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MŰSZAKI
KATONAI
KÖZLÖNY

Bence Tóth[1]

The Effect of Railway Electrification on the Passability of Hungary

The railway network of Hungary is very dense also in international comparison: as the total length of the network is 7,395 km, the aereal density is 8.00 km/100 km2, which is the sixth densest in the world. However, in other parameters it is far behind other countries as, for example, the railway electrification of Switzerland is 100% while of Hungary it is only 42.6%. In this study I investigated how the maximal possible value of freight traffic increases if not only the electrified but also the unelectrified lines are taken into account. This parameter is not only a good tool to quantify which railway lines should be electrified, but also to show how important the diesel engines for the country are.

Keywords: *railway network, graph theory, flow, capacity, Hungarian Defence Forces*

Introduction

If one wants to get an overall picture of a railway network, there are several measures that can be calculated. One of these is density, which is the ratio of the length of the lines in a certain region divided by the area of the same region. In the case of Hungary, the total length of the railway network is 7,395 km[2] while the area of the country is 93,030 km[2] which gives a railway density of 8.00 km/100 km[2] which is the sixth densest in the world.[3] Another measure is the ratio of double-tracked lines, which is only 16.6% for Hungary. This particular example already shows that one good property of a network is not enough to state that it can be operated at high performance.[4]

To be able to utilise the highest possible traffic on a transportation infrastructure network all segments have to operate at full capacity. If some do not, it is called a disruption. For example, in the case of the railway network, the overhead wires can be disrupted by falling

1 Associate Professor, PhD habil, Ludovika University of Public Service, Faculty of Military Sciences and Officer Training, Department of Natural Science, e-mail: toth.bence@uni-nke.hu

2 KSH 2023.

3 UNECE s. a.

4 Szászi 2007.

trees in a storm, or the movement of switches can be hindered by icing in winter. However, these are disruptions of already existing infrastructure elements, but there are some cases when the maximum possible capacities cannot be utilised due to the users of the network. This can happen if the locomotive using the tracks is only capable of lower speeds than the speed limit of the line or when the axle load of the cars is lower than the permitted value of the line and thus only a smaller amount of goods can be transported.

It is also the latter case when only electric engines are available and thus lines with no electrification cannot be used to transport goods or utilised as a detour in the case of a disruption. In fact, the electrification ratio of the railway network of Hungary is also quite low, especially compared to Switzerland where this value is 100% as for Hungary only 42.6% of the railway lines are electrified.[5] As every double-tracked line section is electrified, one can calculate that only 25.3% of the single-tracked lines is electrified.

The international border crossings are not only important because of freight traffic, but also for military operations.[6] The electrification of these connections makes it possible not to change locomotives when crossing from one country to another.

The role of railway electrification

Railway electrification is a two-edged sword. Under normal operational conditions (peacetime) electrified lines are better in almost every aspect than the ones without electrification: higher line speeds are possible, stronger locomotives can be used. These result in a larger amount of transported goods, cheaper traction, and are more environmentally friendly than transportation using diesel engines. However, this adds other critical elements in the network: the overhead wires and the voltage supply stations. Both of them can be disrupted separately, which adds vulnerability in the network. Overhead wires are exposed to weather, which means that storms, ice and also failures of the pantograph can damage them which are all unintentional failures and are unavoidable to some extent. But being present on the whole railway line without guarding they can also be a subject of intentional attacks as they can be damaged by terrorists making the trains in that line section to stop. The electric supply can also be the subject of intentional disruption, which makes several lines connected to a power station to shut down. The map of the electric substations of the Hungarian Railways (MÁV) with the supplied line sections is plotted in Figure 1.

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5 Eurostat 2022.

6 Szászi 2014.

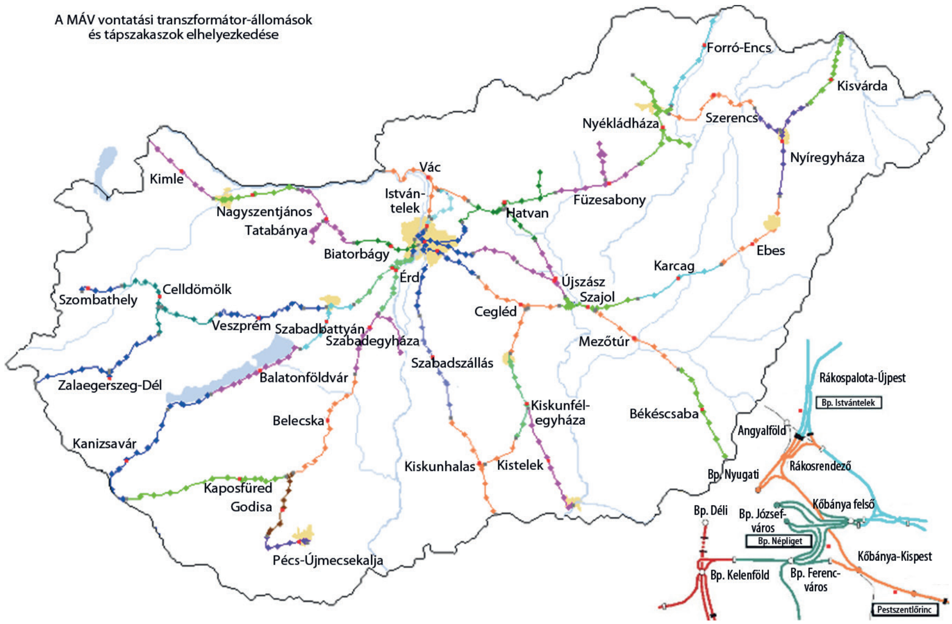

Figure 1: The electrical substations of the Hungarian Railways (MÁV)
Note: The lines supplied by a single substation are coloured accordingly.
Source: https://www.eszk.org/attachments/l279/ea/palmai.pdf

