

An aggregate model for the evaluation of railroad passing constructions

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AN AGGREGATE MODEL FOR THE EVALUATION OF RAILROAD PASSING CONSTRUCTIONS

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Abstract - At Netherlands Railways, the evaluation of infrastructure expansions was traditionally done by establishing a set of detailed time tables that serve the forecasted transportation demand and that can be executed with the proposed infrastructural investment. However, the development of a detailed time table is a very time consuming process, and therefore leaves little opportunity for comparing many alternatives. In this paper, we present an aggregate model to compare alternatives for investments in the railroad infrastructure, specifically passing constructions. The model provides the user with insight into the ranking of the various alternatives and additionally gives a relative insight into the theoretical capacity and flexibility of the proposed infrastructural change. In a test, the model proved to be sufficiently reliable to be used as a support tool for aggregate decision making.

BACKGROUND

N.V. Nederlandse Spoorwegen (NS) is the national railroad company of the Netherlands. Traditionally, NS has been a government owned and operated business. Recently, the company has been privatized and organizational changes have been introduced. The most apparent change in the organizational structure was the creation of three independent divisions, namely NS passenger transport, NS Cargo and Railned. Railned is responsible for the management of the infrastructure. Since NS is planning to double its traffic volume by the year 2010,

Railned needs to determine how the required capacity expansions can be realized by investing as well as possible in the infrastructure. The infrastructure consists of the railway stations and the track network. In this study we will focus on the track network. In order to realize the required expansion of capacity and additionally improve the operations itself, a large number of capacity bottlenecks in the present infrastructure need to be resolved. The available budget is however limited and should be allocated such that (a) maximal expansion of capacity is achieved and (b) maximal flexibility is achieved such that adequate reactions to changes in transportation demand are possible. Capacity and flexibility are related to the number and mix of trains that can be transported between two nodes in the network. The concepts of capacity and flexibility will be discussed in more detail later on.

Decisions regarding infrastructure adaptations need to be taken long in advance (10 to 15 years), since infrastructural projects generally have a long lead time. Traditionally, the evaluation of projects was done by establishing a set of detailed time tables that serve the forecasted transportation demand and that can be executed with the proposed infrastructural investment. However, the development of a detailed time table is a very time consuming process, and therefore leaves little opportunity for comparing many alternative infrastructural design proposals. In this paper, we present a model which evaluates a specific type of infrastructure extensions, namely railroad passing constructions. The model evaluates a passing construction based on the aggregate demand forecast, without developing a detailed time table. The model provides relative measures for the expected capacity and flexibility of the proposed infrastructural change*.

Detailed models of railways networks have been used in many circumstances. An exhaustive overview is given by Assad (1980). In order to enhance modelling capabilities, recently more attention has been given to supporting the modelling process rather than the solution of the problem (e.g., Tsiflakos and Owen, 1993,

* The development of the model has been documented in the unpublished post-graduate design work of Huiskamp (1994).

and Lidén, 1993). This paper will however address the issue whether it is possible to use less detailed models for some specific managerial questions.

In the next section we will present some definitions and describe the railroad passing constructions which are considered in this model. Specific attention will be given to the special characteristics of the concepts of capacity and flexibility in aggregate railroad planning problems. After describing the aggregate model, results of a simulation study are given, which have been used to test the validity of the aggregate model. The paper is concluded by a discussion of the model and its applicability.

DEFINITIONS

The railroad network basically consists of three kinds of entities: nodes, junctions and sections. A *node* is a station where trains can stop and change sequence. Consequently, in a node two trains X and Y can enter in sequence X-Y and leave either in sequence X-Y or in

sequence Y-X. A station where trains cannot change sequence, will not be considered a node, but part of a section. A *junction* is a point in the network where flows of trains join and split, without sequence changes. A *section* is the railroad connection

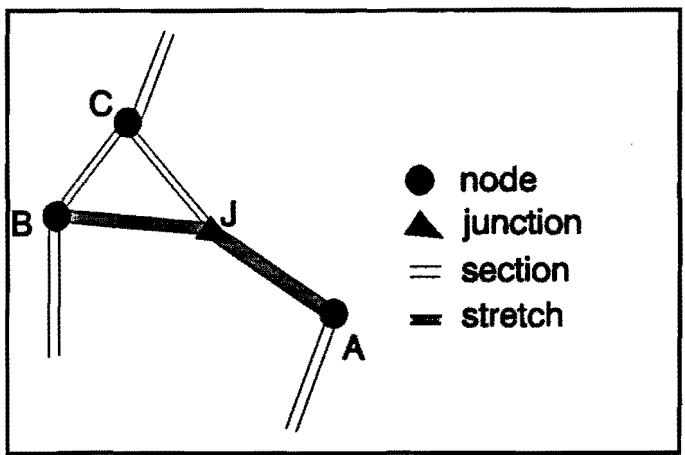


Figure 1. Part of a railroad network.

