THE DEVELOPMENT OF A FUZZY CONTROLLER FOR TRACTIVE EFFORT OF A RESISTOR TECHNOLOGY LOCOMOTIVE

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Abstract. The application of a rule based fuzzy controller, implementing human skill and experience to control tractive effort of a resistor technology locomotive, is presented. The fuzzy controller aims to smoothly and safely accelerate the train from standstill. The controller provides the operational consistency and feedback functions required for improved protection of the traction motors, locomotive, rails and load. A simulation model for the locomotive and load is included.

Keywords. fuzzy, control, train, slip, traction, locomotive.

INTRODUCTION

Background

Old technology. The South African railway company, Spoornet, presently operates a fleet of approximately 1500 electric locomotives, two thirds of which are of the older resistor technology type. (The first of these class 6E and 6E1 locomotives were commissioned during the early seventies). The 3kV DC locomotives comprise four series DC traction motors, two variable traction resistance banks and an interlocked contactor based control system.

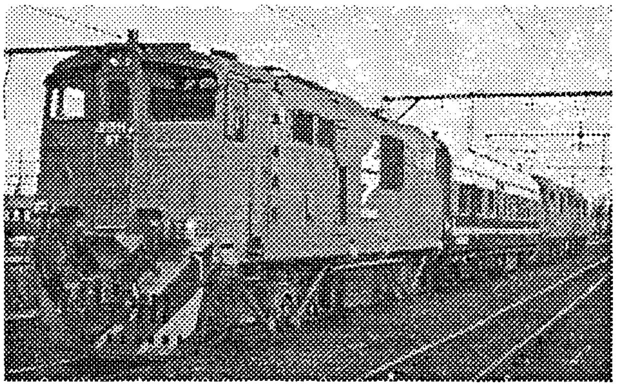


Figure 1: The class 6E1 locomotive test consist.

Master controller function. The master controller is used by the driver to select the notch at which the locomotive should operate. When more than one locomotive is used to haul a train, the selected notch signal is transmitted through 110V train lines to trailing locomotives in the locomotive consist, so that all the locomotives operate at the same notch. During starting the driver controls the notch in a way that will produce the desired smooth acceleration of the train and at the same time not result in overcurrent to the traction motors or excessive wheelslip.

Uncontrolled wheelslip and the incorrect taking up of slack are two of the main causes for damage during starting.

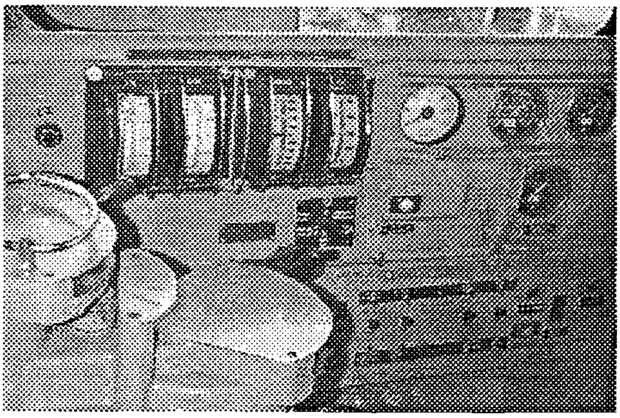


Figure 2: The master controller and instrument panel.

Uncontrolled wheelslip. During starting, sudden changes in the dynamics of the wheel-rail interaction, locomotive switching irregularities or the inattentive or accidental selection of a too high notch can result in slipping wheels and over speed of traction motors anywhere in the locomotive consist. An electronic wheelslip system on these locomotives provides a warning signal to the driver in the leading locomotive, as well as a limited level of protection to the affected locomotive (through engaging an armature divert system and the application of locomotive brakes). However, this system is inherently not completely effective and uncontrolled wheelslip may occur. Furthermore the driver may not immediately take action (by selecting a lower notch), or may have to make a large step reduction. The latter affects the tractive effort (TE) of the whole consist, causing a severe and sudden drop in the overall tractive effort of the consist.

This uncontrolled wheelslip results in wear and creates over speed operating conditions which are potentially destructive of traction motors. It also results in various forms of costly damage to the locomotives and rails.

The large sudden variation in overall tractive effort of the locomotive consist can result in mechanical shocks, damaging other rolling stock and the goods being transported.