However, there is no need for such unexpected events, planned reconstruction or development of existing electrified railway lines can result in cases when the use of unelectrified lines is needed. For example, when line No. 40a (Budapest–Pusztaszabolcs) was reconstructed between 2018 and 2022 to make it available for higher speeds (including the new line 40b between Százhalombatta station and the newly added Ercsi junction which can be practically regarded as a path correction), the electric engines serving the Dunaferr steelworks could not use this line as usual. As a substitute, line No. 5 (Székesfehérvár–Komárom) had to be used, which is not electrified and thus an increased amount of diesel engines was needed (either own or rented) by the forwarder companies.

Similarly, when Pusztaszabolcs station was reconstructed in 2019, every InterCity train between Budapest and Pécs had to take a detour via Dunaújváros. However, the line section between Dunaújváros and Rétszilas, which was part of the detour, was not electrified. This made the use of diesel locomotives as bank engines (i.e. locomotives attached to the front and/or the rear end of the train to help it climb a gradient) necessary, as using buses to replace the trains on this section would have been unrealistically expensive, compared on the usable railway infrastructure in good condition, and changing between buses and trains is also uncomfortable for the passengers.

Another bottleneck can be the engine fleet. Operating electric locomotives is cheaper and more effective. In addition, as more and more of the network is being electrified, the need for diesel engines is decreasing. This makes the existing fleet become old, which in turn results in more frequent failures of the engines, as there is no economic need to buy and operate new engines, but this can lead to the lack of enough diesel engines in the previously mentioned cases.[7]

Research goals

As a consequence of the effect of electrification on the railway network, a thorough examination is necessary. In this research, I calculated the maximum traffic that can be carried on the railway network of Hungary between each pair of border crossings, if only the electrified lines are taken into account, and also if all railway lines can carry traffic. Then, the traffic flow on every line section is summed which shows the difference between the two cases: which railway lines are vital for both cases, which are important when only electric engines are used and which are better to be bypassed when diesel engines are available for traffic.

In the following, I will shortly discuss the graph model of the railway network of Hungary that was used for the modelling, the software environment and the calculation methods.[8]

The main-signal-level graph model of the railway network of Hungary

The railway network of Hungary is represented by a weighted directed graph.[9] The nodes of the graph are the main signals of the network. The main signals are the home signals and exit signals of stations and the block signals of the line sections between the stations (for the lines that are designed for block signalling, naturally). To see how traffic between these signals work, the basic design of stations, line sections and junctions has to be discussed.

Stations

In the railway network of Hungary, a station is defined by the Traffic Instruction (F.2. sz. Forgalmi utasítás) of the Hungarian National Railways (Magyar Államvasutak Zrt., MÁV) as two home signals at its two endpoints[10] (see Figure 2). The destination of a train is usually a station, therefore, it must pass the home signals and reach the exit signal on the other end. Therefore, the routes are always defined as a travel between the exit signals of the departure and the destination station. The path length and the travel time are thus calculated as the sum of the weights of the graph edges on the shortest path between the nodes representing that two specific exit signals.

7 Ardai–Tóth 2023.
8 Tóth 2022.
9 Tóth 2021: 567–587.
10 MÁV – Pályavasúti Főigazgatóság 2008b: 1.2.4.

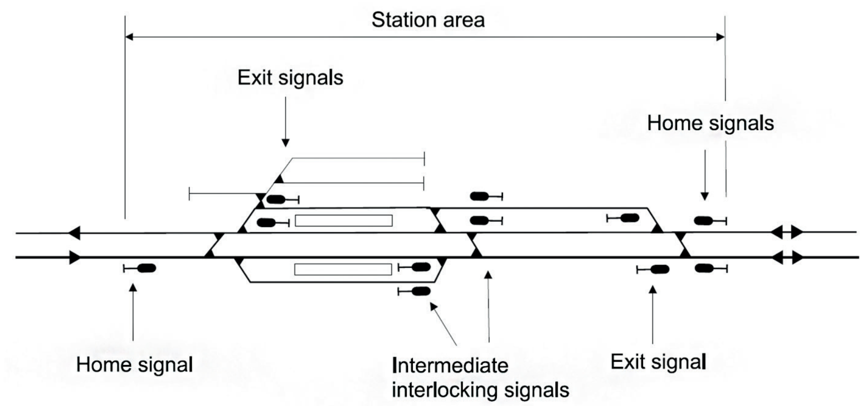

Figure 2: Schematic diagram of the signals of a railway station
Source: Pachl 2020

Block sections

As a rule of thumb, there can only be one train between two main signals. If two neighbouring stations are too far from each other to both satisfy this rule and to pass through the traffic, the open line between these stations can be divided into block sections. As the block signals at the beginning of each block section are counted as main signals, this way the capacity of a line section can significantly be increased. The first block section extends from the exit signal of the departing station (making that specific exit signal technically a block signal, too) up to the first block signal of the line section. The last block section extends from the last block signal of the line section till the home signal of the next station. The principles behind block signalling are summarised in the schematic picture of Figure 3.

