Increasing railway capacity by jointly improving infrastructure and rolling stock

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Abstract

Railways are complex systems that call for comprehensive optimization approaches. Taking into account all system elements - infrastructure, rolling stock, and services - and their interactions is paramount while seeking for an overall improvement of the system.

Optimizing jointly the infrastructure and the rolling stock has always been a prerequisite for the railways to succeed. The result of this optimization effort is eventually better train performances and shorter travel times. Using tilting trains to allow shorter travel times, has thus been instrumental in succeeding with the first stage of the Rail 2000 project, without resorting to huge investments in infrastructure.

A similar approach should be considered to face network congestion. Proposals based on common wisdom often foresee partial or full increase of the number of tracks on saturated links. However, building new tracks may prove extremely expensive and hard to imagine in heavily urbanized environments. We therefore need to consider every possible solution that limits the need to build new tracks.

As a case study, we focus on the between Geneva and Lausanne. At the hourly rate of 6 passenger train paths and one extra freight train per direction, this line has reached its saturation level. There is no capacity left to provide for any additional train paths. Meanwhile, the regional authorities (Cantons of Geneva and Vaud) plan to raise the future supply level to about 10 or 12 passenger trains per hour and direction. We have been able to demonstrate that a significant increase of capacity may be achieved without having to add an extra third track all the way long (from Lausanne to Coppet); to make it possible however, part of the rolling stock should be upgraded.

Results obtained with the comprehensive optimization approach have been generalized to help dealing with other rail lines that are almost saturated. It is moreover argued that, despite the separation between the management of infrastructure and the operation of the trains, railways should jointly improve infrastructure and rolling stock. Not doing so may lead to a halt in any effort to further develop rail supply, as existing facilities reach saturation and infrastructure extension becomes harder.

Keywords

Railway infrastructure – Line capacity – Timetable structures – Rolling stock

1. Introduction

The Swiss railway network provides services with a density that is among the highest worldwide. According to UIC (International Union of Railways) data, an average of 90 trains run daily on every section. Introduction of the Rail 2000 project has been a huge success. As a result, the number of passengers is steadily increasing and new train services are added wherever possible. That brings the network close to its saturation limits, especially in the approaches to major conurbations and on the main lines, as well. This is not an exclusive Swiss phenomenon, as in many countries traffic comes close to saturation levels at exactly the same spots (heavily urbanized areas and main lines), where flow concentration is the highest.

Railways are a major component for passenger and freight mobility. To sustain their mission and to cope with ever increasing demand, railways have to adapt. Unfortunately, extending existing infrastructure is extremely costly, and that greatly impedes the future development of railway services. Because of the scarcity of available space, especially around and in the heart of major conurbations, future extensions should mainly be built underground. That makes it even more interesting to look for solutions in increasing the train traffic while keeping investments at affordable levels.

Railways are complex systems that cannot be optimized piece by piece. Optimum solutions should encompass all interacting system components: infrastructure, rolling stock, and services. The purpose of the paper is to show that joint infrastructure / rolling stock optimization is crucial and may bring up interesting solutions.

This optimization process is shown through the study case of the Lausanne - Geneva line, one of the heaviest loaded lines in the network. Then, a systematic analysis highlights a series of fundamental principles that may be generalized to make the approach more universal and likely to be applied in other cases.

Focusing on double track main lines nearing saturation, the analysis is not applicable as such to single track lines.

2. Defining capacity

A broad definition of capacity may be expressed as the "*maximum volume of trains that may run during a given time interval*". However, railway capacity at the network level cannot be reduced as a single value and cannot be assessed analytically. Capacity is tightly dependent on a given timetable structure. Timetables differing in spatial and time distribution of train paths may exhibit fairly different volumes of extra train paths that may be added before reaching saturation. They may also vary greatly in the requirements for extra infrastructure in order to eliminate bottlenecks.

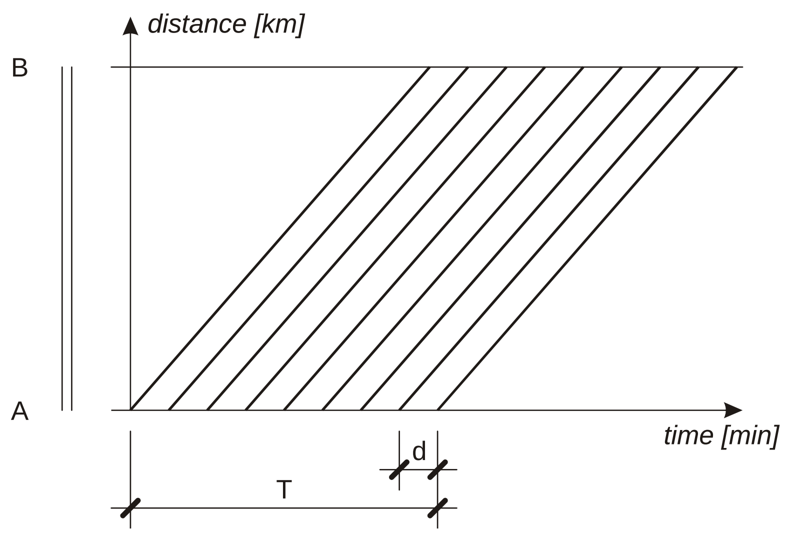
Spare capacity varies also according to the traffic structure (train categories, O/D structure for the services). On a given section, the number of extra train paths that may be provided within spare capacity depends of the very category of the trains one tries to add.

To cope with this complexity, it is necessary to get back to the fundamentals.

2.1 Line capacity when the traffic is homogeneous

When all trains running in a section are identical, i.e. when they have the same performance and follow a unique stopping pattern, computing capacity is straightforward. Train paths are parallel to each other, and capacity depends only on the minimum headway (Fig. 1):

Figure 1 Graphical timetable: Line capacity under homogeneous traffic (trains from A to B)



$$C_T = \frac{T}{d}$$

In some cases, computing capacity this way may be wrongheaded. When intermediate stops provide a single track platform for a direction, the line overall capacity is set by the capacity of the stations. Indeed, as long as a train is stopped in the platform track, following trains cannot enter the station. The stopping time, which depends on and varies with crowding, may thus become a critical factor in determining minimum train headway.