between two nodes, two junctions or a node and a junction. Figure 1 illustrates these three kinds of entities and the stretch. A *stretch* is defined as a set of sections that connect two nodes. The sections being part of a stretch connect either a node with a junction or two junctions.

Let us consider a section between two nodes B and C. This section consists of two tracks, one of which is used for trains going from B to C, the other one for trains going from C to B. Since both tracks are physically separated, trains going in opposite directions will not interfere. Consequently, it is sufficient to consider only one track from B to C. Suppose all trains ride exactly the same speed. In this case, the only restriction which limits the number of trains within a specific time period is the minimal sequence time. The *minimal sequence time* (t_{seq}) is a safety time between two consecutive trains. Additionally, it may be useful, though not necessary, to introduce some *buffer time* between consecutive trains to absorb disturbances that may occur in the execution of the timetable.

This situation is represented in Figure 2a. This graph is a so-called distance-time graph. The horizontal axis shows the distance from node B, the vertical axis the time it takes to reach this distance. At any given distance, the time difference between two consecutive trains equals the

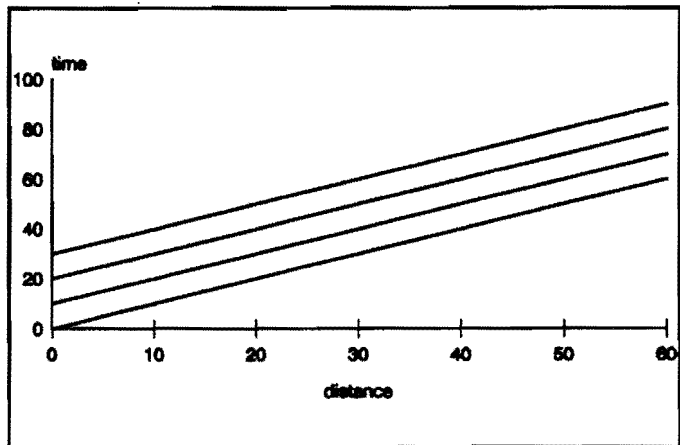


Figure 2a. *Distance-time graph without speed differences.*

minimal sequence time (plus some buffer time, if required). Obviously, the graphs are approximate graphs, because the speeding up and slowing down of the trains are not represented in the shape of the curve.

In many cases, however, not all trains have the same speed. Notably the difference between express trains and local trains leads to a more complex situation. If an express train leaves B shortly after the departure of a local train, the express train will soon catch up the local train and be forced to decrease its speed. Obviously, it is required that the express train rides the full distance from B to C in express speed. In this case, the difference between the departure times of the local train and the express train should be at least the minimal sequence time, augmented by

the difference in riding time from B to C. This situation is represented in the distance-time graph of Figure 2b.

We define the *capacity* of a section as the maximal number of trains that can depart from a node in a given time period. We should note that the utilization and the capacity of a section is not only limited by the number of tracks and the speed of the trains, but also by the difference in train speeds.

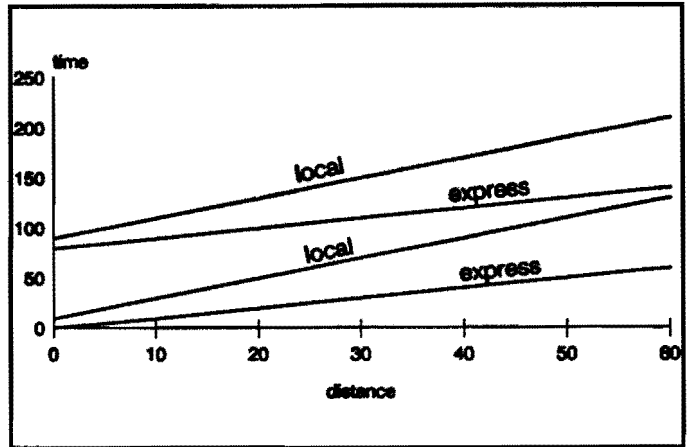


Figure 2b. Distance-time graph with speed differences.

