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Quantitative Analysis of the Possible Sites of a New Danube Bridge to Bypass Budapest on Rail – Part 1[1]

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Since 1920, almost all the traffic on rail crossing the Danube in Hungary, crosses it in Budapest via the Southern Railway Bridge which makes it heavily overloaded. This is a very disadvantageous situation not only for commercial shipping but also for military uses as there is certain heavy military equipment that can only be transported via rail.

In our two-part article, we examine the locations of new bridges that could be alternatives to bypass Budapest and thus to reduce the traffic load on the railway lines of the capital. In this first part of our paper, we present the effect of a new Danube bridge as an alternative to the V0 railway line. We examine the possible sites of the bridge with several different route alternatives connecting it to the existing railway lines by using traffic simulation.

Keywords: *railway, bridge, graph theory, traffic, military engineering*

Introduction

The research priorities in military sciences and especially in military engineering,[4] are changing over time according to the international defence situation. Eight main research areas have been identified by a recent research, namely military theory and warfare, strategy and defence planning, Vision of the Hungarian Armed Forces, defence and good governance, country defence, HR and personnel work, international crisis management and peacekeeping, and military history, preservation of tradition and civil–military relations.[5] From these areas both country defence and defence planning are strongly related to the logistic capacities of the armed forces. A vital part of the logistic network of an army is the transportation sector. Both the railway and the road sector are mainly operated by the

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4 Haig 2016: 115–116.

5 Boda et al. 2016: 2–23.

civil sector and the armed forces own a relatively small part of the infrastructure as the national network is used for everyday civil transportation purposes.

Therefore, the defence preparations of a country requires the transport network to be available in sufficient quantity and quality to perform the necessary military movements and transportation tasks when needed. Therefore, during this defence preparation, the network elements on which the military transportation actions will take place, should be identified. These elements then must be properly maintained and protected to be ready for the transportation tasks at all times. After any damage, they must be rebuilt immediately so traffic can be picked up as soon as possible. This is not only the interest of Hungary but is also an allied obligation and one of the basic conditions for the feasibility of NATO's[6] Host Nation Support tasks.

But not only because of the military applications but also because of the everyday freight traffic share of the railway should the network be developed. The share of rail in the freight traffic of the country in 2021 was 16.48% of the total weight of goods transported, which is 22.04% of freight tonne-kilometres.[7] One-sixth of goods therefore reach their destination by rail, which is quite a small proportion compared to the 55% level in 1985,[8] despite the aim of maintaining the share of rail transport at a higher level than in Western Europe.[9] Furthermore, there is a political will in the European Union (EU) to shift freight traffic from road to rail as much as possible, not only for reasons of economy but also because railway transport is much more environmental friendly due to its lower emissions and lower noise pollution.[10]

One of the critical points in the railway network of Hungary is the crossing of the Danube.[11] The railway infrastructure of the capital is already congested due to the significant passenger traffic, and the additional train paths booked for freight trains reduce the free capacity of the railway tracks further. The overloaded infrastructure raises questions about the solvability of security tasks. This is primarily a question of the feasibility of military rail transportation tasks.[12]

In our two-part article, we examine the locations of new bridges that could be alternatives to bypass Budapest and thus to reduce the traffic load on the railway lines of the capital. In the first part of our paper, we present the effect of a new Danube bridge as an alternative to the V0 railway line. In the second part, we examine the situation on the river Tisza and suggest a combined way of development to treat the capacity changes in the context of the whole network.

6 NATO – North Atlantic Treaty Organization.
7 For more information see www.ksh.hu/stadat_files/sza/hu/sza0002.html
8 Szászi 2010: 101–118.
9 Szászi 2007: 32–59.
10 Berényi–Lévai 2020.
11 Horváth 2006: 321–336.
12 Szászi 2013b: 98–107.

PART 1

The railway infrastructure of Hungary

The density of the railway network of Hungary is relatively high. Its 7,441 km total length[13] means 8.00 km/100 km^2 density which is the sixth highest in the world after Switzerland (12.63), the Czech Republic (12.12), Belgium (11.72), Germany (10.75) and Luxembourg (10.48).[14] However, other parameters are not that good, for example the ratio of electrified lines is only 37.7% and the ratio of double-tracked lines is only 16.6%.[15]

When the border was drawn after World War I, on the Subotica – Timișoara – Arad – Oradea – Satu Mare – Korolevo – Chop – Košice – Rožňava – Lučenec line, i.e. within the railway ring of the Kingdom of Hungary built at the end of the 19th century, the railway network of the remaining part of Hungary became transversally blocked. The remaining connections between the radial main lines were single-tracked lines with low capacity and therefore could not be used as real alternatives in case of disruptions of the main lines. The only connection point was Budapest and still is today.