Metro lines have almost always a homogeneous traffic, just like rapid transit networks (RER, S-Bahn). Even main line sections subjected to heavy traffic (such as the link between Brussels-North and Brussels-South) are often run as lines with homogeneous traffic. This is the operational mode that helps maximizing train throughput, unless network effects induce extra constraints in the margin.

2.2 Line capacity with mixed traffic

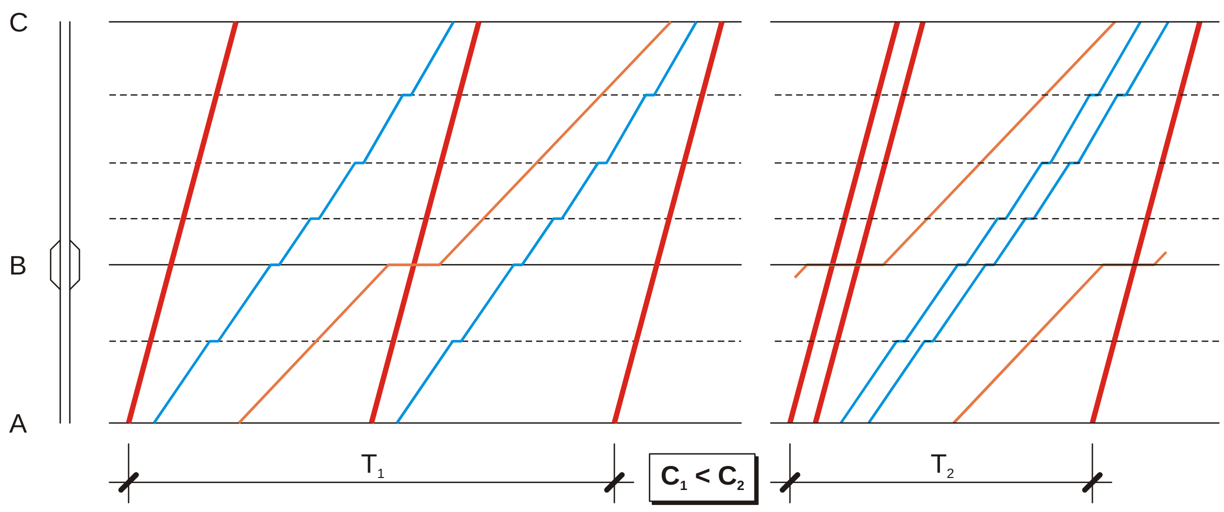
Homogeneous traffic may be seen as a singular case. Most of railway sections involve mixed traffic, with several types of trains providing different services (and different stopping patterns). Commercial speed varies among train paths, which are not parallel anymore.

Two extra factors should be considered to assess the capacity of a line under mixed traffic:

- Distance between consecutive stations where slow trains may be stopped and overtaken by faster ones;
- Order in which the different train paths are scheduled,

The last factor makes it impossible to compute the capacity with a universal formula, as its value is not unique anymore. One has to resort in designing a particular timetable to determine the capacity under the given conditions. This is illustrated by Fig. 2 below, where for the same section 2 different timetables exhibit 2 different values for capacity.

Figure 2 Line capacity under mixed traffic



Whenever stopping a slow train to be overtaken by a faster one increases the line capacity, this increase comes with a reduction of the level of service for the slow train. Largely used in freight traffic, this option is hardly interesting for passenger trains. A minimum of 5 to 6 minutes delay has to be foreseen for the slow train (and this only on lines with an extremely optimized block system), heavily affecting the commercial speed of the train and, thus, its attractiveness.

2.3 Network capacity

Beyond some isolated lines, assessing capacity needs to take into account network effects, as lines interact between each other:

- Trains running on different lines have to share tracks in common nodes (stations, junctions)
- Trains may use a sequence of several lines from their origin to their destination
- Trains on different lines share often common sections

Those needs for sharing induce added constraints that affect the network capacity. The only way to assess the latter is to design a full-scale timetable and to take into account all the operational constraints.

One can therefore define the network capacity as the maximum number of trains that may run in a network under specific operational conditions and for a given level of service.

The operational conditions include:

- The type of timetable (cyclic / periodical or not)
- The route of trains and their stopping pattern
- The traffic structure (share of each train type, e.g. 60% fast trains, 30% regional, 10% freight), and the priorities between train categories

