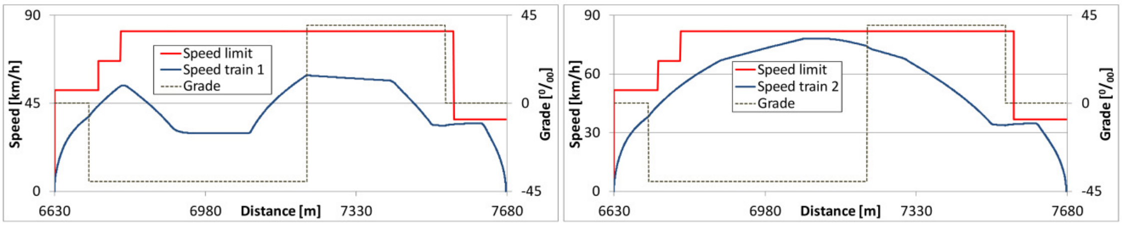
The motor has its own jerk control, to limit variation of the acceleration rate. Typically, the jerk is limited to $1 m/s^3$ and the force applied by the motor takes this limitation into account. This control has been implemented in both basic and fuzzy algorithms thus, in both cases, maximum jerk is limited to this value. In order to analyse the different behavior of both algorithms as they affect passenger comfort, the standard deviation of the jerk is calculated for the basic and the fuzzy tracking algorithms. As a sample calculation, standard deviation of the jerk is 0.554 for the basic tracking with an updating period time of 500ms and 0.437 for the fuzzy algorithm with a possibility measure and an updating period time of 500ms.

Thus jerk variation is higher in the basic tracking algorithm, which makes it less comfortable for passengers.

The second set of examples corresponds to additional case studies of real interstations in Metro de Madrid Line 3 to test the energy efficiency of the fuzzy tracking algorithm under temporal disturbances. The cases tested were ‘Hospital Doce de Octubre’ Platform 1 (DO1) where grades vary between -40 and 40mm/m, ‘Lavapiés’ Platform 1 (LV1) with positive grades between 0 and 41mm/m, and ‘Villaverde Alto’ Platform 1 (VA1) with negative grades between 0 and -26 mm/m.

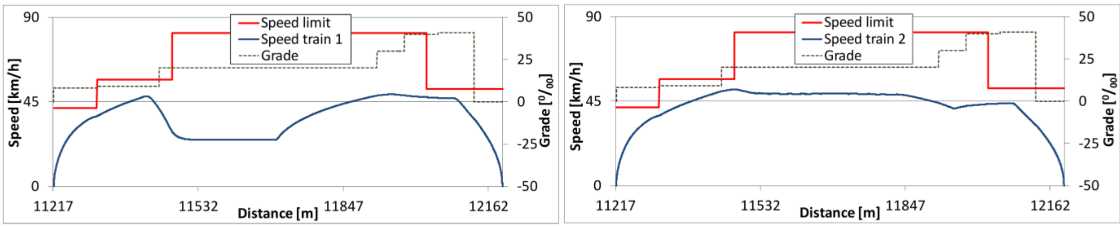
The perturbation of the preceding train is a temporary speed reduction, as shown in figures 4-17, 4-18 and 4-19 for each interstation.

These figures illustrate, at the left side, the speed profile of the preceding train, and at the right side the speed profile of the following train. The LMA updating period is 500ms and energy efficiency of the fuzzy tracking algorithm using possibility measure (α_m=0.8) is compared to the basic tracking algorithm.



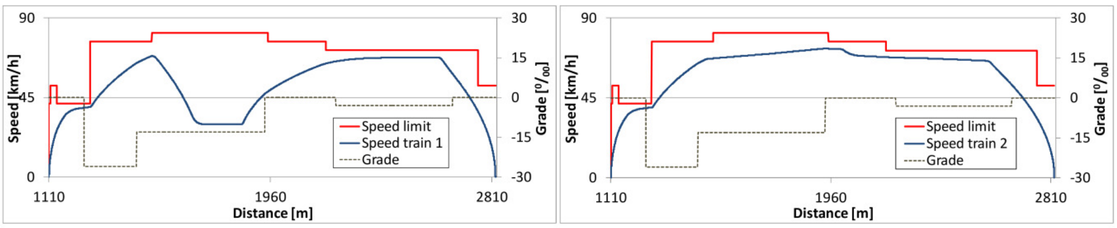
DO1

Figure 4-17. Speed profiles for the preceding and following trains for DO1 interstation with the fuzzy tracking algorithm with possibility measures



LV1

Figure 4-18. Speed profiles for the preceding and following trains for LV1 interstation with the fuzzy tracking algorithm with possibility measures



VA1

Figure 4-19. Speed profiles for the preceding and following trains for VA1 interstation with the fuzzy tracking algorithm with possibility measures

A summary of the results obtained in each case is shown at Table 4-2.