Bottlenecks

After the Treaty of Trianon, only three railway bridges remained in the country. The northernmost was the Újpest Railway Bridge, a single-tracked bridge in the northern part of Budapest. The second, also in Budapest, was the Southern Railway Bridge, a double-tracked crossing. The third was the Türr István Bridge at Baja, 144 km south of Budapest, a single-tracked bridge. To date, these are still the only bridges that provide the possibility of crossing the Danube within Hungary. In the meantime, the Újpest bridge and Southern bridge were electrified, but the railway line that connects the line of the Újpest bridge back to the core network was not, therefore in the view of electrification, it lies on a branch line. A third track of the Southern bridge is currently being built, but this does not solve the substitutability of this bridge.

There is one more railway bridge that connects Komárom in Hungary with Komárno in Slovakia, but it is also a border crossing. This bridge cannot be taken into account in the defence preparations.

Therefore, one of the most neuralgic points of the Hungarian railway infrastructure is the crossing of Budapest. This means two things: passing through the capital and crossing the Danube. The east–west railway lines run long in the city, causing much noise pollution for the residents. International freight trains crossing the Danube in Hungary pass almost exclusively over the Southern Railway Bridge, which is also located in the capital, on the southern edge of the city centre. The problem is most pronounced in the congestion of the

[13] For more information see www.ksh.hu/stadat_files/sza/hu/sza0041.html

[14] Further details at https://w3.unece.org/PXWeb/en/PDFCountryProfiles

[15] See www.mavcsoport.hu/mav/bemutatkozas

Ferencváros–Kelenföld line section, which includes the bridge and as a result, the bridge is on the edge of its capacity.[16]

It is therefore necessary to ensure the possibility of providing an alternative route for the Southern bridge as a critical infrastructure element in case of its disruption (which can also mean the disruption of the Ferencváros–Kelenföld line section that contains it). In the current network, due to the previously described state of the two remaining bridges, neither the Újpest nor the Baja bridge is an alternative to the Southern bridge.

The distance between Budapest and Almásfüzitő via the Újpest bridge is only 8 km longer than the route leading through the Southern bridge, however, it does not provide a direct connection to Kelenföld on the right bank of the Danube. The trains have to pass through the hilly and partly single-tracked Budapest–Esztergom line and the single-tracked Esztergom–Almásfüzitő line which is not electrified, and this causes a significant increase in the travel time. In addition, the capacity of the lines is insufficient to handle the traffic of the Southern bridge. The Baja Bridge is located 144 km south of the Southern bridge, so the length of the route bypassing Budapest would increase so much that it makes this bridge an unrealistic alternative.[17] The Baja bridge is also located on a single-track, non-electrified line, which further increases the travel time and reduces its capacity.

The railway infrastructure of Budapest

Budapest is the most important railway junction in the country. The railway lines to and through the city are used by tens of thousands of people a day, and the freight traffic passing through them also means tens of thousands of tons of goods a day. Most of the railway lines were built in their present form by the beginning of the 20th century, which means that the structure of the network reflects the conditions of the beginning of the last century as it was designed to satisfy the needs of that time (passenger and freight, too). A significant part of the railway developments was and is still carried out on lines outside of Budapest, therefore the railway network of the capital has now become a barrier rather than a facilitator of the spread of modern modes of transport. The capacity of the system did not change over time as no capacity-enhancing developments were implemented and thus Budapest became a bottleneck in the railway network of Hungary.

Budapest is the starting point of 11 main national railway lines and three suburban railway lines (HÉV), which, though operated by the same corporation, uses different voltage system and therefore is not compatible with the railway network. One HÉV line, the one that connects the district of Csepel, runs entirely within the city. The main railway lines start from three main termini, Keleti pályaudvar, Nyugati pályaudvar and Déli pályaudvar (literally, Eastern, Western and Southern Railway Station) but the lines of local interest also start from two different terminals, Kőbánya-Kispest and Rákospalota-Újpest.

A significant part of the railway infrastructure of Budapest is composed of the elements of the so-called Circular Railroad (Figure 1). These are the line network

16 Lévai 2020: 198–223.
17 Szászi 2014: 25–48.

elements that make the connection between each radial line inside the city. The most important element is the Outer Circular Railroad, the railway line between Kőbánya-Felső–Rákos and Rákosrendező–Rákospalota-Újpest stations, which connects railway lines No. 1 (Budapest–Hegyeshalom), 80 (Budapest–Hatvan–Miskolc–Nyíregyháza), 120 (Budapest–Újszász–Szolnok–Békéscsaba–Lőkösháza) and 150 (Budapest–Kelebia) with lines No. 2 (Budapest–Esztergom) and 70 (Budapest–Vác–Szob), thus allowing the north–south passage through the city without entering a terminal station. The significance of the Outer Circular Railroad is shown by the fact that it was built as a double-tracked line, it is electrified and is equipped with automatic block signalling (ABS). At the same time, one of the most important sections, the Angyalföld junction and Rákospalota-Újpest section is only single-tracked and is in poor condition. Between Angyalföld junction and Rákosrendező station, the line speed is only 40 km/h. Though this section provides the north–south connection, its limited capacity significantly reduces the capacity of the entire network. In addition, the so-called "Marchegg Bridge" over lines 70 and 71 (Budapest–Vácrátót–Vác) that connects the Outer Railroad Circular with Angyalföld station and thus with lines No. 2 and 4 (Esztergom–Almásfüzitő), is electrified, but single-tracked.

