Computer Aided Train Operation, CATO

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Summary: This paper gives a short description of the Swedish CATO project, which is also the acronym for a proposed standard for optimised train operation. The paper describes the main aspects of the system, a possible implementation as well as the results of feasibility and field tests performed on the LKAB iron ore line in Sweden. In this operation CATO should, among other benefits, bring more than 25% reduced energy consumption and approximately 10% improvement of line capacity. However, the objective of the project is not only to bring improvements the LKAB heavy haul operation, but also to give a base for a system that may be utilised in mixed operations in Sweden and elsewhere. It is foreseen that a number of CATO system implementations will be done in the next decade.

Index Terms: Optimisation, Operation, Energy, Capacity, CATO, DAS

1. NOTATIONS

- **ATP**: Automatic Train Protection (in Sweden normally called “ATC”)
- **CATO-TCC**: CATO software application in the TCC
- **CATO-TRAIN**: CATO software application on-board the trains
- **(C)DMI**: (CATO) Driver Machine Interface
- **CMP**: CATO optimal Motion Profile. CMP has also been used as name of the optimisation software.
- **CPP**: CATO Power Profile
- **CTP**: CATO Target Point
- **ERTMS/ETCS**: European Railway Traffic Management System
- **MMI**: Man Machine Interface
- **MMP**: Maximum Motion (speed) Profile
- **Net Energy**: Consumed energy at traction minus regenerated energy at braking.
- **SRS**: System Requirement Specification
- **TCC**: Traffic Control Centre

2. BACKGROUND

Train driving by remote control in heavy railways is not new. It has been used specifically to assist the running of heavy freight trains. Normally verbal communication by radio between the dispatcher and the drivers has been used. The main objectives were to improve the traffic flow, but there are also examples where communication between trains and Traffic Control Centres (TCC) is used to handle power loading on electric traction systems.

Today Automatic Train Operation (ATO) is common in metro systems. Driving Assistance Systems (DAS) to achieve optimal driving of trains is another, but relatively new, area of development. In Sweden some promising theoretical studies on optimisation of train driving were carried out in the 1980-ies. However, the results were never implemented in practical operation. At that time there was no possibility for efficient data communication between the TCCs and the trains. At the same time optimisation algorithms and computer hardware were not powerful enough for realistic applications. In recent years, the installation of a GSM-R radio communication in Sweden has brought new interest in this type of systems.

Transrail made a proposal for the CATO project in 1998 and a pre-study was financed by the Swedish National Railway Administration (Banverket). The study [1] identified CATO as an emerging technology, with a good prospect of improvements to the railways. A few similar development activities abroad were identified. Today we can find a number of international development projects in line with CATO. However, most of them are stand-alone on-board Driving Assistance Systems optimising train running when the timetable is fixed. However, at least with regard to Swedish conditions, the most interesting is considered to be a system that communicates with the TCCs. This will bring the possibility to take the daily traffic situation into consideration. This fact, in combination with a mixed traffic situation, make standardisation
important already at an early stage of development.

The main idea of the project has been to build a base for development of a system for more efficient traffic control based on digital radio communication between the trains and the TCCs and using a centralised calculation of how the trains shall be run to achieve as optimal operational conditions as possible. The general idea is to obtain improvements in the railway operation by intelligent use of the time slacks that are built into the timetable and that occur in the daily operation.

Phase 2 of the project focused on the development of a System Requirement Specification (SRS) [2] for the CATO-system. The objective was to define a specification that will make it possible for various suppliers to supply suitable products that will be interoperable.

The objective of phase 3, which was finalised by the turn of last year, has been to further develop the SRS through a prototype system and field tests. The tests were done on the LKAB iron ore transportation system in northern Sweden. Furthermore, the advantages of a CATO system implementation in this traffic system have been studied, since LKAB has expressed their interest for this type of system.

The LKAB railway system is briefly described in Figure 2. Iron pellets are transported from the mines of Kiruna and Malmberget (Gällivare) to the ports of Narvik and Luleå as well as to SSAB steel plant in Luleå. Some products necessary for the production of pellets are transported in the return direction. Otherwise return trains are empty.

LKAB is currently making big investments in the mines as well as in the ports. Together with Banverket big investments are also being done in the railway transport system, the infrastructure and in the rolling stock. The upgrading of the system involves higher axle loads, longer trains and increased train speeds. Improvements of the traffic management system, such as CATO, are on the agenda.

3. THE CATO SYSTEM

The main idea of the CATO system is to make trains run as optimal as possible, considering the daily traffic situation and optimising criteria such as minimum energy consumption. Simplistic, this may be expressed as never to arrive to a red signal but to use available time to run with lowest possible energy consumption. Furthermore, time consuming stops shall be avoided.