In this paper, the *utilization* of a section is defined as the ratio between the minimal time that is required to ride a set of trains on the track and the available time to do this. This ratio is expressed in equation (1):

$$\rho = t_{req} / T \quad (1)$$

where ρ = utilization of the section
 t_{req} = minimal required time to ride a set of trains
 T = available time

Usually this ratio is expressed on an hourly basis ($T=60$ minutes).

As has been stated above, the riding time difference is one of the most important parameters for t_{req} . The riding time difference between an express train and a local train is given in equation (2).

$$\Delta t = L (1 / v_e - 1 / v_x) + t_{s,e} - t_{s,x} \quad (2)$$

where Δt = riding time difference between an express and a local train on

		a section
L	=	length of a section
v_e	=	(average) speed of the local train on the section (not including the stopping time)
v_x	=	(average) speed of the express train on the section (not including the stopping time)
$t_{s,e}$	=	total stopping time of the local train on the section
$t_{s,x}$	=	total stopping time of the express train on the section

Stopping time is usually caused by a train stopping at a station within the section. It should be noted that the sequence in which the trains are operated considerably influences the utilization of the section. If three express trains and three local trains need to be scheduled in one hour, t_{req} is much lower if the express trains are scheduled consecutively than if they are scheduled alternating with local trains. In the latter case, between each couple of an express train and a local train, Δt must be added. Of course, customer service requires similar trains to be spread over T as much as possible, resulting in an alternating sequence of express and local trains.

RAILROAD PASSING CONSTRUCTIONS

The brief analysis of the various concepts introduced in the previous section has made clear that the utilization and the capacity of a section are mainly a consequence of the speed differences between the trains in a section. It is clear that these consequences can be eliminated by creating separate tracks for local and express trains. Double tracks like this can be found in short sections in urban areas of the infrastructural track network and are well known in the New York subway. However, in the majority of the sections, complete double tracks are impossible because of financial (budget) and geographical (lack of space) reasons. If complete double tracks are impossible on long sections, the problem may be partially solved by having trains pass each other at some point in the section. At this specific point, double tracks have to be constructed for a limited length. Such a partial double

track will be referred to as a *passing construction*. A passing construction can be located (i) at a station within the section, such that the local train stops at the station and the express train rides on, or (ii) not at a station, such that the local train (possibly reducing speed) rides on at one of the tracks and the express train passes the local train on the other track. Scheduling trains at a passing construction has been

addressed by Cai and Goh (1994). The consequences of a passing construction are illustrated in the distance-time graph of Figure 3. Note that both at the beginning and at the end of the passing construction the minimal sequence time should be respected. If the temporary decrease in speed of the local

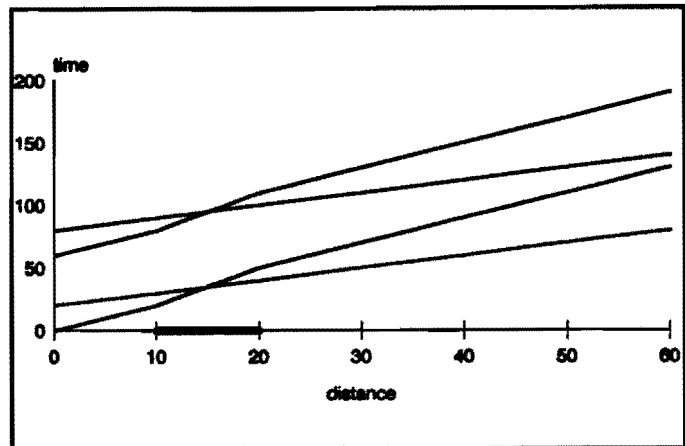


Figure 3. Distance-time graph with passing construction between km 10 and 20.

train is less, the passing construction should be longer. The length of the passing construction is minimal, if a local train stops and waits for the express train to pass. If the section is long, it may be worthwhile to create more than one passing construction. More than one passing construction does not only increase capacity and decrease utilization, but also creates extra flexibility in the execution of the timetable, should unexpected disturbances occur. Furthermore, this flexibility can be used when making the detailed timetable. A high level of flexibility allows for scheduling arrivals and departures at stations such that good connections between various trains are generated.