Interstation	Energy basic tracking [kW-h]	Energy fuzzy algorithm [kW-h]	% Saving
DO1	12.364	10.983	11.169
LV1	22.869	20.661	9.655
VA1	15.383	10.881	29.266

Table 4-2. Comparative results of the real scenarios

The downhill interstation VA1 presented the highest energy savings (29.3%), as expected. The uphill interstation LV1 savings provided by the proposed algorithm are 9.6% and savings at the interstation with mixed positive and negative grades (DO1) are 11.2%.

4.5. CONCLUSIONS AND CONTRIBUTIONS

4.5.1. CONCLUSIONS

The CBTC signalling system allows closer headways between consecutive trains while maintaining safety requirements. When a train runs close enough to the preceding one, the tracking algorithm is triggered. This chapter of the thesis has shown that the existing basic tracking algorithm is associated with high energy consumption due to the execution of traction and braking control cycles.

A new algorithm has been proposed to improve the energy efficiency of the tracking process. It takes into account the uncertainty associated with the preceding train speed, which is modelled as a fuzzy number. This algorithm makes use of coast commands for a smooth approximation to the preceding train.

The proposed fuzzy tracking algorithm has been tested with different updating periods of LMA using necessity and possibility measures, and compared with the typical basic tracking algorithm. It has been shown that the proposed algorithm has a negligible impact on running times and has significant associated energy savings, ranging from 13.3% to 38.4%. The proposed algorithm has been simulated as well in three real Metro de Madrid interstations and provided energy savings between 9.6% and 29.3%.

In addition, the tracking algorithm proposed is suitable for installation in onboard ATO equipment because it is fast and can be run in real-time. It does not affect safety, because the maximum permitted curve is observed.

4.5.2. CONTRIBUTIONS

The contributions of this chapter are listed in the following:

- A fuzzy train tracking algorithm has been proposed for reducing the energy consumption by the application of coasting commands.
- The algorithm takes into account the uncertainty associated with the speed of the preceding train and it is modelled as a fuzzy number. This fuzzy speed is used to calculate the fuzzy reference interval, which is the threshold to apply coast command.
- This algorithm provides a smooth approximation to the preceding train and the ripple of the control cycles is reduced, therefor improving comfort.
- The advantages of using this tracking algorithm have been demonstrated for the different implementations of the CBTC signalling system: virtual-block and moving-block. Significant energy savings are obtained for all the LMA updating periods analysed.

Chapter 5

CONCLUSIONS AND CONTRIBUTIONS

In this chapter, conclusions are drawn about the methods and algorithms proposed, and the main contributions of the research are highlighted. Finally, further future work for new research paths is proposed.

5.1. CONCLUSIONS

Energy-efficient design of speed profiles

In railways systems the aim is to find the most economical and comfortable way to transport passengers to the desired destination while keeping safety. The speed profile of the train can be calculated prior to its operation and stored in the train's computer memory or in the traffic manager database. There are different ways of controlling a train from manual driving to fully automated driving based on wireless communication, where the driving commands can be updated if necessary to solve unexpected traffic situations, maintaining the train movement under safe and comfortable conditions.

The new CBTC signalling system has been increasingly installed in new and upgraded metro systems. As it permits continuous communication between train and wayside systems, transportation capacity is increased and the control possibilities of the train speed profiles are expanded. So, the train speed can be controlled according to the traffic conditions, and the driving commands can be updated at any point of the trip.

This flexibility permits to take advantage of the track and infrastructure configuration to produce efficient and comfortable speed profiles to be used during real-time operation.

As the train could be operated in almost infinite different ways, it is necessary to use optimisation techniques to obtain the best possible way to drive a train given a set of known conditions of the track, train and operational constraints.

An algorithm has been proposed for the design of the ATO CBTC optimal speed profiles for minimising the energy consumption. The Pareto front of the running time vs. energy consumption is obtained by taking the most efficient speed profile for each running time. These speed profiles are stored in the traffic regulation system for selecting the suitable speed profile according to the required running time for each traffic condition. The multi-objective algorithm named NSGA-II-F has been proposed. The uncertainty associated to total train mass due to the variable passengers load component has been modelled as a fuzzy parameter.