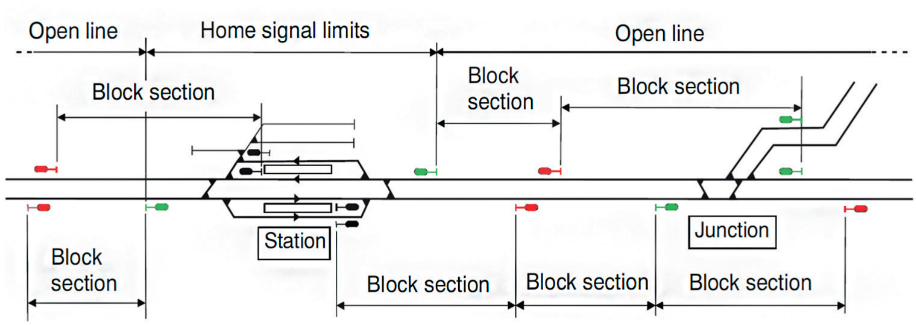

Figure 3: Schematic diagram of block sections
Note: The signals marked with green are home signals, marked with black are exit signals, marked with red are block signals. Note that the block section with a junction is protected by the home signals of the junction.
Source: Lusby et al. 2011

Junctions

When a railway line connects to another line at a station, home signals are used on both lines which mark the beginning of the station. However, if they do not meet at a station, a junction with appropriate signalling has to be built. The switches that provide the connection have to be guarded by signals from each direction. This is carried out technically by home signals. On each railway line, the last main signal before the junction is not a block signal but a home signal which is not followed by an exit signal but (on lines with block signalling) with a block signal or the home signal of the next station. This is because block signals can be passed (with some restrictions[11]) when the signal shows a red light but home signals must not. This ensures the safety of the trains arriving to the junction from the same direction.

Border crossings

Border crossings are not marked with any kind of signal in the real network. However, to be able to run trains up to these points without knowing where the next main signal in the railway network of the bordering country is, virtual main signals were put into the graph at the exact locations of the border crossings. Two nodes were assigned to each border crossing point: a home signal in the direction of leaving Hungary and an exit signal in the direction of entering Hungary.

Signals and tracks

The nodes of the graph were thus the main signals of the railway network of Hungary and the virtual main signals of the border crossings. Their position data from the starting point of the railway line is freely accessible with meter precision on the website of the web page of the Hungarian Rail Capacity Allocation Office (Vasúti Pályakapacitás-elosztó Kft., VPE Kft.).[12] Even if there are no signals at the country border, the positions where each railway line crosses the international border is contained in the VPE database similar to main signals, i.e. not their geographical position but their distance from the starting point of the corresponding railway line. It is important to note that these position data are not GPS coordinates. As the railway lines are not running straight between the signals, connecting only the geographical point of the signals would cause the lines appear more or less shorter than they actually are. Therefore, the distance used is not Euclidean distance between points but the actual running length of the trains.

The edges connecting the nodes of the graph thus represented the tracks between the signals with parameters assigned to them as weights. For the results presented here, these parameters were the length, the travel time and the capacity of the corresponding line section.

[11] MÁV – Pályavasúti Főigazgatóság 2008b: 15.19.2.2.
[12] VPE vasúthálózati térkép.

The travel time was calculated as the ratio of the length of the line section and the line speed of it, the latter also available at the VPE Kft. web page. Therefore, this time value is a lower limit of the real travel time due to the acceleration and deceleration time, temporal speed restrictions, etc.

The graph was designed to be able to model military applications easily. In these cases, trains with locomotives are used. As the line speed differs for locomotives and for electric multiple units (EMUs), the former being lower for some railway lines, this lower line speed was taken into account for the calculations.

The graph contains 5,198 nodes, from which 1,689 represented home signals, 1,491 exit signals, 1,904 block signals and 114 represented other line connections, like border crossings or sidings. The connections between the signals were modelled by 6,803 edges in the graph.

Some lines with 0 km/h line speed were also included in the model (e.g. line No. 49 Lepsény–Csajág–Papkeszi) and even lines completely demolished (e.g. line No. 1CM, the so-called "Greater Burma" track) to ease the future application of the model in development planning. Some of these future expansions can be the Budapest-Kelenföld – Budapest-Nyugati railway tunnel or the connection of line No. 150 to the Southern Railway Bridge both outlined by the Budapest Agglomeration Railway Strategy (Budapesti Agglomerációs Vasúti Stratégia, BAVS).[13]

Reversing

Train reversal was made possible in the model only at those 710 stations at which it can also be done in the real network. It was made possible in the model by connecting the two exit signals of the same station with edges and assigned 0 km and 10 minutes weights to them. The latter is due to the time needed from stopping to departing in the other direction, during which the locomotive has to be disconnected, reconnected to the other end and the brake test has to be done. This is also a lower limit for this time interval.