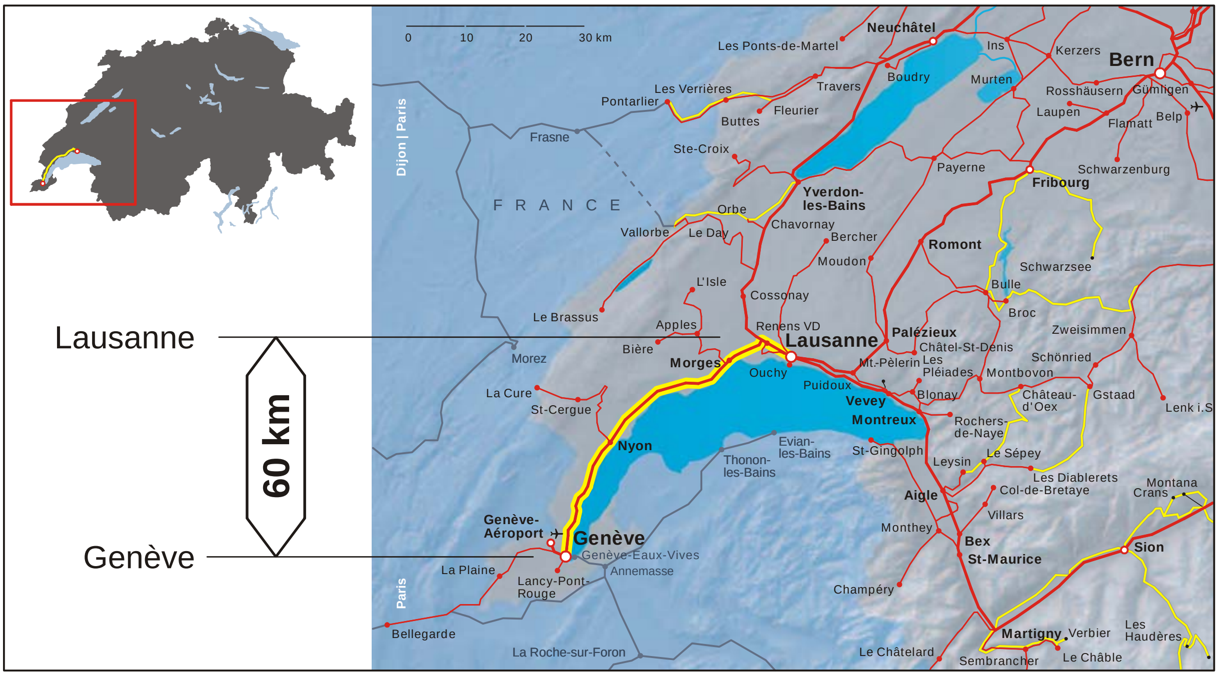
The level of service depends on the desired robustness for the timetable (timetable stability). The greater are the margins in planned travel time and in buffer time to protect against train conflicts, the more stable is the operation, but at the price of reduced capacity.

3. Lausanne – Geneva link; current situation and foreseen evolution

3.1 Current situation and traffic

The Lausanne - Geneva line is the backbone of the Swiss-French rail network. This 150 years old line is used by more than 210 trains daily, which carry about 38'000 passengers. Most of the trains pass through and stop in Lausanne main station then use one of the three lines radiating around Lausanne towards Wallis, the Swiss Mittelland (Freiburg, Bern, Zurich), and the Jura region.

Figure 3 Lausanne – Geneva line and the Swiss-French rail network



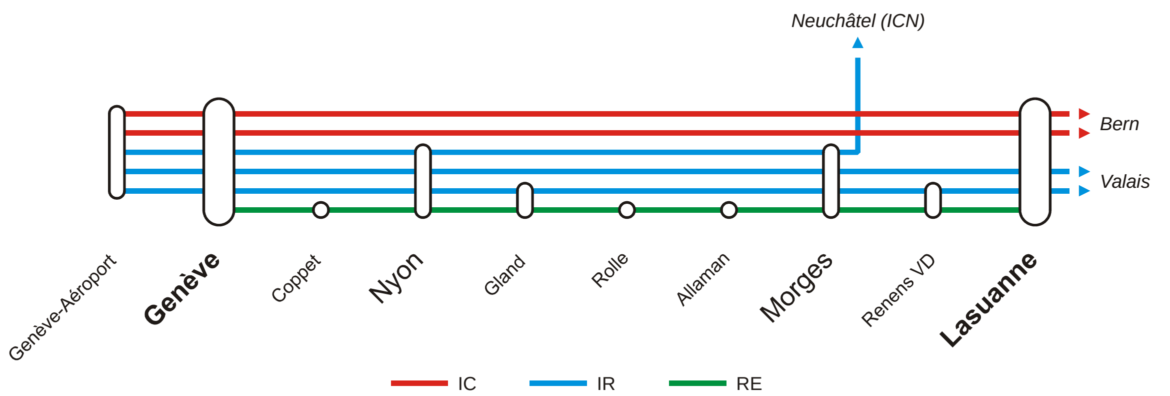
Source of the map: SBB/CFF/FSS

Current services, introduced with the Rail 2000 project, include hourly 6 passenger and 1 freight train running between Geneva and Lausanne[1] and in each direction. On both ends, service is completed by regional trains (the future RERs) between Lausanne and Allaman and between Geneva and Coppet (the latter section is already a 3-track one). Passenger train paths belong to one of the following 3 train categories:

- IC non-stop trains between Lausanne and Geneva (2 trains/hour per direction heading for / coming from Bern),
- IR trains with intermediate stops at Morges and Nyon, and sometimes at Renens and Gland, (2 trains/hour·direction heading for / coming from Wallis, plus 1 going to / coming from Neuchatel and bypassing Lausanne)
- RE shuttle train between Geneva and Lausanne, stopping at 7 intermediate stops (Renens, Morges, Allaman, Rolle, Gland, Nyon, Coppet), and ensuring connections with several bus lines (1 train/hour·direction).

Service in the Lausanne - Geneva line are illustrated in Fig. 4 below. In the section between Lausanne and Renens, which is also part of the Lausanne - Neuchatel line, only trains ensuring services with Geneva are included.

Figure 4 Lausanne - Geneva current services per hour



With the introduction of the Rail 2000 project in December 2004, Lausanne became a type 15/45 connecting section. That means that IC, IR, and RE trains enter the station slightly

[1] The only exception are the ICN trains on the Geneva - Neuchatel link that bypass Lausanne. Those trains use a shunting link between the Lausanne - Geneva line and the Lausanne - Neuchatel one, located near the Lausanne marshalling yard (Denges).

before minutes 15 or 45, to ensure connections between them. The service is structured based on the IC-train scheduling. The 2 hourly IC-trains are not exactly scheduled periodically; they are separated by a 25 - 35 minutes sequence. This creates extra constraints in planning the services and has direct consequences on the capacity of the line.