Taking up slack. The correct train handling practice during starting (acceleration of a train from rest), is described by Van Der Meulen (1). Unevenly distributed slack that may be present in the train when it comes to rest. Consequently, the locomotives pick up the load erratically when starting from rest. After overcoming initial rolling resistance and while the head-end is moving, the driver should maintain very low speed until all the slack has been taken up.

Problem Definition

Lack of inherent feedback. The class 6E and 6E1 locomotive control systems are largely feed forward systems, relying heavily on the train drivers to provide the necessary feedback functions required for protection against jerking, wheelslip and traction motor overcurrent.

Due to human factors these feedback functions can not and are not performed consistently, resulting in major damage to locomotives, load and rails.

The drive control technology employed in these systems prevents the incorporation of simple feedback systems to provide the required protection features.

The proposed solution

To solve the problem of wheelslip and sudden large variations in overall tractive effort of a 6E-locomotive consist, it is necessary to control the tractive effort (rather than the notch) of each locomotive individually, as in modern power converter controlled locomotives. This implies that direct automatic control of the notch position of each individual locomotive must be obtained, as opposed to the transmission of the same notch signal to all the locomotives.

Starting of trains can be optimised through utilising the experience of a skilled driver implementing the correct train handling practices every time a train is started.

Accordingly, an intelligent (fuzzy) controller was developed, implementing experienced drivers' skills to control the tractive effort of the class 6E and 6E1 locomotives individually, and to provide the necessary feedback for the protection of the locomotive (a highly non-linear and time variant system).

The controller has the following features:

- provision of a tractive effort controller as on modern locomotives, rather than a notch controller,
- the ability to start a train smoothly on a level or a slight uphill gradient, eliminating serious jerking,
- a feedback function which brings run-away wheel slip conditions under control,
- a feedback function which prevents over speed (centrifugal damage) of the traction motors,
- a feedback function which prevents overloading of traction motors due to excessive armature currents,
- the prevention of thermal overloading of the traction resistors through optimised switching,
- the prevention of a notch change rate that exceeds the specified constraints,
- the maintaining of specified tractive effort in spite of changes in system characteristics (robustness).

OPERATION OF THE CONTROLLER

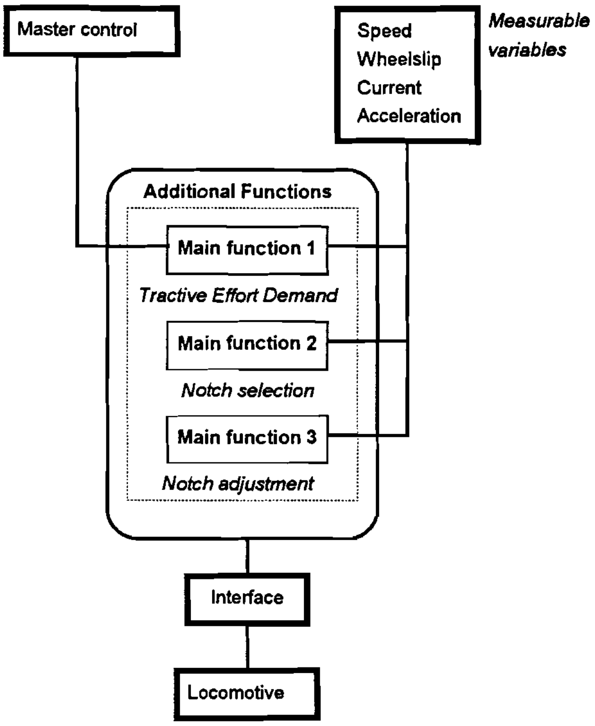


Figure 3: Diagrammatic representation of controller functions

Inputs

The controller inputs are similar to those that are available to the driver.

Functions

The three main functions of the controller are depicted in figure 3.

The first function is the provision a tractive effort demand signal, based on the master controller position.

The second function is the application of systematic and rigorous fuzzy reasoning, through a fuzzy rule base, to determine the required rate of change in notch and percentage weak field.

