PERTURBED TIMETABLE STRUCTURES ANALYSIS AND RAILWAY CIRCULATION QUALITY: A TEST CASE.

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Abstract:

The first part of this study aims to compare two different kinds of railway timetable quality approaches: the one referred to timetable structures and stability, and the other one which concerns the customers' point of view, linked with Level Of Services approach. These aspects have been first studied and then put together in an extended approach of perturbed conditions on railway networks, by means of intensive microsimulation of the system and practical indices of timetables behaviour.
Two different kinds of timetables have been considered, with different symmetry and periodicity characteristics, calculated both on a theoretical and on a real network as a test case. For each structure, it has been possible to compare perturbed timetables indices as compactness, quality (as the system capacity ability to absorb delays) and heterogeneity, with a typical LOS approach defined by on-time performance to a scheduled timetable.
Results allow to define some connections between timetables design behaviour and its changes with increasing perturbations; moreover some characteristics as such as heterogeneity seems to influence less than other indices the evolution of LOS grades in real and theoretical timetables. At this step of the research it is possible to define a design LOS grade, and to calculate how a timetable should be planned in order to guarantee it; moreover it is also possible to define the maximum level of perturbation compatible with the starting LOS grade.

1. Introduction.

The railway circulation and the sequence of trains on railway lines are regulated by severe rules as such as signal security systems, safety distance block and timetables.
Timetable structures and the above rules are some of the aspects that influence capacity and regularity of the railway network. Regularity is of course linked with service customers' satisfaction so that both uncertainly travel times and variability of trains' passage times at the stations may be used as measures of the quality grade of the service. Moreover timetables could not be respected in the event of failures or delays and, at the same time, the timetable in itself could generate delays, because of bad planning or in case of critical ones that present instability without external causes.
The necessity of representing the real circulation quality through simple indicators derives from the requirement to use the common language of Level Of Service, like in the case of other transport services. These indicators should consider both aspects of regularity (as such as timetable structure), and on-time performance to scheduled timetables.
In this paper, after a briefly review of existing literature about main important railway research projects tied up with this study, the attention will be focused on the relationship between indices that represent the behaviour of timetables structures, the perturbed conditions and Level Of Service; after defining the used indicators, both a theoretical case of study and the simulation tool adopted to

calculate the effects on indices of several timetables structures and their relationship with quality, will be presented. General conclusion on a real test case on a network will finally complete this part of the study.

2. Literature Review.

Literature for capacity and regularity in railway networks under perturbed conditions is very large in number and its deep analysis goes beyond the purpose of this paper; however some studies have been developed in order to define the level of railway circulation quality: Malavasi, Marini and Petrilli (1992) [19], by means of simulated models, defined various kind of delays, and stated that, considering a mean value of statistical failures, there are no considerable differences between a scheduled timetable, and a delayed one. Di Marco, Malavasi and Ricci (2000) [8] defined some delay causes, by means of statistical data of system failures and MTBF (Mean Time Between Failures) and MTTR (Mean Time To Repair). This model has been applied at various kind of rail circulation, in order to forecast the behaviour of the system under different failures in the network, such as short term or long term operations.

Regularity and capacity depend also on how a timetable has been built: railway timetables have different characteristics and structures, they come from various requirements, as such as infrastructure constraints, heterogeneous services, and different kind of ways to meet passengers' demand or to adapt the service at the request of users [4],[5].

Another main aspects of a railway quality investigation refer to timetable stability using simulation tools: the most recent timetable stability analysis has been developed by Delft University of Technology (Goverde, 2005) [11],[12] applied to periodic timetables of Dutch railway network. Analysis concerns delay sensibility and stability of periodic railway timetables, by means of a double approach: the first one based on Petri Nets, and the other one based on Max – Plus Algebra. Moreover the software PETER [13] developed by TU in Delft allows an accurate analysis on remaining capacity of timetables, of their stability and on "bottleneck" location in the network.