The virtual home signals and exit signals of the border crossings were not connected as we do not want to enable reversals at these points not only because reversal at the border point is not possible as these signals are not present in the real network but also because the railway network of the neighbouring country should also not be used for reversal, reversal has to be done at the nearest Hungarian station if necessary.

The main purpose for using a directed graph was for the algorithm calculating the shortest path to add these extra 10 minutes to the total travel time. This also made possible to handle the traffic in opposite directions (even if the line was single tracked) separately. The other reason for using a directed graph was the difference in the distances between the exit and the home signals on the same end of a station from the nearest block signal. The notation of the signals is based on the starting point and the endpoint of the corresponding railway line, i.e. if a line starts from Budapest (the national capital), the terminus at Budapest is the starting point of the line. If neither end reaches Budapest, the regional railway directorate defines which end is the starting point. Thus, every railway station has a starting point and an

[13] Lévai 2022.

endpoint. Corresponding to this notation, every station has a starting point and an endpoint, too. The starting point of the station is the end closer to the starting point of the railway line it lies on and the endpoint of the station is the end closer to the endpoint of the railway line.

The structure of the graph is presented in Figure 4 on the example of Győr station and its vicinity and the map of the whole network is plotted in Figure 5.

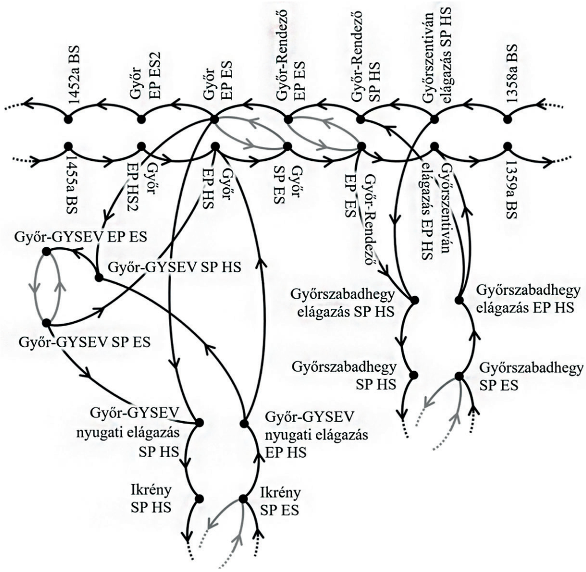

Figure 4: Diagram of the graph representing Győr station and its neighbouring stations

Note: Home signals are denoted by HS, exit signals by ES, block signals by BS. The starting point of a station is denoted by SP and the endpoint by EP.

Source: Lévai 2022

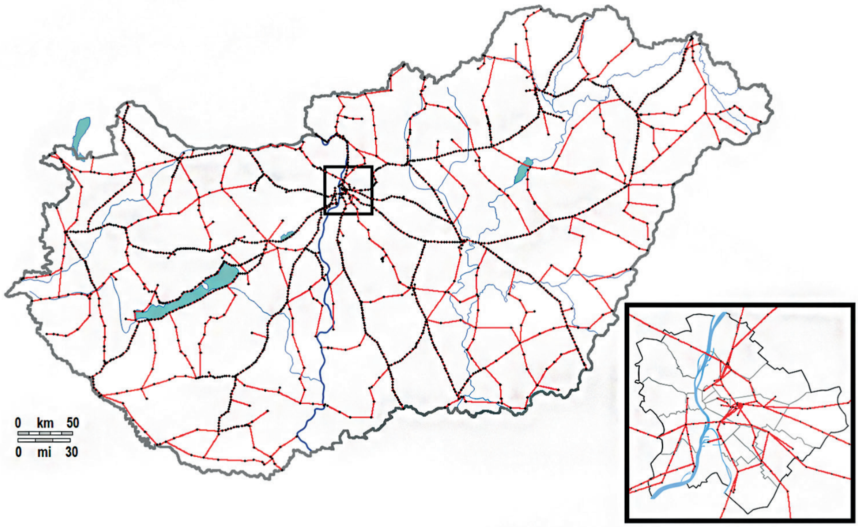

Figure 5: The graph plotted onto the map of Hungary

Source: Lévai 2022

Calculation methods and measures

In the following, I will briefly summarise the software environment used for the modelling.

Software

Calculations were done in the *R* programming language and environment[14] by using the *igraph* package[15] developed by Gabor Csardi and Tamas Nepusz. The distance between two stations (which is the distance of the appropriate exit signals) in length or time can be calculated by the function distances. In case of graphs with only non-negative weights (and a railway network does not have negative lengths or travel times), the function uses Dijkstra's algorithm[16] to calculate the length or travel time of the shortest path,[17] depending on the weights being used.

But as the distance between two nodes represents the distance between the exit signals and not the distance between the stations (whatever would that mean), the length of four shortest paths has to be calculated: between the exit signal at the starting point and the exit signal at the endpoint for both stations and the smallest value has to be chosen. While for path lengths, all four values are close to each other as the distance between the opposite exit signals are only a few hundred meters, for travel times, two have to be longer by 10 minutes and one by 20 minutes than the optimal. In these cases the origin and/or the destination node was chosen incorrectly and the path started and/or ended with an unnecessary reversal. After the correct origin and destination node is determined, the exact route of the path could be calculated with the function *shortest paths()* and the edges passed through can be obtained using the *$epath* value of the result.