Passing constructions are expensive and should therefore be allocated such that (a) maximal expansion of capacity is achieved and (b) maximal flexibility is achieved such that adequate reactions to changes in transportation demand are possible. Given a limited budget, a decision supportive tool is required which ranks the given alternatives for passing constructions. Theoretically, it is possible to compare

various alternatives in detail by computation of the set of possible timetables for each alternative and comparing them in terms of capacity and flexibility. This is however a very costly and time-consuming procedure. Therefore, a model based on aggregate data has been developed.

MODEL

The performance measure that is used to rank the various alternatives is the *theoretical capacity*. The theoretical capacity of a section is the maximal number of trains per hour that can pass the section in one direction. The theoretical capacity can be determined under the following conditions:

- (i) there are maximum two kinds of trains on the section: express trains and local trains.
- (ii) the trains are scheduled as alternating as possible
- (iii) every passing construction on the section is used for passing
- (iv) there are no individual timing constraint on any of the trains
- (v) the following data are known:
 - (a) the relative frequency of the kinds of trains (e.g., one local train for every two express trains)
 - (b) the stopping times on the section for each kind of train
 - (c) the minimal sequence time
 - (d) the average speed of each kind of train
 - (e) the length of the section
 - (f) the length and position of the passing constructions

We do not require the theoretical capacity to be an absolute performance measure. Given a theoretical capacity of x trains, it is uncertain whether, in a situation with specific connection timing requirements at the nodes and possible other transport requirements, always a detailed timetable can be computed. The probability that a timetable can be found in this situation is however higher than in the situation with a lower theoretical capacity y ($y < x$). The theoretical capacity therefore is an

ordinal measure of performance.

It can be observed from Figure 3, that a passing construction may lead to an increase in riding time of the local train on the section. Given a passing construction alternative, the riding time increase may be unacceptably high. Therefore, the riding time increase will be used as an additional performance measure of the evaluation of a certain passing construction.

For the development of the model, let us first consider a section between two nodes, without any passing constructions. Since the express train speed should not be limited by a local train, the express train should depart at least $t_{seq} + \Delta t$ later than the local train. The frequency ratio $f_x:f_\ell$ of express and local trains determines the number of times that an express train follows a local train. This number equals the minimum of f_x and f_ℓ . Consequently, t_{req} can be determined as follows:

$$t_{req} = (f_x + f_\ell) t_{seq} + \Delta t \cdot \min\{f_x, f_\ell\} \quad (3)$$

where f_x = frequency of express trains
 f_ℓ = frequency of local trains

Consequently, the theoretical capacity C can be defined as:

$$C = T(f_x + f_\ell) / t_{req} \quad (4)$$

Now, let us consider a section with one or more passing constructions. The presence of a passing construction influences t_{req} , since t_{req} is determined by the maximum of the minimal required times on regular track section parts (i.e., a section part between two passing constructions or between the beginning or end of a section and a passing construction). Note that a local train should arrive at the passing construction at least t_{seq} before the express train and should leave the passing construction at least t_{seq} after the express train. Consequently, the revised equation for t_{req} is:

$$t'_{req} = (f_x + f_\ell) t_{seq} + \Delta t_{max} \min \{ f_x, f_\ell \} \quad (3')$$

where

$$\Delta t_{max} = \max_j \left\{ L_j \left(\frac{1}{v_\ell} - \frac{1}{v_x} \right) + t_{s,\ell,j} - t_{s,x,j} \right\} \quad (2')$$

where L_j = length of regular track section part j
 $t_{s,\ell,j}$ = total stopping time of a local train on regular track section part j
 $t_{s,x,j}$ = total stopping time of an express train on regular track section part j

Using equation 4, and substituting t'_{req} for t_{req} , the theoretical capacity of a section with one or more passing constructions can be determined.

In the previous section, we briefly addressed the issue that the use of passing constructions may lead to an increase in the riding time of the local trains. This riding time increase may occur in two different instances. First, between consecutive passing constructions, local trains may be forced to reduce speed to arrive at the beginning of the passing construction only just before the express train. This generally occurs if the length of the passing construction is too short to allow the express train to pass the local train, if the local train does slow down. Second, on a passing construction, if the riding time difference between the two trains is smaller than twice the minimal sequence time, the local train will have to reduce speed. By reducing speed, the local train will allow the express train to pass such that the minimal sequence time at the end of the passing construction can be respected.