The simulation and the analysis of timetables behaviour has been accurately described in Luethi, Huerlimann and Nash [18] in a process to optimize timetables in Zurich and in the Swiss railway network using *Opentrack* [15] and *Opentimetable* [20]. L'Ecole Polytechnique Fédérale de Lausanne developed a software called CAPRES (CAPacité des RESéaux ferroviaires) [17],[6], which has been applied in several countries to determine capacity of networks and to compare different kinds of timetables, finding which of these are compatible with various kind of constraints. But the estimation of quality aspects of different kinds of timetable seems missing.

The final aspect to be reviewed concerns of existing timetable practical indices that try to describe a particular status of a timetable in a fixed section and in a fixed time. During the last years, the scientific literature proposed some quality circulation indices (Galatola, 2004) [9] based on train distance time mean square error and to practical capacity, referred to scheduled timetables. This is due to the difficulty to represent analytically the real timetable in all of its component, and especially in case of trains delays. Vromans (2005) [22], in a study about reliability of railway systems, introduces more quality and reliability indicators; the objective of his work was to develop rules and instructions for supporting the generation of more reliable timetables, by means of simulation and indices as SSHR and SAHR (these aspects will be review later in the paper), to evaluate the heterogeneity of the timetable, according to heterogeneous train traffic [16] developed by Huisman and Boucherie (1999). Railway circulation quality and timetable stability studies appears on Demitz, Hübschen and Albrecht (2004) [7] about the optimization of regular interval timetables by means of simulation.

The first studies in which appear some quality approach could be find in Weits (2000), who introduces a so called "*Timetable Complexity Index*" [23] that provide a measure to judge to which extent a timetable is complex, that may be balanced against other measure, as such as the attractiveness of the timetable to passengers. Atkins, Henderson and Kwong [1] offered a study about regularity indices and passenger waiting time by means of simulation and real data from bus schedules while Zhao, Wang, Lee and Shen developed a model of level of service indices applied on rail rapid transit [24].

3. Purpose of the Study.

In literature several approaches exist to define two main aspects on quality: the one referred to the stability of timetables and with regularity of circulation in perturbed conditions, by means of simulation and practical indices; the other one that tries to define quality under customers' point of view, introducing a so called Level Of Service approach. In the remainder part of the paper a new approach will be presented, which tries to keep together these two quality aspects into one LOS measure, and the effect of perturbations on it.
This study aims to analyze the railway service quality referred to a scheduled timetable and to a perturbed one affected by the same kind of failures, by means of intensive synchronous microsimulation model of the network. Moreover it will be investigate the behaviour of timetable structures under planned and perturbed conditions, and how they could be related with the practical indices, which it has referred above.
Different timetable structures (as well as only passenger and both passenger and freight trains) will be compared to extract quantitative measures on how heterogeneity and stability could be related with quality. Quality of service will be measured by means of a LOS approach defining the changes of the timetable in different conditions and delay scenarios. It will also be able to lead a LOS design analysis, and differences in structures and quality might be used to evaluate the design delay conditions.
In the following paragraphs there will be presented three kinds of indices, that have been used in the present study.

4. Timetable compact indices.

Compactness of a railway timetable is represented through the time headways between departure or arrive services in a station or in a general section on the line. "C" (Compactness index) has been introduced in [9] as a measure of train distribution within a fixed time interval. C has been defined as:

[a]. $$C = \frac{\sqrt{(a_1 - M_a)^2 + ... + (a_n - M_a)^2 / n}}{M_a \sqrt{n-1}} = \frac{\sigma}{\sigma_{\max}}$$

where n is the number of trains, a_i are differences in time intervals in departure or arrive at one point and M_a is the mean value of them. C range goes between 0 (minimal timetable compactness, and equal distribution of trains) and 1 (maximum timetable compactness). This index has been developed and used only on scheduled timetables, which are not the real cases.
Timetable compactness indice could also be referred to quality, defined as the ability of the system to absorb various kind of delays; this measure is called "Q" and defined as follows:

[b]. $$Q = 1 - \frac{\left(\frac{n}{P} + \frac{\sigma}{\sigma_{\max}} \right)}{2}$$

where n is the number of trains and P is the practical capacity of the line. Q range goes 0 (when both conditions are true: $n = P$ and $\sigma = \sigma_{max}$ (maximum variability of train distribution); goes 0.5 in saturation conditions ($n = P$ and $\sigma = 0$); goes 1 when the course of n and σ goes towards $n = 0$ and $\sigma = 0$ (equal distribution of trains) respectively.