Capacity

Let us assume that the distance between the block signals is more than the average braking distance. The principles of block signalling are demonstrated in Figure 6. The following train (on the left) can only travel with the line speed v_{max} constantly if it arrives at the visual distance (ℓ_o) of the block signal (3) when it turns green. This means that the next block signal (2) turns from red to yellow at the same time which, in turn, means that the preceding train (on the right) has just left the block section guarded by block signal (2) and turned block signal (1) red, which guards the block section it has just left.[18] Therefore, the tracking distance ($\ell_{tracking}$) is the sum of the train length (ℓ_t), the visual distance (ℓ_o), the length of the two block

[14] R Core Team 2012.
[15] Csardi–Nepusz 2006.
[16] Dijkstra 1959.
[17] From now on, I will use the term 'shortest path' in an inclusive meaning for both paths with shortest length and shortest travel time. In a single calculation, naturally, only that one applies that corresponds with the weight used for the edges of the graph. If only one of it is meant, it will be specifically noted.
[18] MÁV – Pályavasúti Főigazgatóság 2008b: 1.2.117.

sections (ℓ_{b1} and ℓ_{b2}) and a so-called safety distance which is 50 m according to the Signalling Instruction (F.1. sz. Jelzési utasítás) of MÁV.[19]

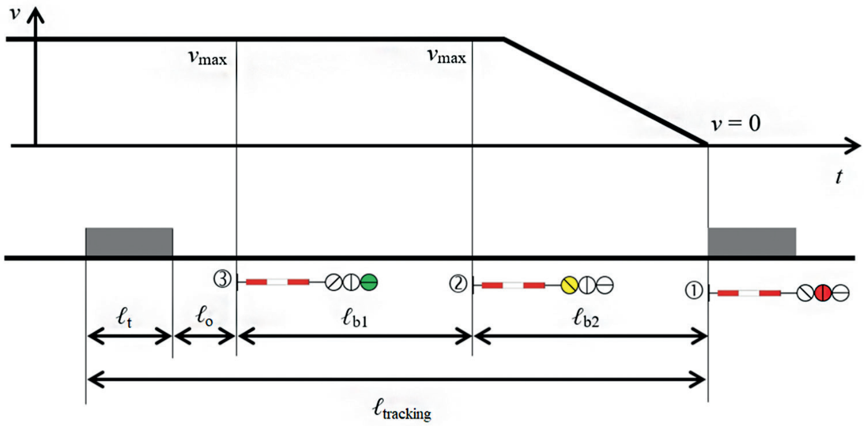

Figure 6: The principles of block signalling
Source: MOLNÁR 1977: 133

The occupancy time (*s*) of a block section can be calculated in a more precise way as follows proposed by UIC (Figure 7).[20]

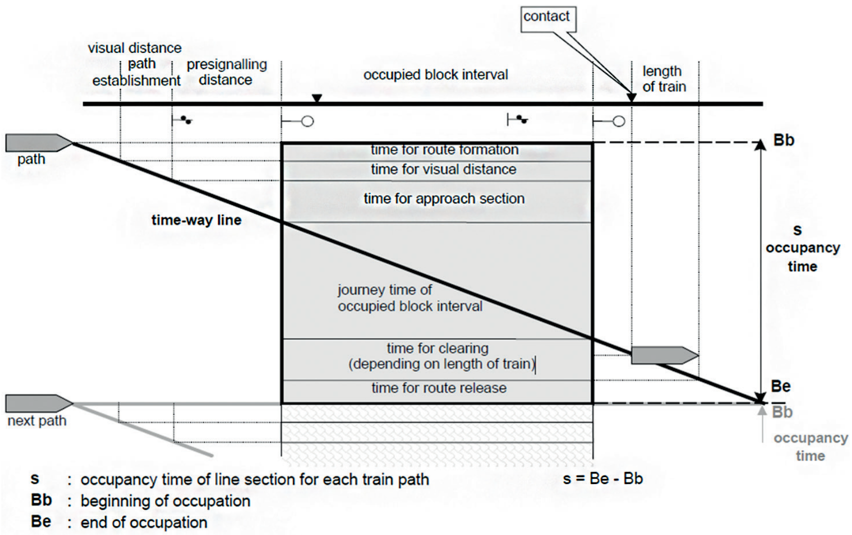

Figure 7: The way of determining the occupancy time of a line section
Source: UIC 2013

19 MÁV – Pályavasúti Főigazgatóság 2008a: 2.3.1.2.
20 UIC 2013.

The occupancy time (*s*) is the difference between the end of occupation (*Be*) and the beginning of occupation (*Bb*). Occupancy time is the total time needed for a train to pass the block section and contains the following:

- safety margin of time required before the train physically enters the block (which is made up by the time for route formation, time for visual distance and time for approach section), the time for route formation was taken as 0 in the calculations
- the time the head of the train passes the block (journey time of occupied block interval)
- time required for clearing the block (time for clearing)
- time required for switching of the signals to allow occupancy of the next train (time for route release), this was also taken to be 0 for the calculations

$$s = t_{\text{route formation}} + t_{\text{visual distance}} + t_{\text{block}} + t_{\text{clearing}} \quad (1)$$

The visual distance can be determined from the F.1. sz. Signalling Instruction of MÁV: "The main signals have to be placed so that their display should be seen from the locomotive or control car from a distance measured in metres equal to ten thirds of the line speed measured in km/h but at least from 200 m."[21] These values can be calculated from the previously mentioned line speed values available at the webpage of VPE Kft.