Note that a riding time increase occurs only for local trains, since they need to adapt their speed such that the express trains can pass. The total riding time increase consists of the sum of the riding time increase between passing constructions and the riding time increase on passing constructions. The riding time

increase *between* passing constructions is determined by the riding time difference on a regular track section part and the maximum riding time difference on all regular track section parts. The maximum riding time difference is required on all regular track section parts to enable an express train to pass a local train on every passing construction. If the riding time difference on a given regular track section part is less than the maximum riding time difference, the local train will have to slow down such that the riding time difference equals the maximum riding time difference on all regular track section parts. The riding time increase *on* passing constructions only occurs if the riding time difference is less than $2t_{seq}$. If this is the case, the local train will have to slow down such that the riding time difference equals $2t_{seq}$. Taking the two causes for riding time increase into account, the total riding time increase can be modeled as follows:

$$\delta t = \sum_{j=1}^m \{ \Delta t_{\max} - \Delta t_j \} + \sum_{i=1}^n \max \left\{ 0, 2t_{seq} - \left(L_i \left(1/v_x - 1/v_d \right) + t_{s,e,i} - t_{s,x,i} \right) \right\} \quad (5)$$

where m = total number of regular track section parts
 n = total number of passing constructions
 Δt_j = riding time difference between an express train and a local train on regular track section part j
 L_i = length of passing construction i
 $t_{s,e,i}$ = total stopping time of a local train on passing construction i
 $t_{s,x,i}$ = total stopping time of an express train on passing construction i

Up to now we have developed the performance measures for a section. To conclude the model development, we now consider the theoretical capacity C of a stretch A-B (cf. Figure 1). To determine C , we need the stretch part frequencies

for A-J, J-B, and A-B. In a stretch part frequency, only those trains are considered that cover the entire stretch part. For each stretch part, C can be determined as if the stretch part were a section, using equation (4). Then, the theoretical capacity of the stretch is determined according to equation (6):

$$C = \min \{ C(b,e) \} \quad (6)$$

where $C(b,e)$ = theoretical capacity of the stretch part beginning at b and ending at e .

EXPERIMENTS

The model described above have been validated using a particular stretch in the Dutch railroad network. For this particular stretch, a simulation model is available which can be used to check the results of the aggregate model. A number of alternative passing constructions from previous infrastructure studies were available for this stretch. Additionally, a partial timetable has been developed for the alternative passing constructions. The description of the stretch Utrecht-Arnhem, the various passing constructions, and the other data are included in the Appendix.

In the experiments, three different market scenarios have been considered, together with five different passing alternatives. Table 1 shows the integer theoretical capacity for each combination of market scenario and passing construction. Table 2 shows the results for the same combinations from the detailed simulation model. It can be concluded that for the theoretical capacity there is a slight difference in the absolute numbers. However, should we decide on a ranking of the passing constructions based on the aggregate model, the result would be the same as if the detailed model was applied. Consequently, we may conclude that in this experiment the aggregate model meets its requirements.

Table 1 *Results of the aggregate model*

<i>construction</i>	<i>theoretical capacity</i>			<i>riding time increase</i>
	BA 34	PLUS 3	REF 2	
2INH	13	13	15	6.64
1INH	12	13	14	1.22
DETH	8	9	12	0
DB	8	9	12	10.88
ED	8	9	10	10.27

Table 2 *Results of the detailed simulation model*

<i>construction</i>	<i>theoretical capacity</i>			<i>riding time increase</i>
	BA 34	PLUS 3	REF 2	
2INH	12	15	15	2.5
1INH	12	13	15	2.0
DETH	8	9	12	0
DB	9	9	12	9.0
ED	7	9	10	10.0

For the riding time increase, the absolute difference between the aggregate model's results and the results of the detailed simulation-based analysis is considerably larger. This is due to a number of factors which have not been taken into account in the aggregate model. First, a riding time increase does not occur if the beginning or end of a passing construction is in a node. In these cases, it is not essential that the local train leaves or arrives exactly at t_{seq} minutes before or after the express train. If this is not necessary, the actual riding time increase is smaller than the one

in the model. Second, in practice it may happen on a long passing construction that a local train is passed by more than one express train. In the simulation tests, this occurred specifically for the constructions DB and ED. This leads to considerable increases in the riding time of the local trains in the detailed model. This effect is considerably larger than the first one and is also much more difficult to capture in the model. Incorporating this at the aggregate level requires a much more detailed analysis than we intend to do at the aggregate level.