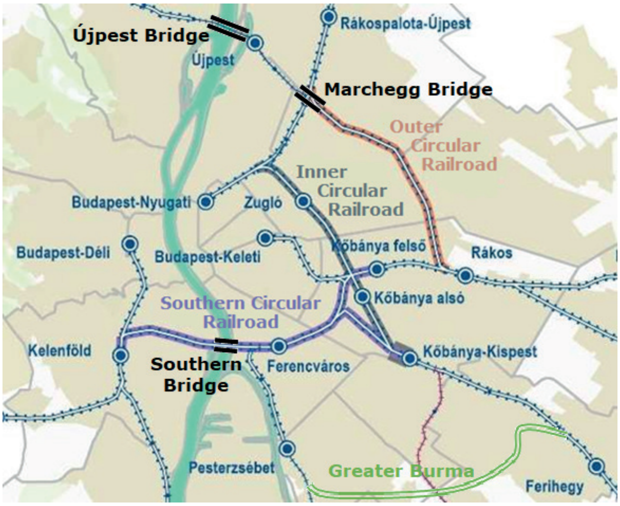

Figure 1: Elements of the Budapest Circular Railroad

Source: Compiled by the authors based on BRNS 2019.

The Inner Circular Railroad is the line Városliget junction – Kőbánya-Teher – Kőbánya-Kispest, which coincides the Budapest section of line No. 100 (Budapest–Cegléd–Szolnok–Debrecen–Nyíregyháza–Záhony).

The third significant section of the Circular Railroad is the Southern Circular Railroad, the Kőbánya-Kispest – Kőbánya felső – Ferencváros – Kelenföld line, which is also double-tracked, electrified and equipped with ABS. This line provides the east–west connection without the need of entering a terminus.

One peculiar element of the Circular Railroad is a short section, a wye, the so-called Királyvágány (literally, "King's track"), which connects the stations Kőbánya felső and

Kőbánya-Teher and thus provides a direct connection between lines No. 80, 120, 100 and 70. Its length is 1.3 km, it is single-tracked, electrified with a line speed of 30 km/h. Its name originates from the person to whom it was specifically built for: Franz Joseph I, emperor of Austria and king of Hungary. By using this wye, the royal train from Nyugati Railway Station could easily turn in the direction of Gödöllő, where the royal summer palace was situated. The track is rarely used but if developed to two tracks with much higher line speed it could have a role in substituting the Outer Circular Railroad.

The so-called Greater Burma line can also be considered part of the Circular Railroad (the Lesser Burma line that connected Ferencváros and Soroksár stations was completely dismantled in 2006). The Greater Burma was once double-tracked, but today it is only single-tracked. It connects Soroksár station on line No. 150 with Pestszentimre station on line No. 142 (Budapest–Lajosmizse–Kecskemét) and Szemeretelep station on line No. 100. The line is out of operation, it was last used in 2001, during the reconstruction of line No. 150 as a bypass route between Soroksár and Pestszentimre.[18] Its condition has significantly deteriorated since, the speed limit is currently 0 km/h. The other part of the line between stations Pestszentimre and Szemeretelep is no longer intact, the tracks are missing in several places.

Brownfield developments

The basic thought behind the studies to be presented is to analyse sites where there are railway lines on both banks of the Danube. Thus, only the most necessary construction costs have to be taken into account as only the building of the bridge is a greenfield development, the connecting railway lines already have the infrastructure which reduces the costs being a brownfield development.[19]

Each path was analysed using a mathematical model and we looked for the alternative with the best properties. These properties included the traffic passing through the new bridge in normal operating circumstances,[20] the ratio with which they can decrease the traffic passing through Budapest and the redundancy they provide in case of disruption of other bridges.

Our study covers several possible sites and route variants. Of course, it is necessary to build new network elements for all variants, but since we are basically looking for brownfield solutions, they always mean significantly less greenfield investment than the construction of a fully greenfield V0.[21]

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[18] Kristóf–Lévai 2002: 3–6.
[19] Lakatos et al. 2016: 181–288.
[20] Tóth 2018: 505–519.
[21] Tóth–Horváth 2019: 109–129.