Figure 1 gives a brief description of the system. Target points (position, time and speed), which define an optimal traffic situation, are sent to the trains from the TCC. The trains are run to reach the requested target points (CTPs), using the most optimal driving style that fulfils defined optimal conditions, e.g. low energy consumption, minimum utilisation of friction braking and no unnecessary stops. The optimal motion profile (CMP) is presented to the driver in case of manual driving or may be used to run the train in an automatic mode.

Figure 3 describes the basic architecture of the system. The system is divided into two separate units, one located in the Traffic Control Centre (CATO-TCC) and one located in each train (CATO-TRAIN). These units communicate by digital radio communication. The CATO Driver Interface (CDMI) forms a part of the system, but should ideally be integrated with the new European Traffic Management System.
(ERTMS/ETCS). The TCC and train systems exchange information via radio communication (GSM-R, the Global System for Mobile Communications – Railways) and communicate with other systems in the TCC and the train. CATO is meant to act as an optimising traffic management layer on top of these systems and the existing signalling and safety system. It shall have no function as a safety system.

The intention of the SRS is to specify a CATO system, including interfaces with the ERTMS/ETCS and the GSM-R systems, as well as, current practices and standards for train control systems.

The new European Railway Traffic Management System (ERTMS/ETCS) specifies a Driver Machine Interface (DMI) as shown in Figure 4. The DMI defines an ergonomic standard for the interaction between the driver and the system. It is intended to become the main driving advisory panel in the driver’s desk, placed in focus in front of the driver.

At the CATO tests, a DMI according to Figure 5 has been used. Additions to the ERTMS/ETCS DMI have been done primarily in the Planning and Monitoring areas.

Apart from a MANUAL operation mode, as described in Figure 5, the system is also foreseen to be used in an AUTO mode, i.e. that the train follows the CMP automatically. Although, the prime idea is to run the system in a REMOTE mode following orders from the TCC, it shall also be possible to operate in a LOCAL mode where target points are set by the driver.

The CATO-TCC implementation during this phase of the project has been limited to the dispatcher’s setting of CTPs from a graphical time table on a PC. The dispatcher MMI has been based on a software tool previously.

Figure 3: Draft architecture of the CATO-system

Figure 4: Main information areas of the ERTMS/ETCS Driver Machine Interface as specified in the standard CENELEC CLC/TS 50459-2:2005. The Most Restrictive Speed Profile (MRSP) ahead of the train is shown in the Planning Area together with other operational information.

Figure 5: The CATO DMI as used during the field tests. Key information is the CMP speed profile shown in the planning area as well as the current deviations from the CMP shown in the monitoring area of the DMI.
designed by Transrail. This *Trains Traffic Management System* offers functionality for timetable planning and operational traffic management. I may be used for presentation of train positions and the forecasted motion for the trains. The application in this phase of the project has been rather simplistic as shown in Figure 6. Based on the latest position update from the train, the possible Maximum Motion Profile (MMP) can be forecasted and presented to the dispatcher. The dispatcher is then free to set mandatory or restrictive target points (CTP) that the train shall fulfil in the further run.

The purpose of the CMP-calculation is to calculate the optimal driving style for the train to arrive at the target point as ordered from the TCC. The calculation must take various restrictions into consideration, e.g. maximum allowable train speed, power consumption and possible restrictive target points on the way. The optimal driving style shall be based on a cost function, in principle arbitrary. In this project we have used a cost function based on energy for motoring compared to energy for braking, regenerative braking as well as mechanical friction braking.

\[
    \text{Generalized Cost} = E_T - 0.5 \times E_{MB} + 2 \times E_{Mech}, \quad (1)
\]

where

- \( E_T \) = Total consumed energy at traction (at pantograph)
- \( E_{MB} \) = Regenerated energy at braking (at pantograph)
- \( E_{Mech} \) = Energy dissipated in the friction brakes (at rail)

There are various optimisation methods to carry out the CMP calculation, i.e. to calculate the optimal way to drive the train between to points defined by position, time and speed. For a practical implementation it is essential not only that the method solves the actual problem in the best possible way, but also that the problem may be solved in reasonable time and with reasonable computer hardware.

In this project we have implemented a network model with time constraints. The network, see Figure 7, describes various ways to run between two points. Network models normally concern calculation of flows in networks. In this case it is a matter of cost and time to pass the links. One advantage of using the network model is that the position/speed-links can be calculated by the TPC, allowing unrestricted complexity of the models representing the train motion and the cost function. In such model each node represents a position and a speed. A time window may be defined for each node, e.g. to define how the available slack may be distributed or to put possible restrictions on passing times. To solve the problem the resource constrained shortest path algorithm, by Desrosiers, Pelletier and Soumis (see e.g. [3] has been used.