3.2 Development of the services

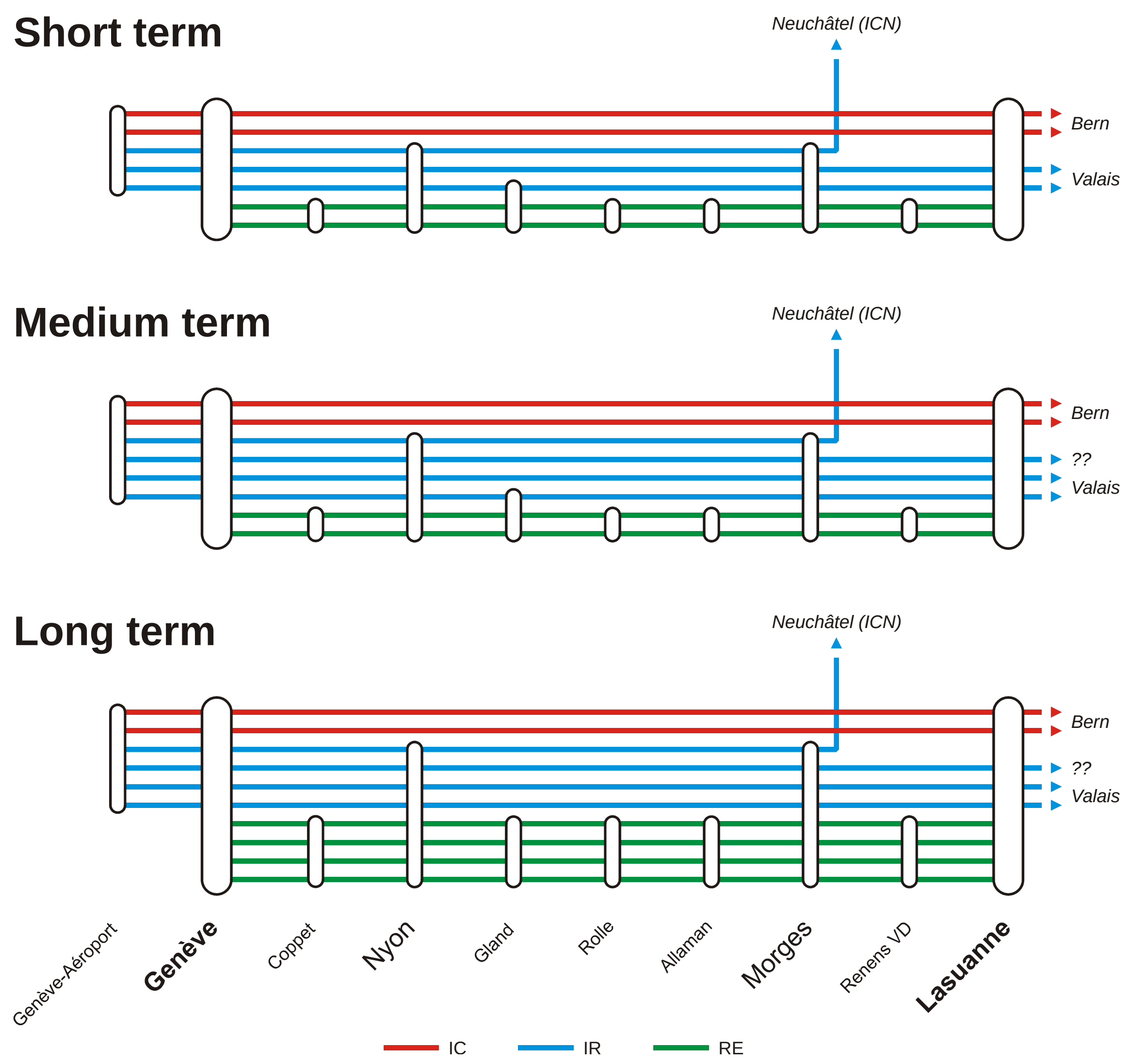
For several years now, economic and demographic growth on the Lemanic Bow[2] exceeds the national average. The trend is continuing and population forecasts show a 30% growth in the next 20 years. Mobility growth follows closely the trend and both rail and road demands grow strongly.

Congestion in road network dictates that a fair share of the future growth in mobility should be directed towards public transport and, especially, railway. Based on this, the Cantons of Vaud and Geneva developed scenarios for the future supply of rail services, both regional and between the 2 conurbations. Planning is referring to 3 terms, for which volume of services has been set:

- Short term a second RE is added to the current service (for a total of 2 IC, 3 IR, and 2 RE) while keeping one freight train path per hour; connection structure in Lausanne remains unchanged;
- Medium term a fourth IR is added (for a total of 2 IC, 4 IR, and 2 RE); regularity of timetable is restored for all train types (with 15 or 30 minutes time interval); one IR is bypassing Lausanne (connecting Geneva with Yverdon);
- Long term the number of REs is doubled (for a total, 2 IC, 4 IR, and 4 RE); consequently, 10 trains would run per hour rand per direction; the possibility to add 2 extra ICs is also considered, leading thus to 12 hourly train paths per direction.

[2] This is roughly the North cost of Lake Geneva, encompassing Geneva, Lausanne, Vevey - Montreux, and up to Villeneuve. The name comes from the arc-shaped pattern of this area.

Figure 5 Supply scenarios for the 3 planning terms



Even a simple analysis can show that, with such an extensive development of the transport supply, infrastructure extension becomes unavoidable. This is also legitimating the recurring demands of the Swiss-French cantons, aiming to include the provision for a third track between Lausanne - Geneva in the national planning of the railway development. Notwithstanding, further analysis is needed to locate exactly the extension of infrastructure.