The graph model of the railway network of Hungary

The mathematical model used for the calculations has been presented in detail earlier, so we will only discuss it here as much as it is necessary for understanding.[22]

A weighted directed graph is used to model the railway network of Hungary. The nodes of the graph corresponds to stations where a change in the direction is possible. The sidings of the Hungarian Army were also included.[23] Stops with no switches were not included in the model. Also, the stations with exactly two neighbouring stations, the so-called joint nodes, were transformed out: each joint node and its two connecting edges were substituted with a single edge with a weight of the sum of the two edges replaced.[24]

The edges of the graph represented the line sections between these stations. Two weights were assigned to an edge: to calculate the shortest path, the length of the corresponding line section, and to determine the fastest path, the ratio of the length of the line sections and the line speed. The latter is the pure travel time, which gives the lowest limit a path could be run within, as it does not take into account any speed limit or acceleration/deceleration time. If the value of the line speed was lower for trains with locomotives than for ECMs, then the former, the lower value was used. The data used is publicly available on the website of the Hungarian Rail Capacity Allocation Office (Vasúti Pályakapacitás-elosztó Kft.).[25]

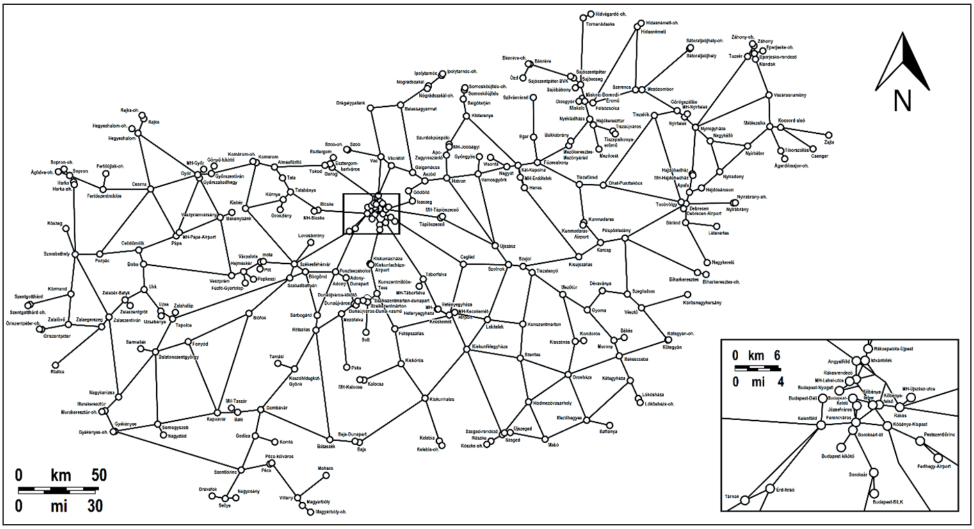

Figure 2: Diagram of the graph modelling the railway network of Hungary

Source: Compiled by the authors.

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22 Tóth 2021: 567–587.

23 Government Decree 277/2014 (XI.14.) on the Amount of Fine the Railway Authority Can Issue and Detailed Rules of Its Payment, 2nd Appendix.

24 Jenelius et al. 2006: 537–560.

25 See www.vpe.hu/takt/vonal_lista.php

For locomotive reversal and direction change, 15 extra minutes were to be added. Therefore, the graph describing the network had to be expanded in order for the algorithm calculating the shortest path to add the extra time of direction changes when needed. No extra trip length or travel time was assigned to passing a station and no extra distance was assigned to reversing. The diagram of the graph is shown in Figure 2.

Methods and measures

In some cases, it is better to choose the length of the path of a train to be minimal, and in other cases the travel time to be as short as possible. The former is one of the main aspects of commercial rail transport, as both transport charges and overhead line charges are kilometre-based, and locomotives are often rented for a fixed amount per working day. However, in case of a state of emergency, time can be a quite important aspect and in many cases, the shortest route may not be the fastest.

The calculations and the visualisation of the results were performed in the R programming language and environment[26] using the *igraph* package[27] developed by Gábor Csárdi and Tamás Nepusz. The graph describing the network is encoded as a two-column matrix, a so-called edge list.[28] Each line describes a line section, the first number being the index of the origin and the second the number of the destination station of the line section. For each edge, a weight can also be assigned, using a vector with a dimension equal to the number of edges, which in our case was either the distance between the nodes representing neighbouring stations or the corresponding travel time. The shortest distance (in distance or time) between any two stations can be determined by the *distance()* function of the *igraph* package, which uses Dijkstra's algorithm[29] in graphs with positive weights (such as the one we use) by default. The function *shortest_paths()* can be used to determine which edges and nodes fall on the shortest path.