5. Timetable heterogeneity measures.

According to [22], timetable heterogeneity measures could also give some piece of information about timetable structures and their behaviour in various scenarios. To consider how trains are spread over the cycle time, the sum of the reciprocals of the headways has been used to evaluate the heterogeneity of timetables and for the prediction of their quality (LOS). SSHR (Sum of the Shortest Headway Reciprocals) and SAHR (Sum of Arrival Headway Reciprocals) are defined as follows:

[c]. $SSHR = \sum_{i=1}^{n} \frac{1}{\bar{h}_i}$; $\bar{h}_i$ is the smallest scheduled headway between trains i and i +1;

[d]. $SAHR = \sum_{i=1}^{n} \frac{1}{h_i^A}$; h_i^A is the scheduled headway at arrival between trains i and i +1;

where n is the number of trains on the track section. The lower value they have, the more homogeneous the timetable it is.

6. Timetable quality measures.

After defining some circulation indices based on timetable structures and behaviour in different cases (heterogeneous circulation, delays, headways etc.), now attention will be focused on railway circulation quality.

There are two different types of quality: the one referred to the system capacity of absorbing delays (Q) and the one referred to the customers' point of view. In [21] some measures of quality in a transport system are defined; three main factors contribute to reflect the users' point of view (LOS): availability of the service, comfort and convenience.

In the following of the paper the on-time performance will be considered as the measure of the service quality. A service it'll be considered "on time" as being 0 to 5 minutes late; at this step of the study it has been calculated arrival time performance, because this measure tend to be more important to passengers.

7. Theoretical case.

The following analysis has been supported by a microsimulation software [14],[15] which simulated the run of trains on the modelled network, their conflicts, various kinds of block systems and all the remaining railway circulation characteristics. Microsimulation approaches are today a standard tool for analysis and forecasting and, as reported by Axhausen and Pendyala (1997) [2], these kind of models should be applied for description of system evolution over time, or for modelling of interactions in time and space and non-equilibrium situations. These topics are relevant with this study.

These tools exploits an intuitive graphic interface to let the user built the network by means of vertexes and edges. Every edge is described by length and gradient characteristics and speed limitations. All the block sections on the network have been defined, and the railway stock has been implemented in terms of engines (by means of the tractive effort / speed diagram), and trailers; every service is assigned to a single train, which runs the network according to a scheduled timetable.
Output data such as scheduled timetable, actual timetable (simulated) and difference between them have been easily exported to an external application and then used to calculate the indices.
The first case that has been analyzed is a theoretical case: an artificial timetable has been built on a simple network to provide a model and output data to calculate the parameters of circulation and to compare them to circulation quality. The modelled network consists of four double-track lines of about 30 kilometres each converging on a single double-track line with the same length (Figure 1); services are alternate between intercity and regional trains from all terminal stations. Both category of trains stops at Stations E and F, while regional trains stops at all stations.

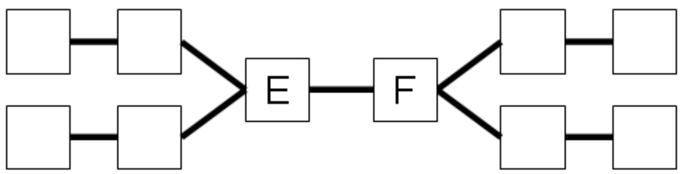

Figure 1: Theoretical network model.