Each ATO driving in a CBTC system is modelled as a list of distance-based commands to be executed during the journey from a station to the next. Each speed profile is the result of a detailed simulation of the train and the infrastructure interaction along with the safety constraints and the driving commands given. The NSGA-II-F optimisation algorithm is based on that detailed simulation of the train motion. The weak and strong fuzzy-dominance concepts, and the fuzzy crowding distance defined by means of the possibility and necessity measures using alpha-cut arithmetic are the main concepts used for the resolution of the proposed NSGA-II-F.

The discontinuity in the Pareto front, because of the absence of non-dominated points during the optimisation process, is solved by implementing an algorithm to fill the running time gaps with bounded dominated points. The result is a pseudo-Pareto curve which includes a more even distribution of the solutions, and thus a wide range of options to meet the target running time for a given traffic situation.

The optimisation algorithm has been used for the design of ATO speed profiles of a real interstation of Metro de Madrid. Energy savings around 7-8% were obtained when the speed profiles were re-designed considering the flexible driving features of the CBTC signalling system. A uniformly distributed pseudo-Pareto front along the running time range was obtained.

As a general conclusion, the benefit of the CBTC signalling system is twofold. On one hand the transportation capacity is improved and on the other the energy consumption is reduced because of the new optimised ATO speed profiles.

Train tracking algorithm

In unscheduled situations such as a sudden speed reduction of the leading train, the following train must modify its speed profile and take actions to avoid colliding with the previous train. The train must react and follow the leading train by means of a tracking algorithm.

The tracking algorithm monitors the distance between consecutive trains and is triggered when the proximity between them demands it. The existing tracking algorithms have high associated energy consumption and are uncomfortable due to the use of the traction and braking control cycles.

A new tracking algorithm is proposed to avoid inefficient and uncomfortable behavior. The algorithm takes into account the uncertainty in the speed variation of the leading train along the LMA updating period, making use of three different commands: the scheduled ATO command, coast command, and the braking curve according to a decision rule proposed to implement the algorithm. The use of coast commands produces a smooth approximation to the preceding train saving energy.

The proposed fuzzy tracking algorithm was tested using different updating periods of the LMA to cover from the virtual-block to the moving-block implementation of CBTC signalling system. Comparisons with the basic tracking algorithm were carried out using necessity and possibility measures. The simulations show that the influence of the tracking algorithm over the running time is negligible while the energy savings are significant: from 13.3% up to 38.4%. Additional tests over real interstations of Metro de Madrid were performed obtaining savings ranged from 9.6% up to 29.3%.

The algorithm formulation makes it suitable for onboard ATO installation and the safety is guaranteed because the maximum permitted curve is observed.

5.2. CONTRIBUTIONS

This section summarises the contributions of this thesis.

Regarding the design of **efficient ATO speed profiles in CBTC equipped lines**, the contributions are:

- A multi-objective optimisation algorithm NSGA-II-F for the off-line design of CBTC speed profiles based on detailed simulation of the train motion has been proposed in this thesis.
- The NSGA-II-F is a multi-objective genetic algorithm that includes the uncertainty associated to the mass of the train (passengers load) modelled as a fuzzy number.
- In addition, an improvement was added to fill the gaps in the Pareto front and a pseudo-Pareto front is calculated to provide solutions well distributed in running time terms.
- The NSGA-II-F is based on the detailed simulation of the train motion, where ATO CBTC driving is modelled as a list of distance-command to be executed along the interstation.
- For the resolution of the NSGA-II-F, a definition for the weak and strong fuzzy-dominance have been proposed in this thesis as well as for the fuzzy crowding distance by means of the possibility and necessity measures, and a procedure based on alpha-cut arithmetic has been designed.

- It has been shown the important impact that the new CBTC signalling system can have not only in transportation capacity but also in reducing the energy consumption of traffic operation.
- An analysis of the effect of the regenerated energy flow in the design of CBTC ATO speed profiles has been developed to show that the solutions provided remain optimal or quasi-optimal in different receptivity scenarios.