The possible locations of the new Danube bridge

In the following, from north to south in Hungary, we examine the possible locations of the new Danube bridge. For each alternative, we present the exact route, the spatial distribution of the routes passing through the bridge (i.e. which regions of the country does the bridge connect on the shortest path), the effect of the bridge on the change of the traffic of each line section in the network, and how does the traffic pass through the other bridges in light of the existence of the new one.

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[26] R Core Team s. a.
[27] Csárdi–Nepusz 2006: 1–9.
[28] Tóth 2017: 52–66.
[29] Dijkstra 1959: 269–271.

Szob–Esztergom

The northernmost possible location to build the crossing is at Szob. According to our model, the track leading to the bridge branches off from Szob station and reaches the Danube with a 90-degree leftward curve. After the bridge, it immediately enters a 7 km long tunnel and at the end of it the line connects to line No. 2 (Budapest–Esztergom) at Esztergom-Kertváros (Figure 3).

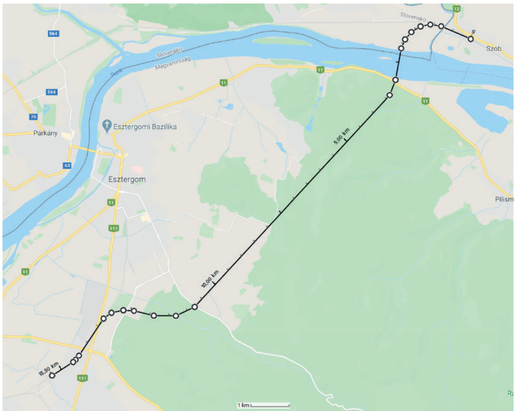

Figure 3: The Szob–Esztergom bridge and planned railway line

Source: *maps.google.hu*

As Szob is a border station, after the Ipoly bridge, the tracks run already in Slovakia. As the left bank of the Danube is highly built-in in this region, a branching before Szob could only be solved with an even larger amount of earthworks. The issue of ownership of the northern bridgehead therefore requires an interstate solution, but several alternatives are conceivable. The most obvious solution is similar to the Losonc–Kalonda–Nagykürtös line, which is part of the Aszód–Balassagyarmat–Ipolytarnóc railway line and the Slovakian railway infrastructure manager, ŽSR, uses it as a passage line. The same model could be applied at Szob as well: the 1.5 km section to the Danube bridge after the Ipoly Bridge in Slovakia could be operated as a passage line. However, it should be emphasised that this line section would not have a connection to the Slovak railway network, although the line itself would branch off from the main line in Slovakia.

Furthermore, it is the most expensive alternative. Due to the built-in, the line should immediately enter the 7 km long tunnel at the southern bridgehead all the way to Esztergom Diósvölgy, from where it would be connected to line No. 2 at Esztergom-Kertváros.

Dunaföldvár–Solt

The 13 km long single-tracked, non-electrified Solt–Dunaföldvár railway line, which is numbered 151a, was finished in 1940. The bridge over Dunaföldvár, through which it crossed the river, was originally designed exclusively for road traffic and the tracks were built in only during the construction of the railway line when it was converted into a common crossing. The bridge would have played a role in replacing the railway ring road outside the country borders mentioned earlier, as line No. 151a was intended to be part of an "internal railway ring". The line would have continued from Solt to Fülöpszállás (the sectioning of the line also started at Fülöpszállás station); but the latter section was never built.

We examined 6 alternatives at the Dunaföldvár bridge. Alternatives 1–3 took into account the Solt–Dunaföldvár section with the original route and only a higher line speed (120 km/h) was assumed for the existing lines. Alternatives 4–6 took into account the planned Fülöpszállás–Solt line section with the same line speed, too (Figure 4).

Alternatives 1, 2 and 3

In case of the first three alternatives, only the existence of the Dunaföldvár–Solt line section including the bridge was assumed with the same length as it was at the time of its closure (13 km). Alternative 1 takes into account line No. 151a only with 60 km/h line speed. Alternative 2 further supposes the line speed of lines No. 42 (Pusztaszabolcs–Mezőfalva–Dunaföldvár–Paks), 43 (Mezőfalva–Rétszilas) and 151 (Kunszentmiklós-Tass–Solt) to be 120 km/h. In addition to these, Alternative 3 also takes into account railway line No. 150 (Budapest–Kelebia) with a line speed of 120 km/h (Figure 4).