DISCUSSION

Evaluating the consequences of introducing a passing construction in a stretch is a tedious and time-consuming process if a detailed model is used. Additionally, a detailed model may be very sensitive to unexpected changes in market demand. Therefore, we have developed an aggregate model to compare alternatives for investments in the railroad infrastructure, specifically passing constructions. The model aims to provide the user with information about the ranking of the various alternatives and additionally gives a relative insight into the theoretical capacity and flexibility of the proposed infrastructural change. In a test, the model proved to be sufficiently reliable to be used as a support tool for aggregate decision making, if the decision is based on the primary performance measure of capacity/flexibility. Its advantages are primarily its simplicity, the short computation times, and its relative insensitivity to market changes. The secondary performance measure (riding time increase) gave unsatisfactory results. If this performance measure is considered to be necessary at the aggregate level, additional work needs to be performed to derive a better measure.

The need for these aggregate models is not always recognized in railroad infrastructure management. However, fast, robust and reliable models for aggregate decisions can be useful for many other design questions.

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APPENDIX: CASE DATA

Figure A1 defines the regular stretch Utrecht (Ut) - Arnhem (Ah), and the five infrastructural proposals that were investigated in the case. Note that the first section of the stretch considered is also a section of another stretch (leading, at the junction, to Veenendaal). The market scenarios BA34, REF2 and PLUS3 refer to the ratio of the number of trains that is considered. In each of the scenarios, two kinds of local trains and one kind of express train are considered. Since the aggregate model only considers two kinds of trains (local and express trains), these data were

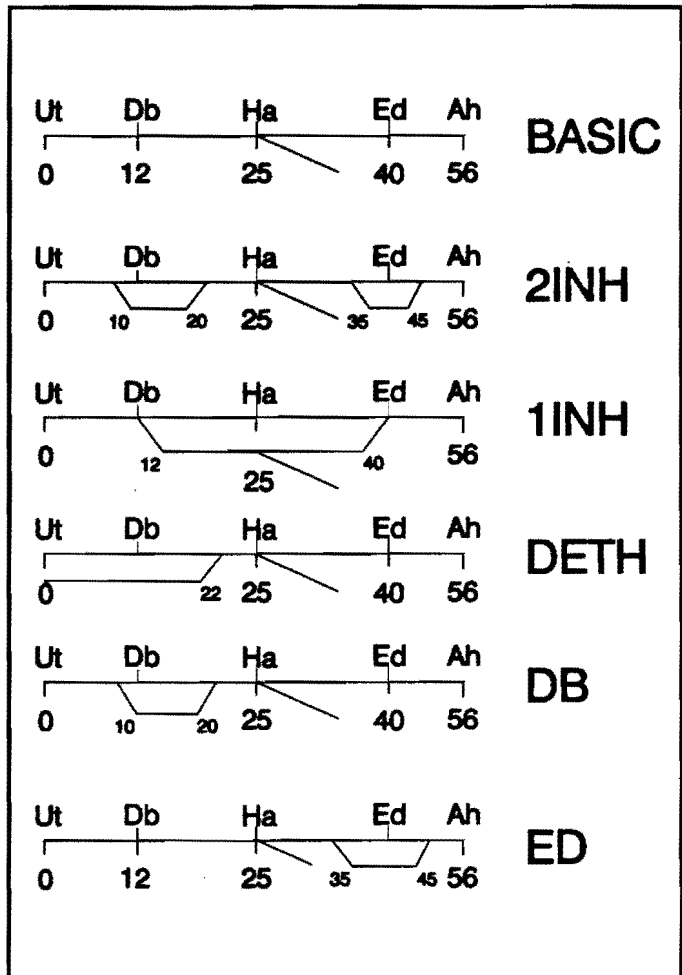


Figure A1. Regular stretch Utrecht-Arnhem and five infrastructural alternatives.

aggregated such that an adequate representation was obtained. Since the first section of the stretch Ut-Ah is also a section of the stretch Utrecht (Ut) - Veenendaal, the ratio of the number of trains for both stretches is relevant for this particular case. They are presented in Table A1.

Table A1. Different kinds of trains on the stretch considered.

<i>scenario</i>	Utrecht - Arnhem			Utrecht - Veenendaal		
	<i>ℓ1</i>	<i>ℓ2</i>	<i>x</i>	<i>ℓ1</i>	<i>ℓ2</i>	<i>x</i>
BA34	2	2	2	2	0	0
REF2	2	2	3	1	0	0
PLUS3	1	2	3	1	0	0