The capacity consumption can be calculated according to the UIC Code:

$$Capacity\ Consumption = \frac{Occupancy\ Time \times (1 + Additional\ Time\ Rate)}{Defined\ Time\ Period} \quad (2)$$

where the Capacity Consumption was set to 0.6 and the Additional Time Rate was taken to be 0.18 according to the proposal of UIC for mixed-traffic lines. The Defined Time Period was one day, 1,440 minutes.

From equations (1) and (2) *s* and the Capacity Consumption the number of trains (*N*) that can be sent through the line section in question for on track can be determined:

$$N = \frac{Capacity\ Consumption}{s} \quad (3)$$

For every main signal every possible combination of the two following line sections were determined and those were chosen for which the travel time is the smallest. Similarly, the visual distance was determined for every main signal from the values of the preceding line section(s) and using this and the maximal permitted train length the Occupancy Times were determined and from these the capacity *N* for one day could be calculated.

The possible extra time needed to pass the stations were not taken into account and the signals of the stations were treated as they were at open lines. Therefore, the calculated capacity values are an absolute supremum of the real value for the line section in question.

[21] MÁV – Pályavasúti Főigazgatóság 2008a: 1.2.31.

Traffic

The maximal traffic between every pair of border crossing was determined but with the restriction that the shortest path must always be used. For this, the following steps of calculation are used.

0. The flow on each line section is set to zero.

1. The shortest path (either in length or time) is determined between the two border crossing points;

2a. if the length or travel time on the shortest path is infinite, the cycle terminates

2b. if the length or travel time on the shortest path is finite, the maximal flow along this path is determined and its value is added to the flow of each line section on the path.

3. The value of the flow is subtracted from the capacity of the line sections along this path.

4. If the capacity of a line section has been reduced to zero, then its length or travel time is set to infinity, thus it will not be taken into account in the following determinations of the shortest paths.

5. Repeat from step 1.

The cycle was conducted for every pair of border crossing and the flow values of the line sections obtained in every case was summed. The calculation was carried out both in the case when all the capacities were of the values described in the previous section and in the case when the capacity of not electrified line sections was set to zero at the beginning of the calculations.

Results and discussion

The results of the calculation are discussed in the following section. The 29 border crossings are the following from the Budapest–Wien crossing in counter clockwise direction (the neighbouring country is noted in parentheses: Hegyeshalom (A), Fertőújlak határ (A), Sopron határ (A), Ágfalva határ (A), Harka (A), Szentgotthárd (A), Őriszentpéter (SLO), Murakeresztúr (HR), Gyékényes (HR), Magyarbóly (HR), Kelebia (SRB), Röszke (SRB), Lőkösháza (RO), Kötegyán (RO), Biharkeresztes (RO), Nyírábrány (RO), Ágerdőmajor (RO), Eperjeske (UA), Záhony (UA), Sátoraljaújhely (SK), Hidasnémeti (SK), Hídvégardó (SK), Bánréve (SK), Somoskőújfalu (SK), Ipolytarnóc (SK), Nógrádszakál (SK), Szob (SK), Komárom (SK) and Rajka (SK).

From these crossings the following 13 (which means less than half) are electrified: Hegyeshalom, Fertőújlak határ, Sopron határ, Harka, Őriszentpéter, Gyékényes, Kelebia, Lőkösháza, Biharkeresztes, Hidasnémeti, Szob, Komárom and Rajka.

Electrified line sections only

In Figure 8, one can see the results when traffic was only made possible on the electrified lines and the fastest path was chosen for every route. The calculations resulted in the same total traffic and mostly the same distribution of paths for the minimal path lengths so a map presenting these latter results is not shown here.

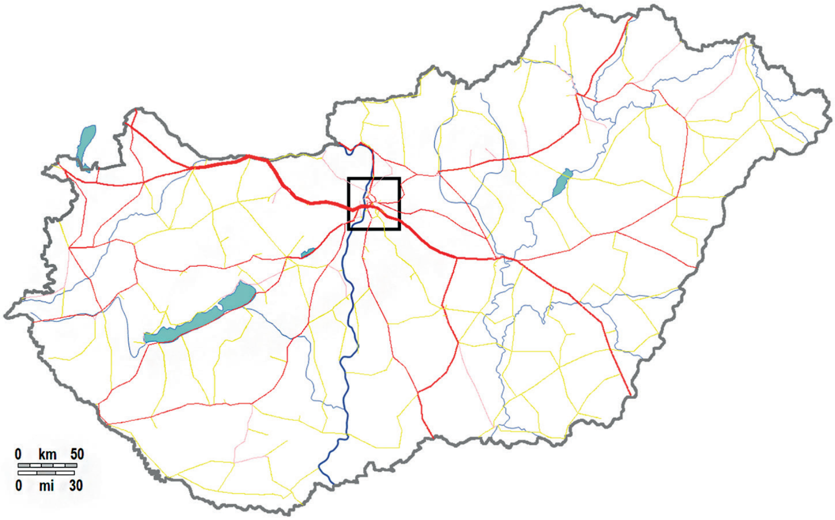

Figure 8: The maximal possible traffic on paths with minimal travel time between the border crossings for electric locomotives

Note: The thickness of the lines is proportional to the traffic on them. Red: electrified lines with traffic; pink: electrified lines with no traffic; yellow: unelectrified lines.