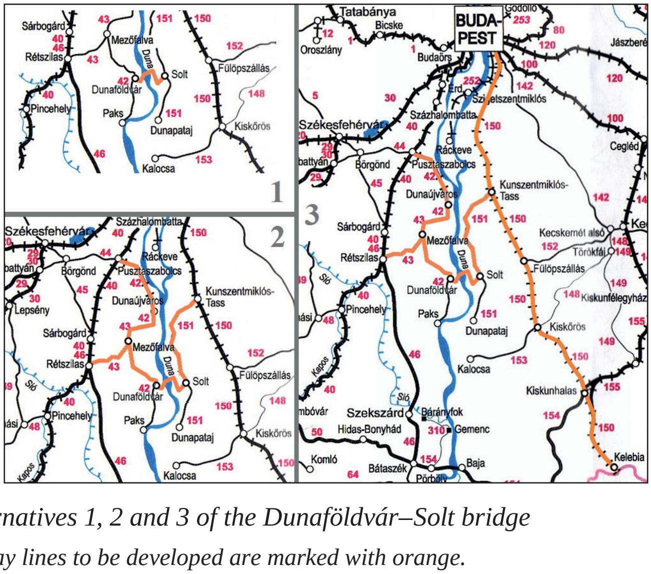

Figure 4: Alternatives 1, 2 and 3 of the Dunaföldvár–Solt bridge

Note: The railway lines to be developed are marked with orange.

Source: Compiled by the authors based on www.logsped.hu/vasutterkep.htm

Alternatives 4, 5 and 6

Alternatives 4, 5 and 6 assume that line No. 5 (Székesfehérvár–Komárom), 44 (Pusztaszabolcs–Székesfehérvár), 42, 150 and 152 (Fülöpszállás–Kecskemét) have a line speed of 120 km/h. This is considered to be sufficient to lead the traffic to the bridge that replaces the Southern railway bridge in case of its disruption. As currently lines No. 1, 80, 100 and 120, which are all radial lines connecting Budapest and the country border, are the most busy in the country, in case of the damage of the Southern bridge, which is their connection point, it is necessary to have transverse lines that lead to the bypass bridge that has about the same throughput.

The infrastructure to be built as a greenfield development is only the tracks from the southeastern end of Dunaföldvár station to line No. 150. The wyes both in the northern and the southern directions at Fülöpszállás are assumed to have the same 120 km/h line speed. The connection between lines No. 42 and 44, between Zichyújfalu and Adony over line No. 40 (Budapest–Pusztaszabolcs–Pécs) was also treated in the model with 120 km/h line speed (Figure 5).

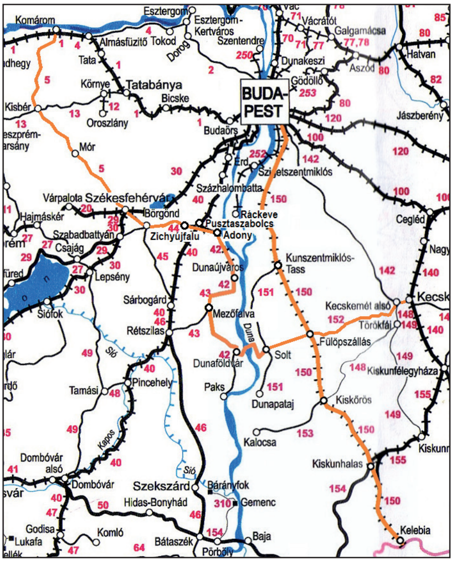

Figure 5: Alternatives 4, 5 and 6 of the Dunaföldvár–Solt bridge

Note: The railway lines to be developed are marked with orange.

Source: Compiled by authors based on www.logsped.hu/vasutterkep.htm

Alternative 4 (Figure 6) follows the original route of line No. 151a from Dunaföldvár station in the immediate vicinity of the currently existing bridge structure, then turns south and then turns back to reach Solt station from the south then it branches east from line No. 151 to approach line No. 150. Due to the narrow curves, the line speed is 80 km/h for the Dunaföldvár–Solt section.

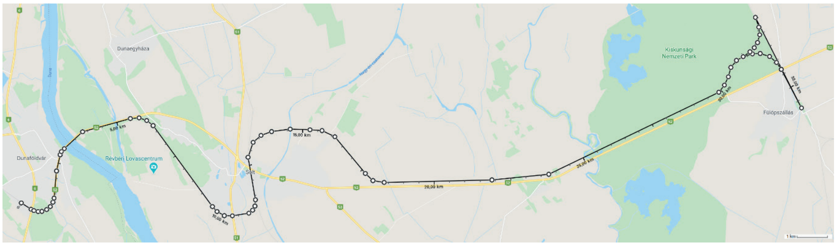

Figure 6: Alternative 4 of the Dunaföldvár–Solt bridge and planned railway line

Source: maps.google.hu

Alternative 5 (Figure 7) also crosses the Danube at the current bridge structure, but contrary to Alternative 4, it bypasses Solt from the north and then follows Road 52 on the same route as Alternative 4 until line No. 150. Due to the route, the crossing of line No. 151 can only be implemented as a separate level crossing, and Solt station can only be reached from the direction of Fülöpszállás, with a maximum speed of 80 km/h. There is a short curved section with 80 km/h line speed immediately after Dunaföldvár station, but the line speed is 120 km/h in the rest of the line.