4. THE TRANSRAIL CATO-TRAIN PROTOTYPE

The main modules of the software system are the Train Performance Calculation (TPC) and the calculation of the CATO Motion Profile (CMP). Both these calculators have been developed by Transrail. CMP has been developed as part of the CATO project.

The TPC is based on a modular simulation system (named *Trains*), where some specific modules have been developed in order to handle the specific aspects related to the function and driving of the long and heavy LKAB iron ore trains. The TPC is the core module, calculating all aspects of the motion of the train, including energy consumption depending on train data, the railway line, power supply and driving style.

In the onboard software, the TPC is used to calculate the minimum running time to the target point, and thus the available time slack. It is also used to calculate the motion profile, energy consumption etc of alternative driving styles throughout the CMP calculation.
Substantial effort has been put on the issue of reasonable time to solve the problem as well as to identify the network, taking all possible train operation situations into consideration.

As implemented so far, the problem is solved in three steps. To start with, long sections with more or less constant speed are identified. The principle is to run at slow speed and to avoid short accelerations and retardations. A part of the available slack is spent by a speed reduction on these sections. In the next step, the driving style is adjusted in sections of accelerations and retardations as well as coasting in connection to gradients or retardations. A large number of alternative arcs are calculated and stored in the computer memory. The third step is to combine the best set of arcs that will give the correct arrival time to the target point at the lowest generalized cost.

Figure 8 shows examples of calculated CMP-curves depending on the available slack.

Comparisons of calculated CMP-curves, i.e. optimal speed profiles, with those followed by the drivers show significant differences. Figure 10 shows one example. The diagram shows the speed profile used by the driver and the CMP when using the same running time as used by the driver. The driver has primarily used regenerative braking. This is even more the case of the CMP.

5. RESULTS FROM LABORATORY AND FIELD TESTS

Considerable effort has been given to verify the TPC calculation and the various models for traction, regenerative braking, mechanical braking, efficiency of main circuits, running resistance, the traction/braking control system etc. In specific, the control system must take into consideration a realistic driving style for the operation of the long and heavy trains.

Data logging of a large number of variables from one of the LKAB locomotives has been a very useful tool throughout the project. Figure 9 shows one of the most demanding verification tests of the TPC model. Logged positions of the master- and brake controllers have been used as input to a TPC calculation. In the diagram the calculated speed curve is compared to the logged speed curve.

The accuracy is very good both as regards the speed curve and the traction/braking energies during the run. The accuracy of the energy calculations at pantograph is within 5%. The differences are identified to be mainly due to variation of the aerodynamic resistance, possibly also the curve resistance.
As can be seen, the CMP looks very different from the speed profile used by the driver, i.e. the optimal speed profile is not obvious even if the driver knows the railway line and driving conditions very well. It will, as a matter of fact, vary from one time to another depending on the available running time. Another advantage of following the CMP is that it ensures that the train will arrive at the target just in time.

The next issue concerns the accuracy by which the drivers can follow the CMP as presented on the DMI, in specific the possibility to fulfil the target points. Figure 11 shows an example from the laboratory tests. The arrival time accuracy is within 10 seconds. Net energy consumption is +3%. The field tests show that a skilled driver has minor problem to fulfil a stop target point with a very high accuracy, i.e. within +/-10 seconds and +/- 50 m.

For the LKAB iron ore transport system, the energy saving depending on available running time may be described by the diagrams below (Figure 13-15). The diagrams show the average for the north and south circulations (see Figure 2), taking running in both directions into consideration. The values on individual line sections may deviate quite much from the figures in the diagrams.

6. BENEFITS OF CATO IN THE LKAB IRON ORE TRAFFIC SYSTEM.

6.1. Reduced energy consumption

The energy saving that can be reached depends on a number of factors, e.g. the vertical profile of the line, train weight and available time for the train to run the distance to the target point. Figure 12 illustrates the train run illustrated in Figure 10 and how the net energy may be reduced depending on the running time compared to the MMP, the fastest possible run.
The saving of consumed energy, i.e. considering only the energy drawn from the catenary but excluding regenerated energy, looks slightly different. Figure 15 shows the situation for the North Circulation. Note that for this calculation, the cost function given in (1) is used. A generalized cost function that consider only the consumed energy ($\text{GeneralizedCost} = E_t$) will give different results.

It is estimated that a complete CATO system (Case B of Table 1) should make it possible to reduce the net energy consumption of the LKAB current traffic operation by more than 25%, i.e. somewhat less than the difference between the ideal CMP (column 6) and the recorded net energies in the table (column 3). Case A corresponds roughly to a situation with CATO installed in the trains only, and operating in a local mode.