In the case called Scenario SC02, the timetable presents a symmetrical periodic passenger timetable with four trains/hour in both directions between E and F stations; meanwhile other branches of the network are covered by two trains/hour, in both directions. In the second case (SC01) the original timetable had been mixed by another symmetric timetable in the scheduled model, which increased the number of trains from four to six trains/hour between the common branch, and from two to three in the others, in both directions.
In the first analysis, perturbed conditions on the network have been defined in term of "mean departure delays" for services, which have not changes in scheduled timetable. Mean delays are been defined from 0 seconds (scheduled timetable simulation) to 1800 seconds, by steps of 60 seconds. This method has been used in order to compare runs of different timetables on the same network with the same perturbed conditions.
After simulating all delay scenarios, timetable data have been exported in an external application in order to calculate indices referred to these two scenarios, and to evaluate the behaviour of these with increasing delays. Measures have been calculated on one section of the network, between E and F stations and in one direction (F-E).

7.1. C and Q.

The first indices to be compared with quality are C and Q. Considering a given timetable, it is possible to determine C and Q values at esch step of delay simulation. In the following Figure 2 and Figure 3 C and Q have been diagrammed in function of the delay scenario, from 0 seconds to half an hour of mean departure delays.
The red line represents the Scenario 02, with only passenger symmetrical and periodical services; according to predictions, in this case the initial value of C (par. 4) is low and Q values are high because of the limited number of trains; it means that the system has a good capacity of absorbing perturbations in the first phase, but from almost 1560 seconds of mean delay and over this step, quality remains constant with increasing delays.

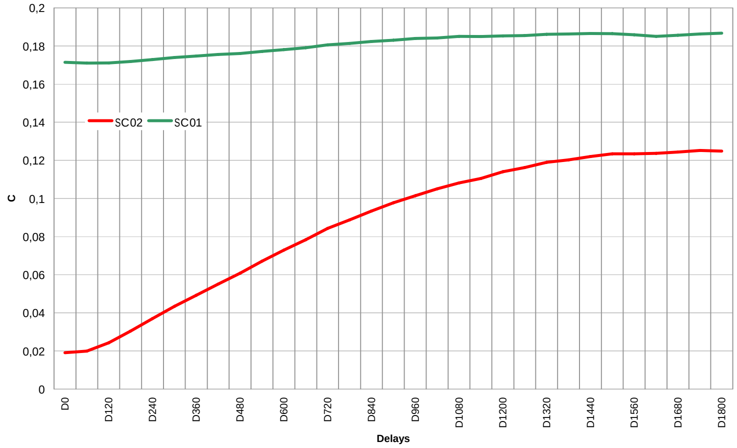

Figure 2: C-Delay diagram (theoretical case).

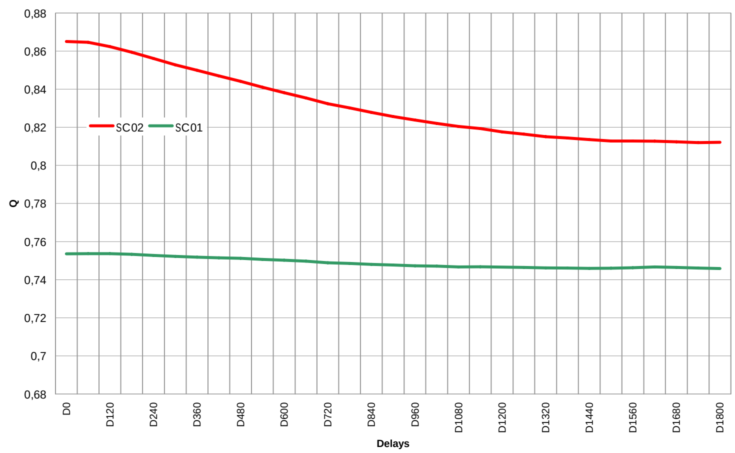

Figure 3: Q-Delay diagram (theoretical case)

The green line referrers to Scenario 01, in which the higher number of circulating trains is due to the insertion, in the original timetable, of another symmetrical and periodical one. The compactness of the resulting timetable is so higher than the previous case, the capacity of the system to absorbing delays decreases with increasing delays and with increasing compactness, but its course remains almost constant on all delay scenarios, because of the more complex structure of the timetable and services restrictions.