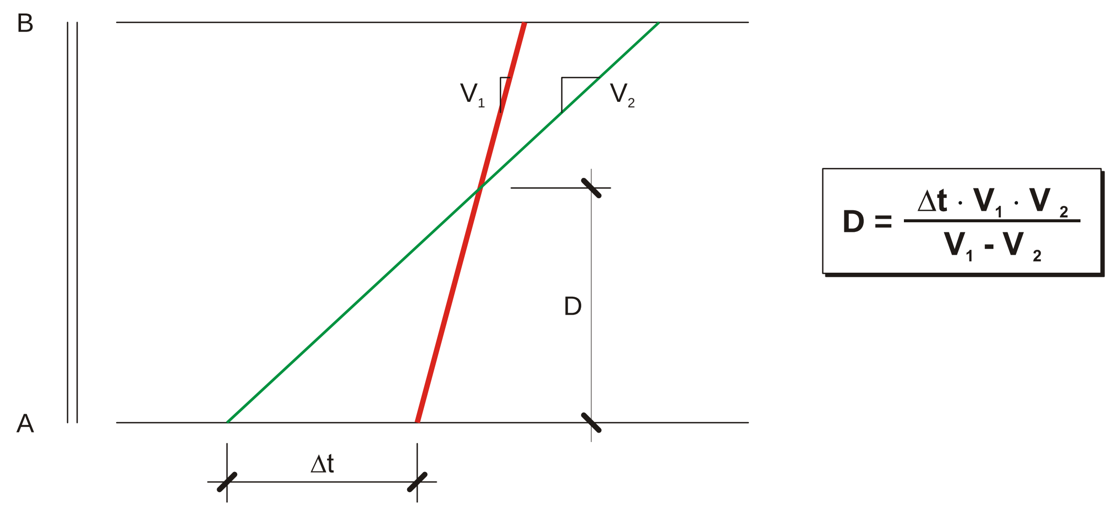
4. The issues

4.1 One-way traffic

When trains of different types run on the same line, increasing traffic eventually results in slow trains will be caught up by faster ones. The bigger the speed differences, the faster the problem occurs.

The distance before a faster train catches up a slower one depends on the commercial speeds of both trains (their slope in the graphical timetable) and on the time lag between the departures of each train (Fig. 6).

Figure 6 Catching up distance



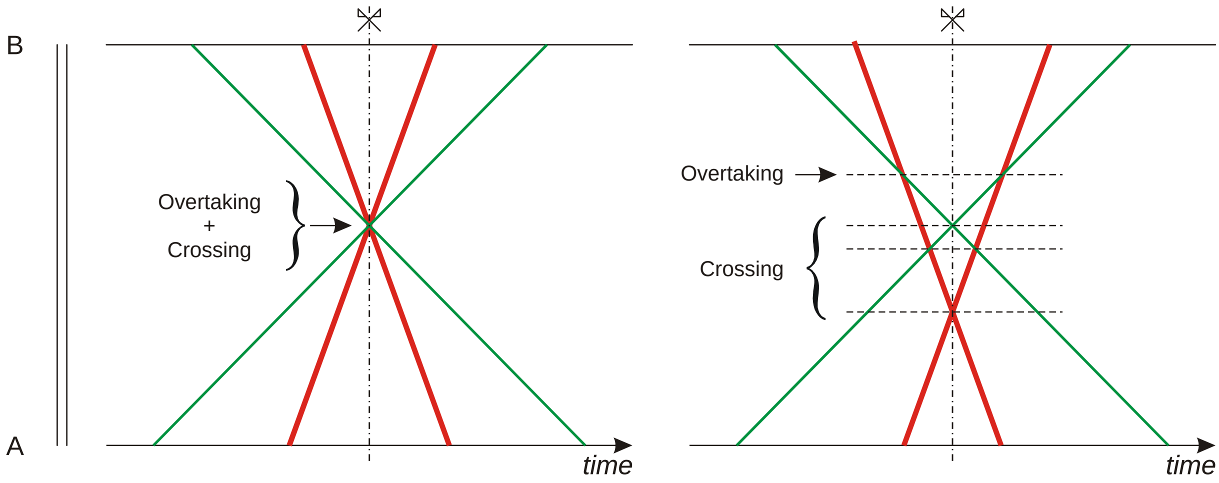
When one of those 2 parameters is modified (speed differential or departure time differential), the catching up point moves along the section.

4.2 Interaction between running directions

In coordinated cyclic timetables (where in connection nodes connections are meant to be ensured in both directions), train paths in opposite directions are symmetrical. Usually, axis of symmetry is set at minute 00. Trains of the same type (family) always cross at the symmetry minute, then - periodically - with intervals equal to half their period. Thus, for instance, trains running at 30-minutes interval cross every 15 minutes, at minutes 00, 15, 30, and 45. In this case, four spots in an hour, those 00 - 15 -30 - 45 minutes, may be seen as symmetry axes.

The corollary of this propriety is that when a fast train overtaking a slow train occurs at about those spots, there are not only 2, but 4 trains crossing at the same location (Fig. 7), where a 4-track configuration becomes necessary (either a 4-track section, or a station with 2 direct tracks plus 2 tracks for the trains waiting to be overtaken).

Figure 7 Overtaking at about a symmetry spot



This is a quite demanding condition and may create severe difficulties if the 4-track section should be built in a densely urbanized area.

This is actually the case for some alternatives developed for the Lausanne - Geneva line, where such a configuration would be required at the very place of Rolle main station. There were some land provisions with the building of a 3rd track in mind, but insufficient for a 4-track configuration. Finding more land at the heart of a town in full growth is next to impossible. That calls for alternative solutions.

5. Multiple and contrasting solutions

Without pretending to be exhaustive, we will try to show that various solutions exist and that they may be assessed quite differently according to the point of view (infrastructure manager, operator).

5.1 Minimising the operational constraints

Railway operators (freight or passenger) aim at running their trains with as few constraints as possible. When capacity limits are reached, they generally claim for increasing the number of tracks. Thus, former double track lines become full-length 3- or 4-track lines. In some cases, this leads to build a new double track line (this has been the case for high speed lines or base tunnels).

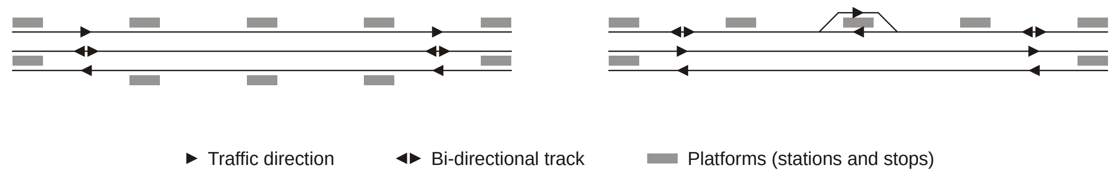
Extending from 2 to 4 tracks is certainly the costlier solution, but the one that offers the greatest flexibility in operations. With 2 parallel tracks assigned to one direction, active overtaking (both trains moving) is possible at any place, without interfering with trains running in the opposite direction. This configuration allows also operation as 2 parallel independent lines, one assigned to fast trains, and the other one reserves for slow ones.