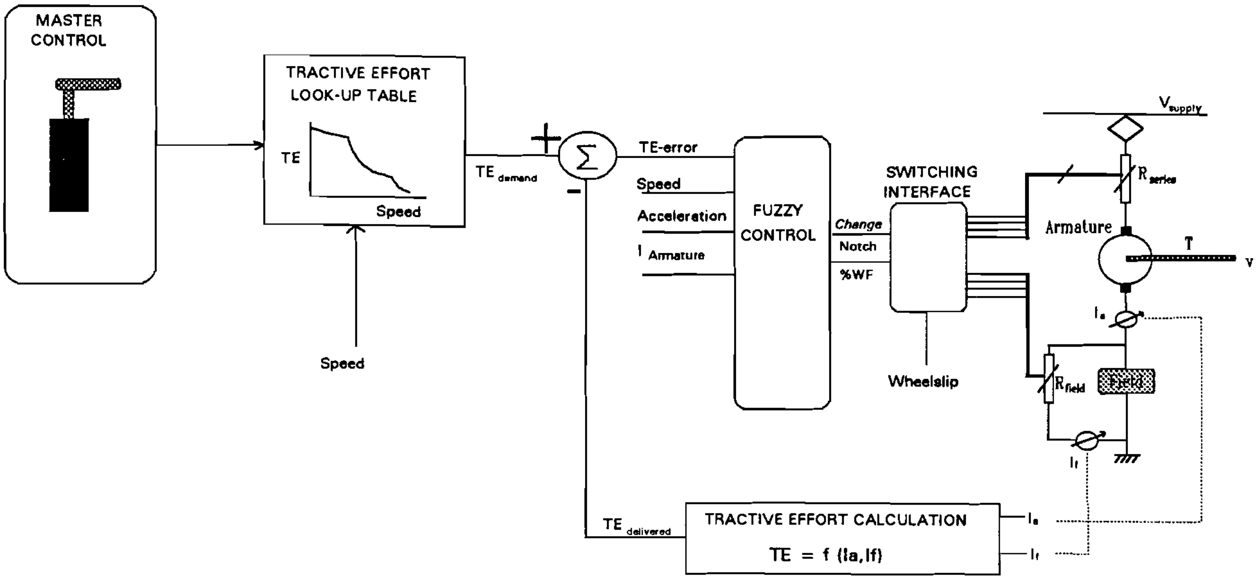


Figure 4 : Controller block diagram

The third function is the switching interface, that ensures smooth and correct transitions during switching. It ensures compliance with the timing requirements for switching, preventing unnecessary or too rapid transitions.

Fuzzy controller block diagram

The controller block diagram is shown in figure 4. The controller obtains the driver's demand for tractive effort from the master controller. This signal is then combined with the locomotive speed in a look-up table, containing the design tractive effort vs. speed characteristics, to determine the tractive effort demand signal. The actual tractive effort is calculated from measured parameters. The tractive effort error signal (the first input to the fuzzy controller) is then determined as the difference between the demand and calculated tractive effort signals.

The other inputs to the fuzzy logic controller are the speed signal, locomotive absolute acceleration and measured armature current signal.

A fuzzy rule base, containing a skilled driver's knowledge and experience, then determines the required rate of change of the main- and weak field notch signals. Field control is utilised to minimise jerking during transitions.

The defuzzified rate of change output signals are then numerically integrated to obtain notch position demand signals. These analogue signals are then "digitised" by means of a software implemented Schmitt trigger with hysteresis. The discrete notch signals are then sent to the locomotive's existing traction control system through a relay switching interface.

LOCOMOTIVE SIMULATION

Model objectives

The development of fuzzy controllers requires several iterations, which could not be afforded on a locomotive, so that a model of the locomotive had to be developed.

The model was required for:
- identification and testing of the basic fuzzy rules,
- investigation of the stability of the controller,
- identification of rules for handling of system faults, for example, a notch that will not engage, and
- the handling of emergency operating conditions, for example, an emergency stop.

Advantages of the model included:
- the ability to test new control strategies, for example, the use of weak field for the reduction in tractive effort jumps between notches,
- usage for other train simulation applications,
- the minimisation of the risk to staff and of potential damage to locomotives and load through evaluation on the model prior to in-service testing.

Model requirements

Development of the fuzzy controller required a PC-based fuzzy development system, supporting a "real time"-link to a "C"-simulation of the controlled system.

Components of the model. Since the model and the controller were ultimately implemented in a closed loop, both the locomotive and load were simulated

As fuzzy control strategies are based on the human operator's skills, only those variables that the train driver uses required simulation, namely the speed, acceleration, armature current and field current.