7.2. Q, SAHR and On-Time Performance.

After defining the connections between a structural index of a given timetable (C) and its capacity to absorb perturbations (Q), now the relations between this last topic, heterogeneity and a measure of Level Of Service as On-Time Performance will be investigated.
This measure is linked with LOS grades provided by [21], and the Figure 4 shows that, as it should have been, decreasing quality attend upon lower values of OTF (On-Time Performance) together with higher values of mean delays, and consequently lower LOS grades.

As the previous diagram, the red line represents the course of only passenger Scenario 02, while the green one the more complex timetable of Scenario 01.

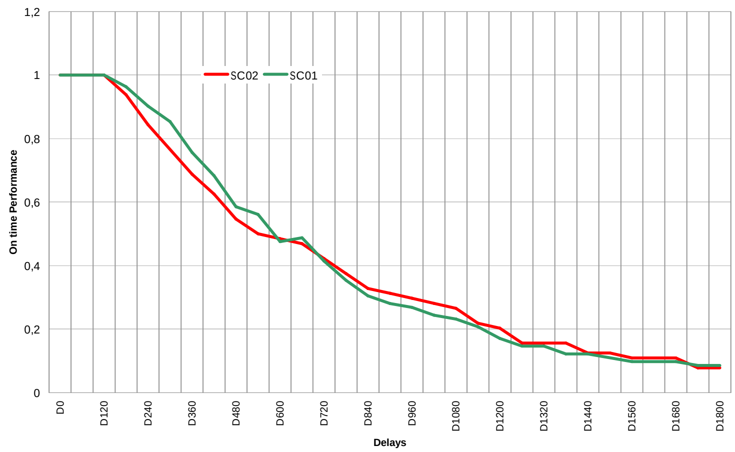

Figure 4: On-time Performance diagram (theoretical case).

It is interesting to note that, despite the first Scenario is more complex than the other and less able to absorbing delays, its particularly structure allows the system to have a better LOS grades than a simple one in the first delay phase, until almost 600 seconds of mean delay.

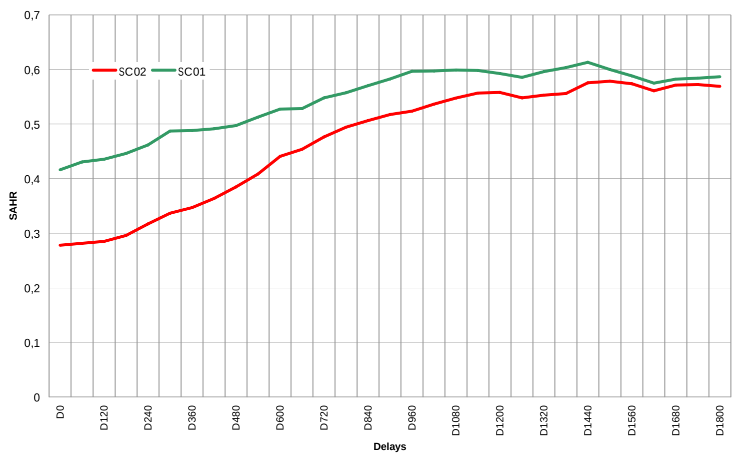

Figure 5: SAHR diagram (theoretical case).

One last aspect to be investigated concerns the possible connection between timetable capacity of absorbing delays, maximum guaranteed Level Of Service and timetable heterogeneity measures; in Figure 5 the plotting of SAHR with increasing mean delays is shown.

It could be noticed that the grade of heterogeneity at the final step of mean delay is almost the same between the two studied different timetables. This means that heterogeneity of a timetable, both in planned and perturbed conditions, is not hardly linked with quality of service, intended as LOS grade; it seems that despite a more heterogeneous timetable is less stable that an homogeneous one, it is less able to guarantee a fixed design LOS.

8. Test case.

The test case is a part of the Friuli – Venezia Giulia network, in the north east of Italy. In particular it is limited to the stations of Trieste, Monfalcone and Villa Opicina. In order to simulate the circulation in the knot more reliable, also nearest branches until stations of Cervignano, Gorizia and Trieste Campo Marzio have been considered (Figure 6).