There are several cases of 4-track lines, in Switzerland, and abroad as well. For obvious financial reasons however, this is not a generic solution to the problem, especially in dense urban areas, where underground building of a "second" line would have skyrocketed the costs. Moreover, full length doubling of a line is hardly justified economically. Full length 4-tracks lines are still a niche solution, intended to solve specific requirements.

Full length 3-track lines alleviate already many capacity concerns. However, extending a line from 2 to 3 tracks does not result in a 50% increasing of capacity, as one track at least has to be used for both directions, which reduces its capacity compared with a mono-directional track.

There are several ways (Fig. 8) in operating a 3-track line and each has its own advantages and limitations.

Figure 8 Usage typology of a 3-track line



The first type is the most common and the most conventional. External tracks are mono-directional, and the central one is bi-directional and used by all types of trains. The central track is used for active overtaking. This is possible as long as overtaking does not occur on a symmetry spot (c.f. § 4.2).

The second type is to operate the system as a double track line at which a single track line is juxtaposed. The double track line is used for the main traffic, and slow trains (the most penalizing for the capacity) are diverted to the single track line. As with any single track line, side tracks are necessary for crossing. The line is thus equipped with limited 4-tracks sections. The 3-tracks section built between Geneva and Coppet is operating according to this second principle. There is already a crossing spot and 2 additional ones are already planned to face future extension of services.

5.2 Increasing the transport supply within constant infrastructure

Infrastructure managers often face serious difficulties in finding financing for infrastructure extension. They are then forced to consider traffic development under the "constant infrastructure" constraint.

On a saturated double track line, the only way to increase transport supply is to reduce service variability. To make it possible, both number of train types and number of stopping patterns should be reduced to bring more homogeneity in the train behavior (e.g. braking and acceleration characteristics) and more homogeneity in the timetable, respectively. Such a policy involves either canceling of some stops to accelerate slow trains, or artificial slowing of fast trains (by forcing some extra stops or imposing speed reductions). The idea is to make train paths parallel, avoiding thus capacity-hungry overtaking operations.

This is usually foreseen, and sometimes unavoidable, in urban lines (Rapid transit ones, or lines crossing dense urban areas), especially in underground sections. In urban traffic, slight slowing down some services is acceptable, as rail travel times remain still competitive compared to other public transport (buses or tramways).

This policy, applied to long lines (to the 60-km long line between Lausanne and Geneva, for instance), may produce severe adverse effects on travel time. Moreover, slowing down fast trains may annihilate time gains obtained in other parts of their route. It is therefore important to analyze carefully the impacts on demand of such a policy.

5.3 The rolling stock, a crucial factor in optimizing the system

Both solutions already considered (full length extension of number of tracks and increasing the transport supply within constant infrastructure) should mostly apply in specific cases. Other in-between solutions may also be considered, but they still tend to optimize a single element of the system. For global optimization, taking into account the rolling stock is paramount. This is because:

- Maximum speed, tractive and braking performances, and other characteristics such as number of doors and step height, determine considerably the commercial speed of a train (and thus the capacity assessed as number of possible train paths);
- The length of the train-set, and the type of coaches (single or double stack) determine directly transport capacity, i.e. the volume of passenger that can be moves in a given time interval.

By increasing the train length, or by using double stack coaches, we may increase passenger comfort (number of seated passengers) without more infrastructure investment than the one needed to extend platforms in stations and to adapt them to the increased height. Investment is shared between the infrastructure manager and train operators.

If those measures are insufficient or ill-adapted to the basic needs (such as to provide a more balances transport supply through the time spectrum), one has to consider actions in the first afore-mentioned group. They can accelerate slow trains, without canceling intermediate stops. To reduce impact of intermediate stops, frequently stopping trains should exhibit the best possible performances in acceleration and braking.

Frequently in saturated lines, slow trains are slowed down not only because of frequent stops, but also because or poor performance. Actually, rail operators tend to assign the oldest material to the least noble services: regional trains.

Fortunately, this trend is reversed the last years; many recent orders for rolling stock are linked to regional trains. There are however cases where the full potential of the opportunity while ordering new rolling stock has not been fully exploited.

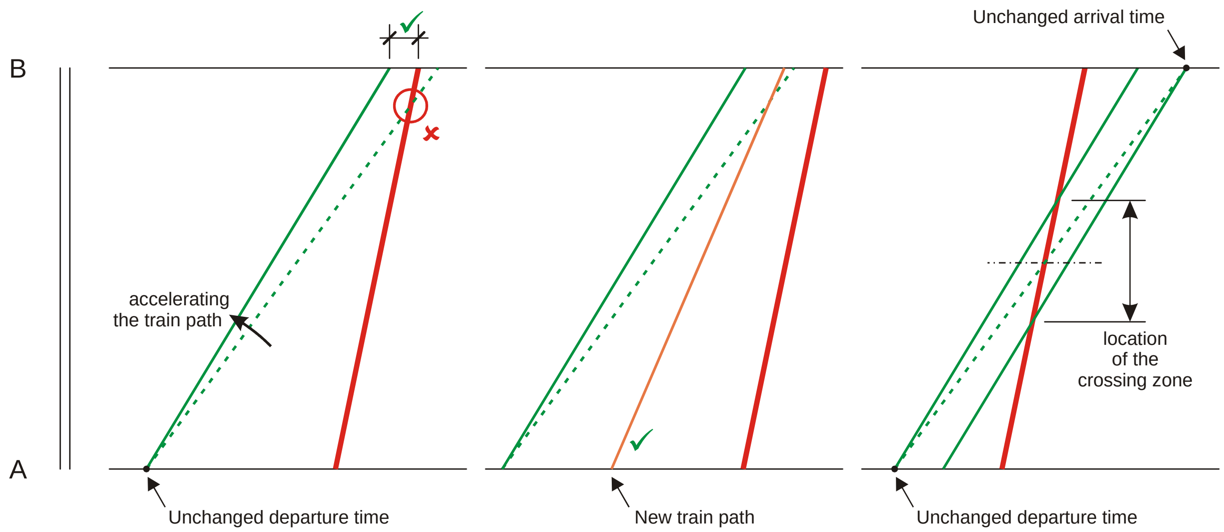
There is still room for improvement. Capacity extension is primarily an infrastructure issue; however, rolling stock contribution should always be considered within this frame.