The locomotive model uses line voltage, speed and notch as input variables. The output variables are the armature current, field current and tractive effort. (These imply that the motor- and bogie voltage are also calculated).

The locomotive's tractive effort is supplied to the load model as an input. The acceleration is then calculated and the speed is determined through numerical integration.

Existing models. The possible use of other models was first investigated, for example, the train simulator models and an Electro Magnetic Transients Program (EMTP) model for a similar Italian locomotive, Ghiara et al (2). Problems with these models included (a) the difficulty of linking these models to the fuzzy development system, and (b) the generic nature of these models, the consequence of which was that tractive effort was determined through look-up tables, and essential parameters such as the armature currents were not available while the accurate simulation of transients was lacking.

Description of the locomotive model

The traction power circuit for the locomotive in series powering configuration is shown in figure 5.

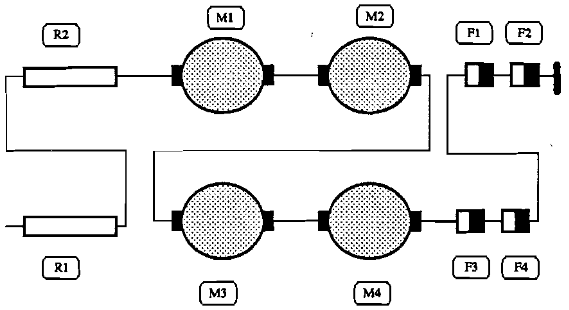


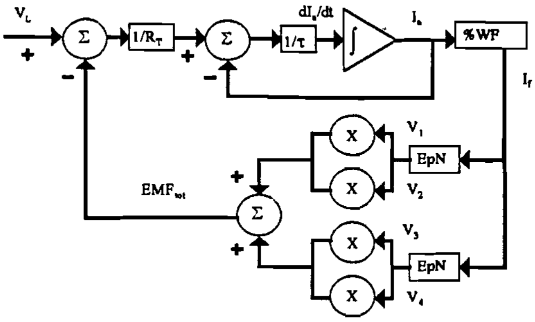
Figure 5 : Traction power circuit for series powering

The symbols R, M and F in figure 5 depict the series resistors, traction motors and field coils respectively.

The model for this traction circuit was based on the differential equation for the calculation of the armature current for a series connected direct current (DC) motor:

$$dI_a/dt = [(V_L - EMF) / R_T - I_a] / \tau \qquad (1)$$

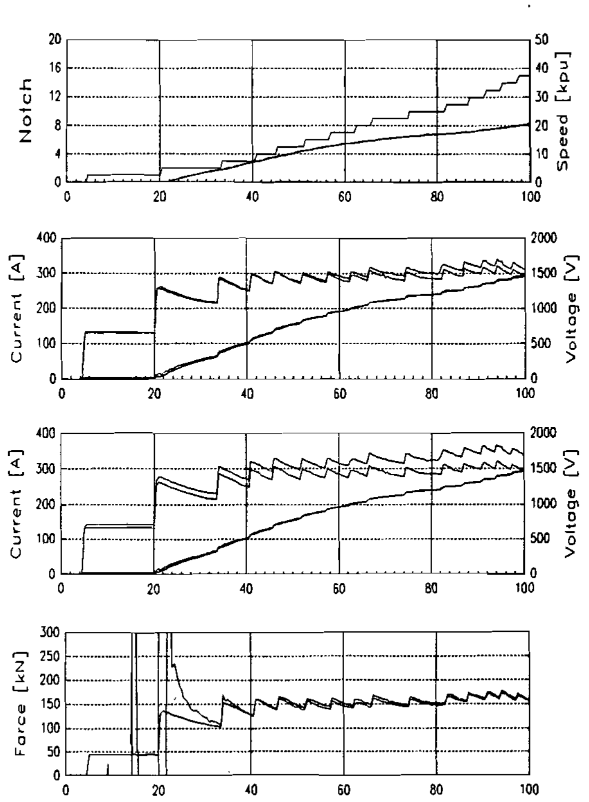
The block diagram in figure 6 shows how the basic differential equation was implemented for the four traction motors connected in series.