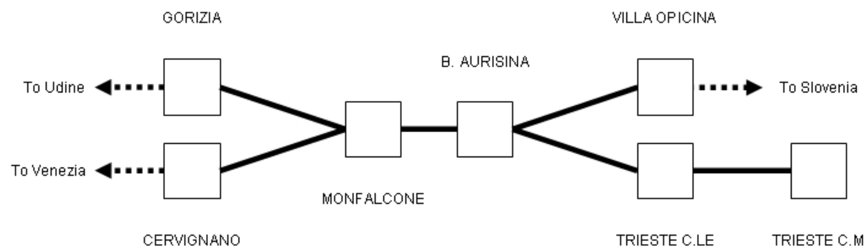

Figure 6: Trieste's test case network.

The 2004 timetable has been implemented; the network has been simulated in two different hypothesis: in the first one only the circulation of passenger trains on a working day for 24 hours has been considered in the simulation while in the second one for the same period of time two kinds of services have been considered (for example passenger and another stock of trains that might be freight train or other passenger services). Analysis have been performed on one section of the network, between B. Aurisina and Monfalcone stations, in one direction.

8.1. C and Q.

Analyses concerning the real test case are reported below: Figure 7 and Figure 8 show the course of C and Q indices for different delay scenarios.

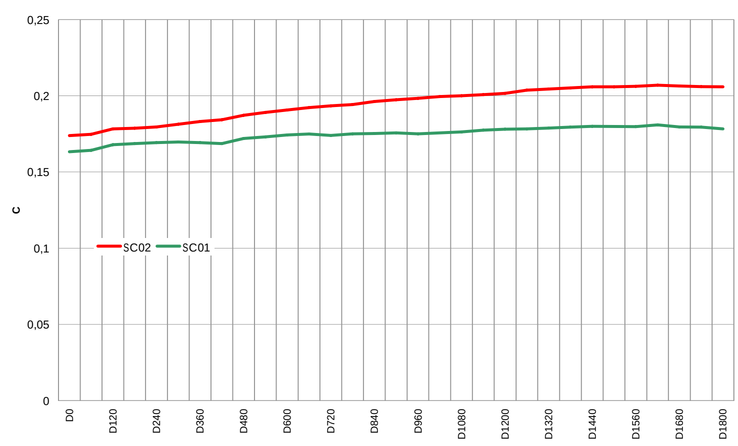

Figure 7: C-Delay diagram (real case).

As in the previous theoretical case, compactness of Scenario 02 is lower than the other one, and corresponds to an higher ability of absorbing delays than Scenario 01.

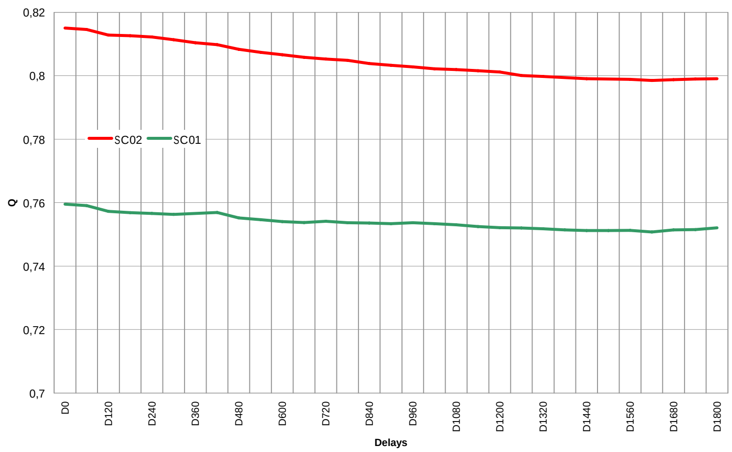

Figure 8: Q-Delay diagram (real case)

So this real only passenger timetable, that hasn't got symmetry, periodicity and other previous characteristics of homogeneity, is liable to variations of delays almost as equal than another one, that mixed both passenger and freight trains.

8.2. Q, SAHR and On-Time Performance.

Figure 9 shows the course of OTF with increasing delays, in two different scenarios, defined as in the previous case.