Source: Tóth 2019

The similarity of the distribution of the results for minimal path lengths and travel times is caused by the fact that electrified border crossings are mostly situated on the main lines of the network, which are not only the fastest but also the shortest paths in the network due to historical reasons.[22] Therefore, the paths with minimal travel time will not take a path that is longer in distance but faster. These lines are the most important ones in the network, most of them being part of the Trans-European Transport Network (TEN-T),[23] but this also makes international transport highly dependent on a small number of highly developed railway lines which in turn makes it vulnerable[24] having no realistic bypass routes in case of disruption.

As the border crossings at the northwestern part of Hungary are the most electrified but there are only a few electrified crossings in the direction of Serbia, Romania and Slovakia to the north, east and south, the traffic concentrates on the most prominent line in the west–east direction, line No. 1, especially its Budapest–Győr section. As the only electrified crossing on the river Danube is the Southern Railway Bridge at Budapest, all of the traffic crossing this river has to use this bridge which is, therefore, the bottleneck of the

[22] Tóth 2017.
[23] Szászi 2018.
[24] Szászi 2012.

international traffic.[25] The only solution to provide some redundancy[26] that can be utilised during disruptions[27] would be a new Danube bridge.[28]

The results highlight the core network of the Hungarian Railways but also highlight the "electric dead ends" of the network (plotted in pink in Figure 7). These are line No. 21 (Szombathely–Szentgotthárd) because the border crossing is not electrified; the southern part of line No. 40 (Dombóvár–Pécs) since the main purpose of this section is to serve Pécs, the most important city of the southwest; the southern section of line No. 140 (Kecskemét–Szeged) which has the same purpose: to provide fast railway connection to Szeged, the most important city of the southeast; and the northeastern parts of lines No. 100 and 80 which are both important main lines inland but do not have electrified connections abroad.

Every line section

In Figure 9, the results for the calculations when all line sections were allowed to be used, even the not electrified ones, can be seen. Here, the paths with minimal travel times are shown. Similarly to the previous case, the calculations resulted the same total traffic and mostly the same distribution of paths for the shortest paths so a map presenting these latter results is not shown here.

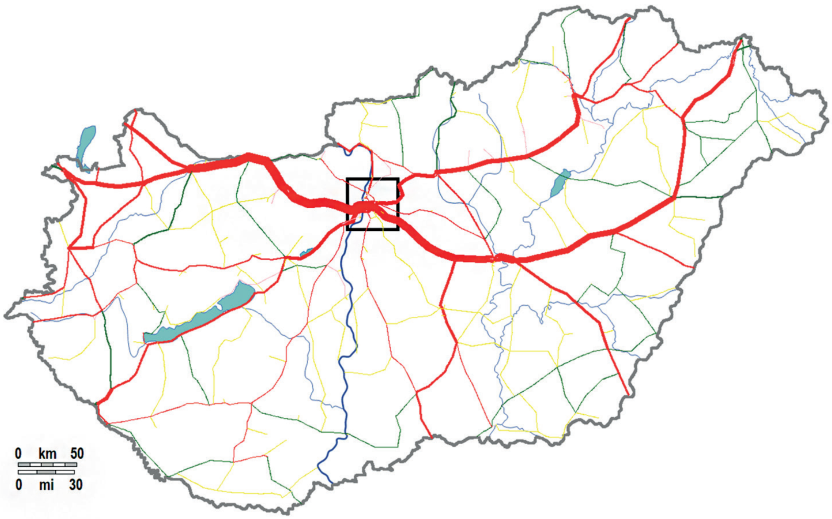

Figure 9: The maximal possible traffic on paths with minimal travel time between the border crossings
Note: The thickness of the lines is proportional to the traffic on them. Red: electrified lines with traffic; pink: electrified lines with no traffic; green: unelectrified lines with traffic; yellow: unelectrified lines with no traffic.
Source: Tóth 2019

[25] Szászi 2013.
[26] Tóth 2019.
[27] Tóth 2021.
[28] Tóth–Lévai 2021.

By allowing 27 instead of 13 border crossings to be used, the total summarised flow is tripled. If we make a rough estimate, the number of all possible paths are $n(n-1)/2$, where n is the number of border crossings. This value is 78 when $n = 13$ and when $n = 27$, $n(n-1)/2$ results in 351. Their ratio is 4.5 which should apply for the total traffic passing through them were their capacity (and of the connecting lines) the same. However, the results remarkably deviate from this ratio. This is fairly visible in Figure 8, too, as the unelectrified line sections (marked with green) are very thin showing the low flow value passing through them. This is due to the fact that their line speed is in general lower than the electrified line sections and also there are only a few short line sections with block sections which radically reduces their capacity.