The situations at stops have been subject to a specific evaluation. This was based on a driver inquiry asking the drivers to report stops as well as reasons for and length of the stops. The answers have, among other things, been used to estimate the time slacks that occur in the operation. The inquiry indicates 6,6 stop situations per 1000 train kms. There are also in average 6,1 arrivals to end stations per 1000 train kms, situations where the trains could possibly be run with a slack in order to optimize the train operation.
The slack is the unnecessary time that a train needs to stand still at a stop if it has run as fast as possible to the stop position, i.e. according to the MMP. In this case the trains have run as normal, which means that they have run in average 5-9% slower than the MMP (cf Table 1). Thus the slack lengths according to Figure 16 are underestimated and should include also the slacks related to the lower average speeds vs. the MMP.

6.2. More efficient train dispatching, Better utilisation of line capacity

The advantages of the CATO system as regards improvements to dispatching and line capacity utilisation have become more and more evident during the project. The benefits are important.

Information on the current status of the trains on a railway line, as provided by the CATO system, brings the possibility to equip the TCCs with software functions that make it possible to foresee the motion of the trains. This makes it possible to introduce manual or automatic methods for an optimised train dispatching. CATO add on the functions of detailed information to the drivers so that dispatching decisions are fulfilled by the trains as optimal as possible, thus reducing and/or solving disturbed traffic situations as efficient as possible.

It is estimated that line capacity may be increased by approximately 10% through the use of CATO. However, the full reasoning behind this value goes beyond this paper. It may roughly be assessed based on a situation as described in Figure 17, which also describes the benefits of CATO traffic control in some more detail.

Stations are located at a distance of approximately 10 kms. Figure 17 shows the total delay of the trains, with and without CATO control, at the station depending on the difference of their arrival times. The minimum delay (520 sec) occurs when train T2 arrives 230 sec after T1. In such case T1 stops at the side track exactly in time for train T2 to pick up a green signal message when reaching the pre-signal balise. CATO will always make it possible to control the difference of arrivals to be approximately 230 sec. However, either T1 or T2 needs to be slowed down, and consume the available slack (see axis “Z” in the diagram), before arriving to the station. Taking the largest delay (at X=0) into consideration, the capacity (pairs of trains per hour) in case of no CATO control may be calculated as 3600/(1440+1050)=1,45. With CATO the capacity is 1,64, i.e. CATO brings a 13% increase of capacity.

CATO control has the further advantage of using any slack, depending on the timing of the trains, to optimise the running in order to minimise the Generalised Cost (1).

6.3. Reduced power consumption

This aspect has not been further elaborated during this project phase. However, the main idea is illustrated in Figure 18.
Power Control needs to be done on a central computer in the TCC. The CATO SRS includes such information in the format of Power Profile (CPP) which is sent from the TCC to the train. The CPP is the maximum supply power (at pantograph) that a train must not exceed at a certain time interval. This power level may even be negative, thus forcing the train to regenerate a certain amount of power to the energy supply system.

6.4. Reduced wear on vehicles (and track)

Current statistics do not make it possible to evaluate the reduction of wear on brakes and wheels that may be achieved by the CATO system. The wear depends on the utilisation of the mechanical brakes, but also of flange wear and various types of wheel damages. However, the calculations show that CATO, already at a small increase of the running time, should make it possible to reduce the mechanical brake energy, compared to a running at shortest possible time, by as much as 40% on the North Circulation (see )and by 80% on the South Circulation.

6.5. Improved working environment for dispatchers and drivers

It has become obvious during the project, that CATO has the potential to improve the working environment of the dispatchers and drivers. They will get a more relaxed working situation since the system will help them to control the motion of the trains and to fulfil the traffic management needs, i.e. for the dispatcher to set target points and for the driver to fulfil target points / train schedules.

6.6. Better utilisation of rolling stock and train staff

A better utilisation of the rolling stock and the train staff is expected to follow as a result of less traffic disturbances and delays as well as the possibility to run at slightly higher average train speeds.

7. CONCLUSIONS

Computer Aided Train Operation (CATO) may today be regarded as a maturing technology. One example is the system developed within the CATO project. It will have an important impact on train operations in the future, not only in isolated but also in mixed traffic systems.

Coming infrastructure investments in a new European signalling system, ERTMS/ETCS, and radio communication, GSM-R, will make the introduction of CATO feasible.

A general introduction of CATO in mixed traffic systems requires a CATO standard, a standard that will support future interoperability of CATO.
systems built by different suppliers. Interfaces to ERTMS/ETCS and to TCC systems need to be defined urgently.

Various implementations of CATO systems will most likely be done in the next decade.

8. REFERENCES