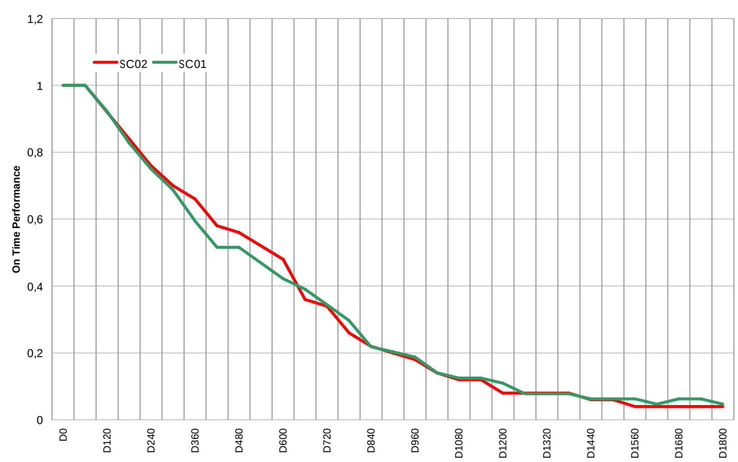

Figure 9: On-time performance diagram (real case).

In the real case, the performance of both mixed train Scenario 01 and Scenario 02 is almost the same all along the delay course.

Heterogeneity measures, provided by Figure 10, shows that a real timetable with increasing headway adherence with delays takes mainly constant course of SAHR; fluctuations are due to the particular structure of the original timetable, that mixed both no-symmetrical passenger services with another typical freight structure.

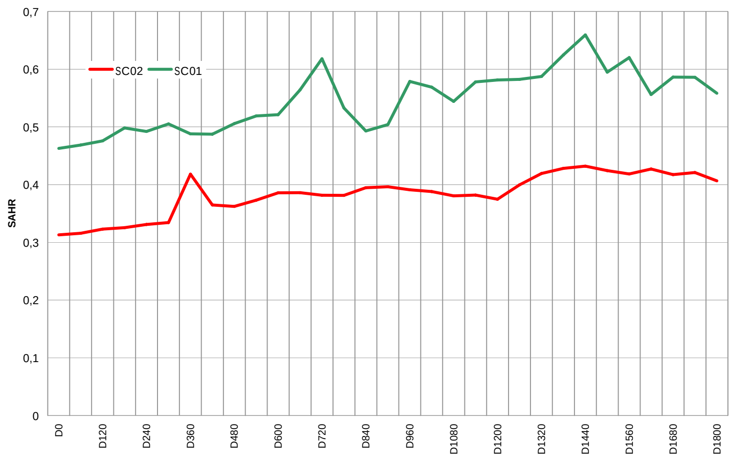

Figure 10: SAHR diagram (real case).

So even in a real case, with no-symmetrical and no-periodical timetables, heterogeneity measures are not a good index to measure the LOS grade reliability and its course in case of no-scheduled planned timetables.

9. Conclusions and further research.

In this part of the study two different approaches on railway circulation quality have been mixed together: the one linked with aspects as such as typology of timetables, their structures and grade of heterogeneity of trains that would be circulating; the second connected with design frequency of services, hours of services and in general on aspects linked with customers' point of view.
Given two different timetables, different in complexity and structures, it has been possible to define a relationship between a structural index (Q) and a LOS index (OTF); for every timetable, choosing a desired design LOS, particular timetables structures and statistical data of failures, it is possible to evaluate the maximum grade of compactness of each timetable (function of delays), its quality (in function of compactness and delays), its measure of heterogeneity (in function of compactness, quality and delays) and the maximum value of perturbation in order to guarantee it. It seems that heterogeneity measures are not the best to evaluate a prediction of a LOS grade desirable timetable.
Actually this research is now directed to evaluate the behaviour of quality of timetables under real perturbed conditions; it will be investigate how differences in structure and quality of several timetables could be compared with initial design delays, to the aim of calculate quality indices on more reliable hypothesis of system failures. Moreover it will be evaluate how a single train delay could influence others in the timetable, and in LOS grades.

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