Furthermore, there are much fewer unelectrified lines that actually take part in the traffic than electrified lines. This is because their line speed is lower and thus the paths prefer to reach a main line with higher line speed and continue there (as it will be proven in the next section). As the main lines still have free capacity, they can pass through most of this extra flow.

The most important unelectrified lines are the ones that are transverse (i.e. the ones that connect the radial lines which start from Budapest, at a significant distance away from the capital), making the radial main lines accessible from each other and have a relatively high line speed. Namely, these are Lines No. 17 (Zalaszentiván–Nagykanizsa), No. 10 (Celldömölk–Pápa–Győr), No. 108 (Füzesabony–Debrecen), No. 5 (Komárom–Székesfehérvár), No. 154 (Bátaszék–Baja–Kiskunhalas) and No. 135 (Szeged–Hódmezővásárhely–Békéscsaba). Line No. 108 could be especially important in providing connection between the two lines with the most traffic in the eastern region of the country.[29]

Similarly to the previous case, the Southern Railway Bridge is still a bottleneck as the two other Danube bridges, the Újpest Bridge and the Türr István Bridge at Baja in the south are not capable of handling much traffic due to their (and of the connecting lines) lower line speeds and the lack of block sections. The best solution, however, would be a double-tracked electrified transverse route, named V0 during its planning,[30] which would satisfy both the freight and military needs,[31] but final decision has still not been made about it.

The difference unelectrified lines make

If we subtract the traffic values obtained in the case when only the electrified lines were taken into account from the case when both the electrified and unelectrified lines were taken into account, the results seen in Figure 10 are obtained.

[29] Lévai 2020.
[30] Tóth–Horváth 2019.
[31] Somogyvári–Tóth 2023.

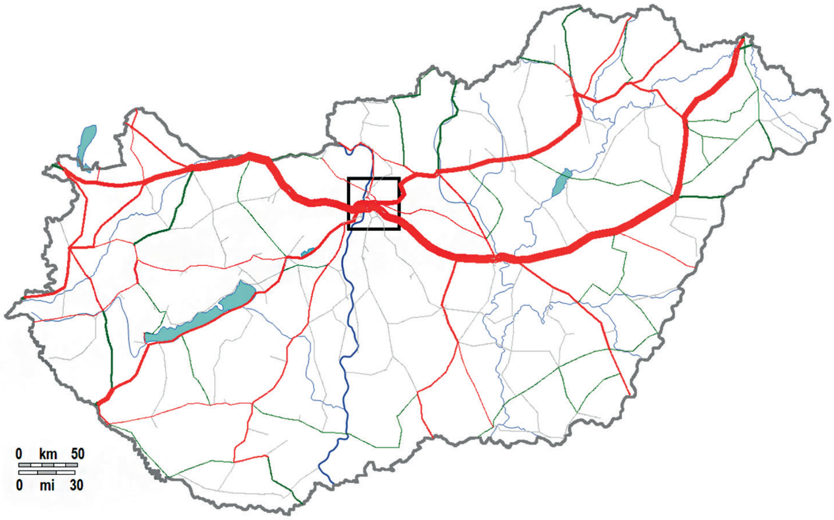

Figure 10: The change in traffic when the unelectrified lines are also taken into for minimal travel times between the border crossings

Note: The thickness of the lines is proportional to the traffic on them. Red: increase in the traffic for electrified lines; orange: decrease in the traffic for electrified lines; green: increase in the traffic for unelectrified lines.

Source: Tóth 2019.

The results show that the electrified lines handle most of the extra traffic in the network. The most increase is caused on a west–east direction. West of the Danube a continuous traffic flow appears on Lines No. 8 (Sopron–Győr), No. 1 (Győr–Budapest) but east to the Danube lines No. 100a/100 (Budapest–Szolnok–Debrecen–Nyíregyháza–Záhony) and No. 80 (Hatvan–Miskolc) jointly take the traffic. Plus a short line section on the southwest between Nagykanizsa and Murakeresztúr also shows a great increase.

The increase in the west–east direction comes from the fact that not the main railway lines but the border crossings make the traffic to saturate due to the capacity of the line sections connecting the border crossings to the main network.

The transverse unelectrified lines that have the most significant role in making these connections as their line speed is relatively high (and mostly have block sections) are practically the same as the unelectrified lines that were important in handling the traffic (seen in the previous section): Lines No. 10 (Győr–Celldömölk), No. 18 (Zalaszentiván–Nagykanizsa), No. 108.(Füzesabony–Debrecen). This means that these lines handle a significant amount of traffic arising from the inclusion of the unelectrified border crossings.

Conclusion

In this paper, the change in the maximal traffic between all pairs of international border crossings in the railway network of Hungary was presented using a graph model containing all the main signals in the network. For the calculations, the *igraph* package of the *R* programming language and environment was used. When only the electrified lines are taken into account, the traffic flows the main lines regardless of the fact that a minimal path length or a minimal travel time was prescribed. This means that the electrified main lines of the network provide not only the fastest but also the shortest route. When all border crossings were allowed to be passed, even the not electrified ones, only some transverse unelectrified lines gave significant contribution to conducting the flow. This means that only these are possible candidates for future development by electrification due to their geographical situation in the network.

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