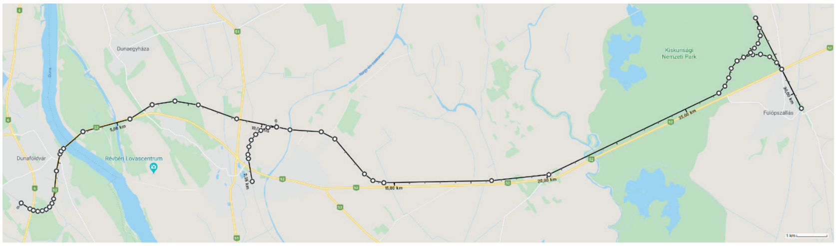

Figure 7: Alternative 5 of the Dunaföldvár–Solt bridge and planned railway line

Source: maps.google.hu

Alternative 6 (Figure 8) follows a completely different route: here, road and rail bridges would be spatially separated. As a result, the line speed may be 120 km/h along the totally new line No. 151a, as there is no need for narrow curves. The line bypasses Solt from the south and provides a connection from the direction of Fülöpszállás to the line No. 151, which curve, however, can only be built with a line speed of 60 km/h due to the built-in vicinity of the branching.

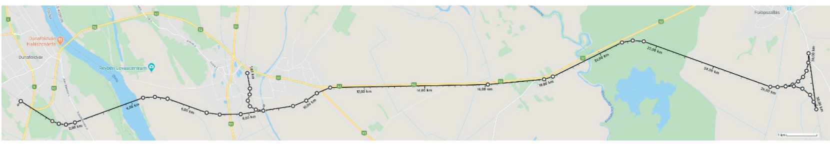

Figure 8: Alternative 6 of the Dunaföldvár–Solt bridge and planned railway line

Source: maps.google.hu

Dunaújváros–Szalkszentmárton

The Dunaújváros bridge would be built at the former crossing between the bridgeheads of the former TS floating bridge.[30] The newly built tracks branch off at Rácalmás from line No. 42 and run along the embankment to Szalki Island to the bridgehead of the TS floating bridge, with a curve of 60 km/h line speed. After the Szalkszentmárton bridgehead, it follows the existing embankment, but unlike the current line, it bypasses the village of Szalkszentmárton from the north (Figure 9).

Two alternatives were examined. In both, the new line sections and the existing lines No. 42, 44, 5 and 150 have a line speed of 120 km/h, and the separate level connection between Adony and Zichyújfalu was also taken into account. In Alternative 1, the Greater Burma line in Budapest is assumed to be rebuilt with 120 km/h line speed, and in Alternative 2, line No. 152 is assumed to be developed to 120 km/h line speed (Figure 8).

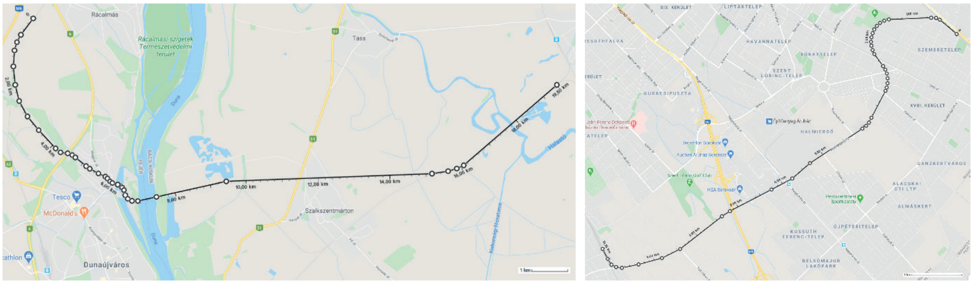

Figure 9: The Dunaföldvár–Solt bridge and planned railway line (left) and the Greater Burma railway (right)

Source: maps.google.hu

Paks–Kalocsa

The bridge between Paks and Kalocsa would be established as a completely new crossing between two railway lines on the two banks of the Danube. As the Paks Nuclear Power Plant regularly uses line No. 42, it is in relatively good condition. The route is the continuation of line No. 42 from Paks and it connects into the endpoint of line No. 153 (Kiskőrös–Kalocsa) at Kalocsa. More precisely, it runs on the path of the industrial tracks of Foktő.

The nuclear power plant should be bypassed from the west while maintaining an adequate safety distance, so the line runs along Highway No. 6. The crossing of the northern entrance of the nuclear power plant cannot be planned as a level crossing, so after the endpoint of Paks station, the lowering of the tracks must be started immediately so that the railway can be taken to a depth of 5 m during this 2–2.5 km long section, which means a 2–2.5‰ fall. Bypassing the nuclear power plant and the planned location of Paks II from the south, it crosses the Danube north of Foktő, then the line runs along the embankment

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30 Szászi 2013a: 101.

of the vegetable oil factory to Kalocsa station. This means a total of 18.9 km of new tracks (Figure 10).