Regarding the **tracking algorithm** between consecutive trains in CBTC equipped lines, the contributions are:

- A fuzzy train tracking algorithm has been proposed for reducing the energy consumption by the application of coasting commands.
- The algorithm takes into account the uncertainty associated with the speed of the preceding train and it is modelled as a fuzzy number. This fuzzy speed is used to calculate the fuzzy reference interval, which is the threshold to apply coast command.
- This algorithm provides a smooth approximation to the real-time position of the preceding train, and the ripple of the control cycles is reduced. Therefor comfort is also improved.
- A procedure based on alpha-cut arithmetic and possibility and necessity measures has been designed for the resolution of the tracking algorithm.
- The advantages of using this tracking algorithm have been demonstrated for the different implementations of the CBTC signalling system: virtual-block and moving-block. Significant energy savings are obtained for all the LMA updating periods analysed.

In addition, a detailed **simulation model** for the motion of a train equipped with CBTC ATO system has been developed in this thesis, including realistic characteristics of the train, the line and the ATO equipment. The simulation model has the following features:

- Time-step based simulation of the train motion.
- Detailed model of the train motion, including aerodynamical constants, traction motor curves and consideration of physical characteristics such as length and mass.
- Detailed representation of the track characteristics as slopes, bends, speed limits and stopping points at the platforms.
- A detailed model of actual ATO equipment considering hysteresis, variable gains and saturation functions.
- The protection system functions needed to meet the safety requirements as maximum speed limits and braking curves.
- Modelling of the CBTC speed profile as a sequence of distance-based driving commands (traction, coasting-remotoring cycles, speed holding and coasting).
- Traction energy and net energy consumption calculation.
- The implementation of a two-train simulation feature for the analysis of the tracking process for different LMA updating rates, including energy calculations for efficiency analysis.

5.3. FURTHER WORK

During the research development future research areas related with the efficient operation of metro lines equipped with CBTC signalling system have been identified.

The natural next stage of the research is the implementation of the proposed methods in a complete centralised traffic regulation system where punctuality, operational headway, comfort and energy efficiency should be considered to control all the trains in the line.

Design of efficient ATO CBTC speed profiles. Other optimisation methods based on simulation could be investigated and compared with the NSGA-II-F proposed in this thesis, such as MOPSO (multi-objective particle swarm optimisation), or MO-ACO (multi-objective ant colony optimisation).

Tracking algorithm. The consideration of slope and speed limits ahead, given that the track profile and geometry is known, is feasible. This additional complexity of the algorithm should be evaluated because the calculation time could introduce additional delay in the real-time operation of the train. Calculation time, software complexity and hardware capability vs. energy savings should be evaluated to decide if the inclusion of these features is worthwhile.

The convergence of CBTC/ERTMS/PTC (Positive Train Control) could open different research areas about the techniques and strategies to implement energy saving strategies in the future unified systems.

List of publications

JCR IMPACT FACTOR JOURNALS

Optimal design of energy-efficient ATO CBTC driving for metro lines based on NSGA-II with fuzzy parameters, W. Carvajal-Carreño, A.P. Cucala, A. Fernández-Cardador. Engineering Applications of Artificial Intelligence. vol. 36, pp. 164-177, November 2014. [Online: August 2014].

Fuzzy train tracking algorithm for the energy efficient operation of CBTC equipped metro lines, W. Carvajal-Carreño, A.P. Cucala, A. Fernández-Cardador. Engineering Applications of Artificial Intelligence. vol. 53, pp. 19-31, August 2016. [Online: April 2016].

CONFERENCE PARTICIPATION

Efficient driving algorithms for non-disturbed and disturbed trains with the CBTC signalling system, W. Carvajal, A.P. Cucala, A. Fernández-Cardador, L. Söder, 4th International Conference on Models and Technologies for Intelligent Transportation Systems. MT-ITS 2015. ISBN: 978-963-313-142-8, Budapest, Hungary, 03-05 June 2015.

Curriculum Vitae

William Carvajal Carreño was born in Bucaramanga, Colombia. He received the electrical engineering and MSc. degrees from the Industrial University of Santander (UIS), Colombia, in 1997 and 2009. From 1998 to 2012, he worked as a lecturer in public and private universities in the region of Santander, Colombia, where he taught courses about electrical circuits, electrical machines, power electronics, signal processing and control systems. During his undergraduate and master studies at UIS he worked in the research group GISEL in the area of power quality and harmonic analysis.

In 2012, William joined the Institute for Research in Technology of Comillas Pontifical University in Madrid to serve as Assistant Researcher in the framework of the SETS (Sustainable Energy Technologies and Strategies) Erasmus Mundus Joint Doctorate within the Railways Research Group. Besides his research work, he participated in research projects in the field of ecodriving design applied to metro systems. His areas of interest are railway systems, energy efficiency, metaheuristic optimisation, power electronics and control systems.

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