V_L	Line Voltage	I_a	Armature Current
I_f	Field Current	τ	Time Constant
%WF	% Weak Field	EpN	EMF as a function of I_f
$V_{1,2,3,4}$	Motor speeds	EMF_{tot}	EMF for all the motors
R_T	Total resistance	X	Multiply
Σ	Summation		

Figure 6: Block diagram of locomotive model

The difference between the supply voltage and the induced armature voltage (EMF) of the traction motors is determined. This voltage is applied over the total circuit resistance to determine the armature current through the series connected motors. The field current is a percentage of the armature current. The generated EMF's per revolution are then calculated from a curve fit relating the field currents to the motor characteristics. The actual EMF per motor is determined by multiplication with the respective motor angular velocities, thereby allowing the simulation of slip on a particular motor.



Graph 1: Notch and Speed
Graph 2: Armature current and voltage - bogie 1
Graph 3: Armature current and voltage - bogie 2
Graph 4: Tractive Effort

Figure 7: Comparison of simulation results with in-service recordings

Simulation results

The simulation results were compared with actual in-service recordings. For this purpose a test consist as in figure 1, consisting of one class 6E1 locomotive (in powering), a test coach (fitted with an advanced measurement system) and two class 6E1 locomotives (in braking, to regulate the speed), was used.

A comparison, as given in figure 7, of the simulation results with recordings of current, voltage and tractive effort of a locomotive, as done in the field, verified that the simulation results were very accurate, with errors of less than five percent being obtained. In fact in most parts of the figure it is difficult to distinguish between experimental and simulated results.

Similarly, accurate results for the combined simulation of a locomotive and a 20 truck load have been obtained.

FUZZY CONTROLLER DEVELOPMENT

Development system

A personal computer based fuzzy logic development system was chosen for the development of the fuzzy controller. The development software provided the facility to interactively change the relative weights of rules in the rule base, as well as to adjust of the various membership functions while the plant was being controlled.

The development software and simulations were run simultaneously on a multitasking operating system. The simulations for the locomotive and load were linked to the development system through a software data transfer facility.

Structure

The schematic diagram in figure 8 illustrates the structure of the fuzzy controller.

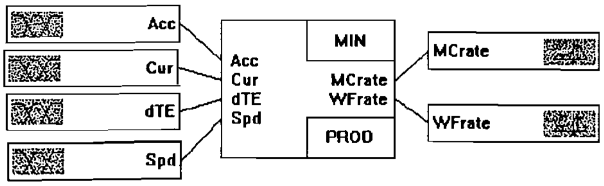


Figure 8: Schematic diagram of the fuzzy controller

Variables. The fuzzification of the four linguistic input variables, namely acceleration (Acc), armature current (Cur), tractive effort error (dTE) and speed (Spd) are represented on the left of figure 8.

SIGNAL	LINGUISTIC VARIABLE	RANGE
INPUT		
Absolute acceleration	Acc	$\pm$ 0.25 m/s^2
Armature current	Cur	0 - 600 A
Percentage tractive effort error	dTE	± 100 %
Locomotive speed	Spd	0 - 50 km/h
OUTPUT		
Rate of change of the master controller	MCrate	± 1 notch/s
Rate of change of the percentage weak field	WFrate	± 1 notch/s

TABLE 1 - Linguistic variables for the fuzzy controller

The range of each of these variables was sub-divided into seven overlapping linguistic terms and each given labels such as "pos_small". Triangular shaped membership functions, shown in figure 9, were used for all the terms of both input and output variables.

The rate of change of the master controller notch, called MCrate was used as an output signal, rather than the notch itself. This was possible, since the same basic strategy applies for the changing of all the notches. The speed input variable is used to achieve a low rate of increase of notch when the train is starting from rest.

The rate-of-change output was numerically integrated, with a time constant equal to the sample period. This limited the maximum rate of change to within the one notch per second locomotive constraint. The integration produced an analogue notch position signal,. The discrete notch position was then determined using a software implemented Schmitt trigger with a hysteresis band of 1. This prevented the occurrence of any unwanted notch transitions.

The technique greatly simplified the rule base, since the need for separate rules for each notch was eliminated. It also eliminated the need for a highly complicated and insensitive output membership function consisting of multiple singletons for the range (0-19) of different notch positions.

Rules. The fuzzy inputs were fed to the rule base, depicted at the centre of figure 8, where the fuzzy rule inference was performed.