5.4 Accelerating the slowest trains

As already mentioned, accelerating slow trains reduces the speed differential by (Fig. 9):

- Avoiding that a fast train catches up a slow one just before an overtaking station or a terminal station
- Freeing up time slots in the timetable that can be devoted to extra train paths that can be added behind slow trains
- Making it possible to move along the line the place where slow trains should be overtaken and, within some limits, to set the location for infrastructure extension (third track, or overtaking point) at more favorable places, where they can be built at lower cost

Figure 9 Impact on capacity of accelerating the slowest train



It is clear that such an action may not be sufficient by itself to provide an answer to all capacity requirements, although it is important to not neglect it in a global optimization effort.

6. Possible solutions for the Lausanne - Geneva line

On the Lausanne - Geneva line, a short term increase of capacity is only possible under constant infrastructure, both for budgetary and practical reasons. Infrastructure extension works are time consuming in planning and realization; they are therefore not considered for the short term. Moreover, the Vaud and Geneva Cantons are not willing to consider restructuring the current typology of services. Consequently, the only way for improvement is through actions on the rolling stock.

At longer range, acting solely on rolling stock improvements may prove insufficient, and consequent extension of infrastructure should also be considered. Smart choices can however reduce the required investment effort.

6.1 New rolling stock for the RE rapid regional trains

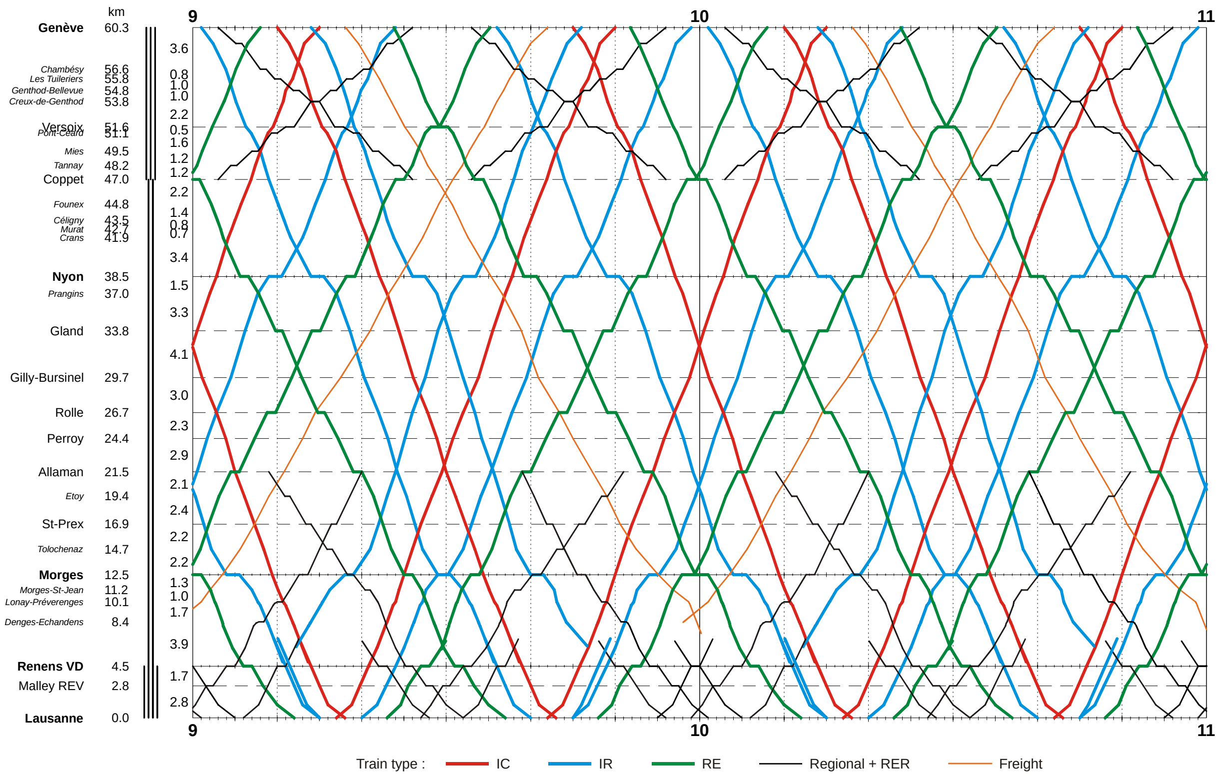
With the exception of the very regional (omnibus) trains, RE rapid regional services are the slowest ones. They use also the oldest rolling stock, initially designed for main line services, then recycled to regional ones; it is not the best solution for frequently stopping services in a heavily loaded line.

Already today, SBB/CFF use and have ordered more performing train-sets that are better fitted to this type of service. Those are; a) Flirt train-sets, already in operation in several rapid regional transit networks (S-Bahn); b) the 3rd series of double stack train-sets ordered for the Zurich S-Bahn. Both of those offer installed specific powers of about 20 kW/ton (able thus to start with accelerations exceeding 1 m/s^2) and are equipped with powerful braking systems.

Computing running times with those train-sets on the Lausanne - Geneva line shows substantial time savings of about 5 minutes over the existing rolling stock (there is a 10% reduction in travel time from the current 51 minutes in the timetable down to 46 minutes). Such a magnitude in reducing the travel times has direct consequences in capacity:

- At short term — It makes it possible to run a second RE train without disrupting the freight train path. On the contrary, freight services will be improved, as trains would not need anymore to stop and being overtaken in Gilly-Bursinel station, reducing thus by 10 minutes their travel time between Geneva and Lausanne's marshalling yard (Fig. 10).

Figure 10 Horaire Lausanne Genève avec 2 RE par heure (nouveau matériel roulant)



- At medium term This will avoid RE train paths being caught up by IR ones, and it will eliminate the need to add new tracks in the entry zone of Geneva's main station (which is extremely difficult, due to urban constraints).
- At long term This will also move away from the symmetry axis, the IC / RE overtaking zone, limiting thus the need of extended infrastructure (see also section 6.2, below).

6.2 New 3-tracks sections

Upgrading the rolling stock will not be sufficient to in medium term. New 3-track sections will also need to be built.

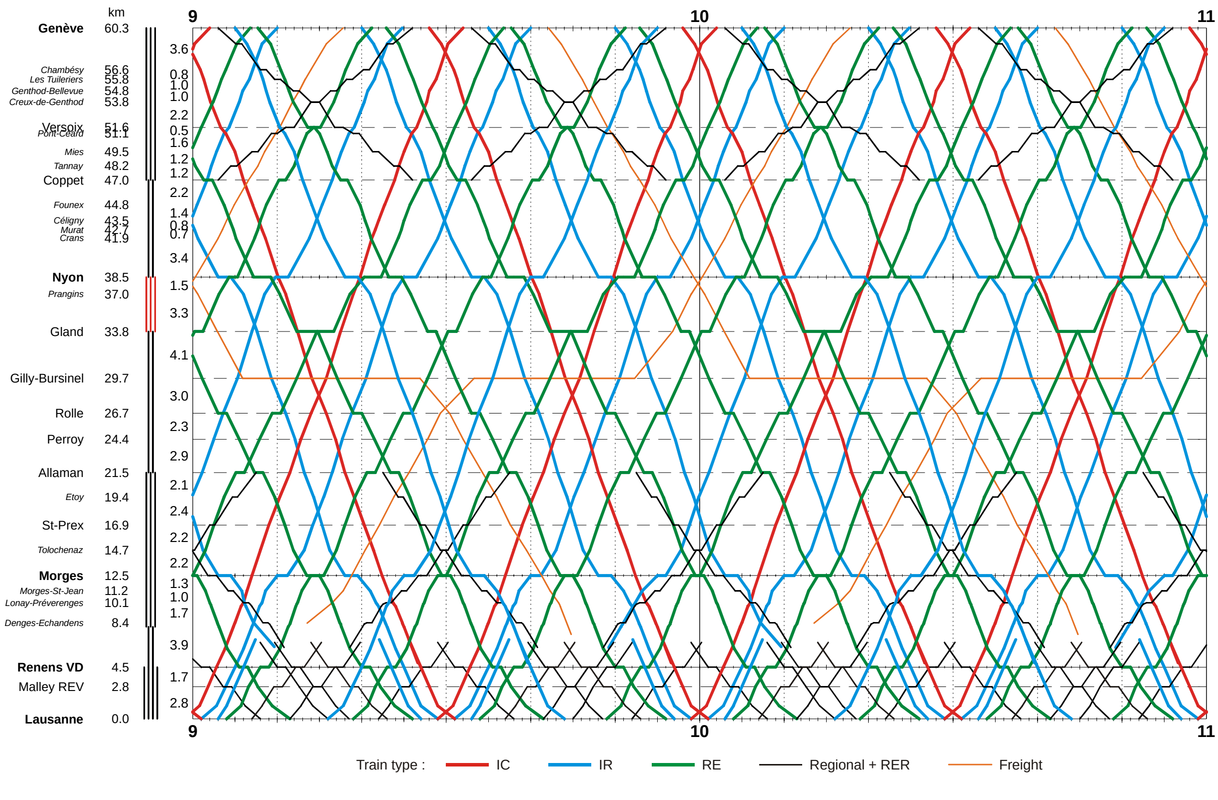
At medium term, providing a 15-minutes regular IR service (by adding a 4th train-path) will be impossible without a third track in the section between Renens and Allaman. The time slot between 2 consecutive IRs is not enough to run a Rapid Regional Transit service (REV, the future RER of the Vaud Canton) without being overtaken. To ensure the future development of REV, one has to provide the same solution that has been applied between Geneva and Coppet: a third track. Existence of a 3rd track in the Renens - Allaman section is thus considered as established, further on.

At long term, increasing the volume of RE services will induce REs being overtaken by ICs. As already stated, accelerating RE train paths makes it possible to avoid building a 4-tracks section, thanks to the moving away of the overtaking zone from the symmetry axis. Overtaking becomes possible within the Gland - Nyon section, by:

- Building a third track in this section and modifying the track layout;
- Assigning the central track to the IC trains, and the external tracks to RE ones;
- Extending the stopping time of RE trains in Gland and Nyon stations.

This solution both minimizes the need for extra infrastructure and offers the possibility to provide 10, and even 12 hourly train paths per direction. By extending the length of the third track in this section, stability of the timetable could improve up to the point where two opposite-running IC trains start conflicting in entering / exiting the central track. A detailed stability analysis is still needed to define the optimum length of the third track.

Figure 11 Long term timetable with 10 hourly train paths per direction



7. Conclusions

We state in this paper that to deal with capacity issues, one has to consider the full set of the railway system components, and not only the infrastructure. Unfortunately, rolling stock is often considered as a constraint and not as an optimization variable.

Railway reform, induced by the European Union, bears risks to push towards more partial optimization. Now, the railway manager is the one in charge of capacity management, whilst rolling stock choices are done by the rail operators. Infrastructure managers have little leverage to force rail operators in opting for a more performing rolling stock that could reduce the needs for extra infrastructure. Attaining global optimization of the system becomes more cumbersome. The challenge we are facing for now is to find means for both partners to work together and to reach a common vision toward global system optimization, paving thus for railways the way to success.

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