The rules were all in the form: IF "Acc" is *pos_small* AND "Cur" is *about_300* AND "dTE" is *pos_med* AND "Spd" is *crawling* THEN "MCrate" is *up_fast* AND "WFrate" is *zero*.

The contributions of all the respective rules to the outputs were calculated employing the Centre-of-Maximum (CoM) method of defuzzification.

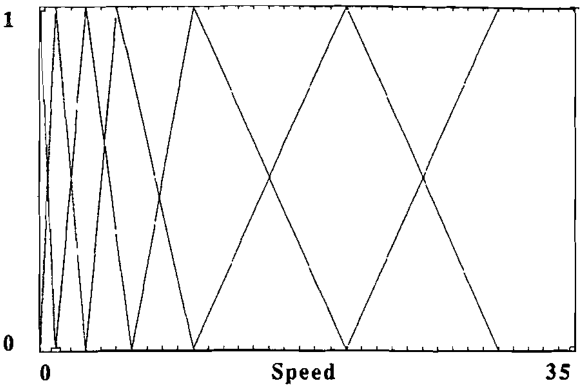


Figure 9: Membership functions for the linguistic input variable "Spd"

Control strategy

The aim of the controller was to smoothly accelerate the train from rest to about 25 km/h, using the resistance notches in series powering only.

The control strategy was directed at changing the notch as fast as possible to the point where the error in tractive effort would be minimised. This rate of change was increasingly reduced as the "Cur" input increased to *about_400* A and higher.

The operating conditions where the "Acl" is *pos_small* (or *pos_med*) AND "Spd" is *zero* (or *crawling*) were used to achieve the required very slow train starting practice.

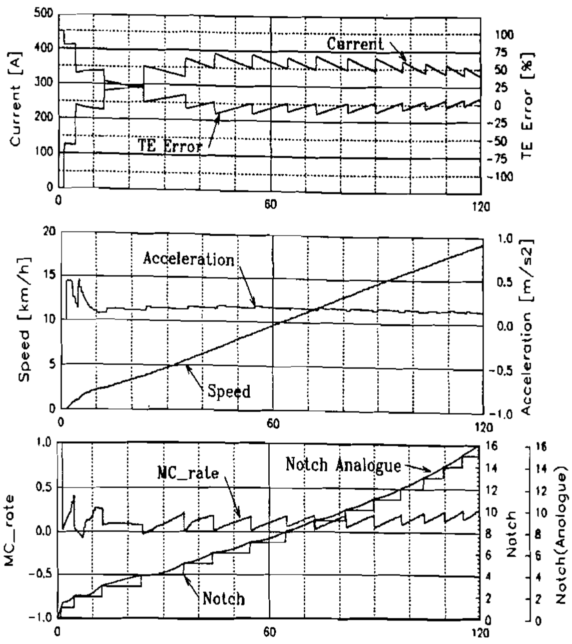
The protection against the wheelslip is achieved by an extra input of -1 to the MCrate integrator. This input is activated only when a wheelslip signal is received from the wheelslip protection equipment. The signal overrides the MCrate output signal from the fuzzy controller and provides the maximum rate of decrease of the notch.

Locomotive interface

The 110V relay interface was designed to ensure safety. A "fail to safe" mechanism was provided for all possible failures. An emergency switch enabled the driver to regain complete control of the locomotive at any point in time. Any failure would cut out the controller immediately and return the locomotive to notch 1, ensuring that an open traction circuit was not suddenly created.

FUZZY CONTROL RESULTS

From the results in figure 10 it is evident that, throughout the speed range, the controller successfully reduces the percentage tractive effort error, while simultaneously limiting the armature current and acceleration to acceptable levels.



Graph 1: Current and %Tractive effort error
Graph 2: Speed and acceleration
Graph 3: MCrate and Notch

Figure 10: Simulated fuzzy control results

CONCLUSION

The fuzzy controller successfully produces the desired starting characteristics for the simulated train.

The success achieved with the implementation of the fuzzy controller on the model served as the basis for the practical implementation of the controller on an in-service locomotive.

A personal computer based fuzzy controller on the locomotive itself is used for the interactive completion the rule base and fine tuning of the various membership functions. This final stage of the development will be finalised before the commencement of the conference and. the results from the in-service evaluation will be presented at the conference.

References

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