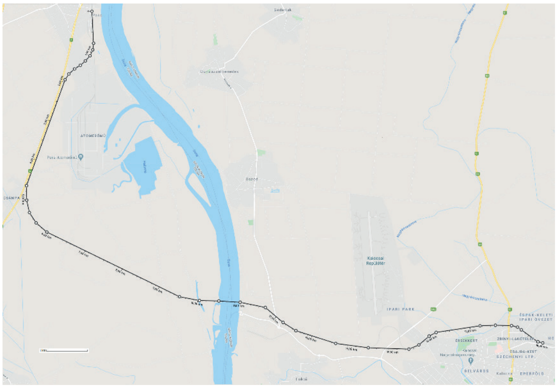


Figure 10: The Paks–Kalocsa bridge and planned railway line

Source: maps.google.hu

We examined two alternatives here, too. Both include the new track with a line speed of 120 km/h for lines No. 42, 44, 5, 150 and 153 and the Adony–Zichyújfalu connection, too.

In addition, in case of Alternative 1, the line speed of line No. 152 was assumed to be 120 km/h while in case of Alternative 2, a wye at the junction of lines No. 150 and 153 was inserted in the direction of Kiskunhalas to make line No. 155 (Kiskunahalas–Kiskunfélegyháza) accessible without a change in the direction.

Results

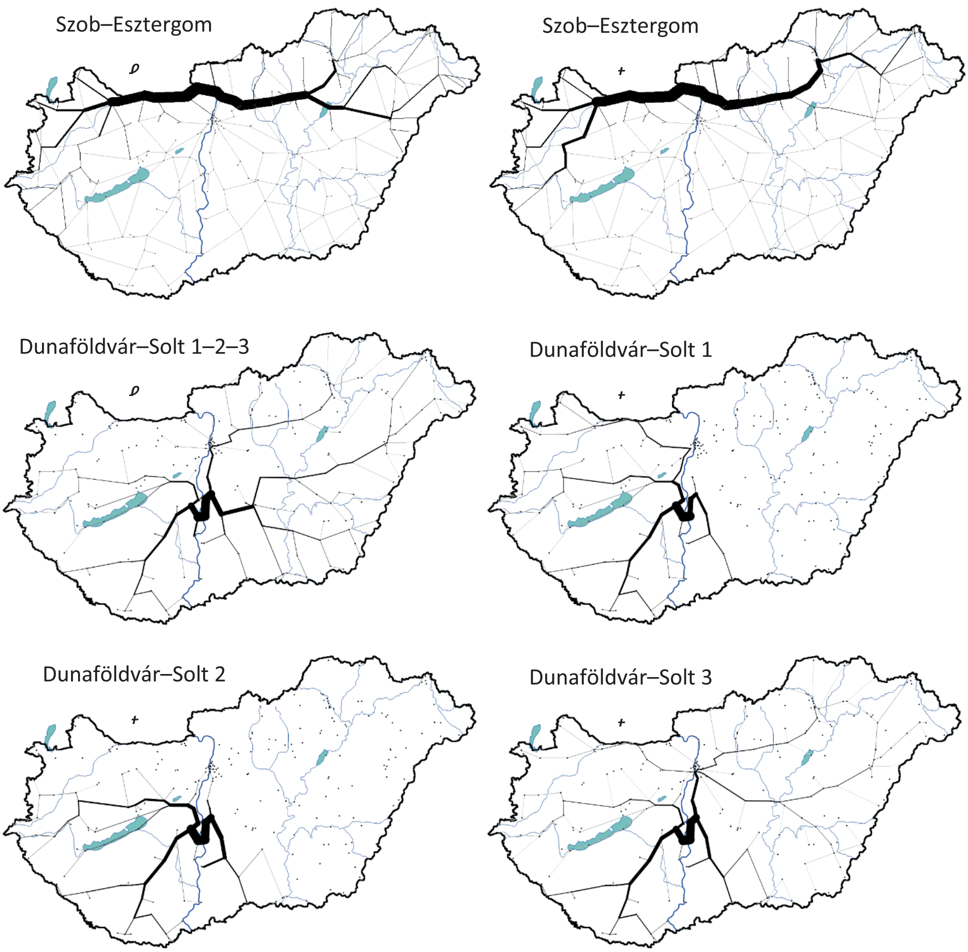
Determining the minimal distance and minimum travel time between all pairs of stations and selecting the ones that cross the new bridge we get the plot in Figure 11.

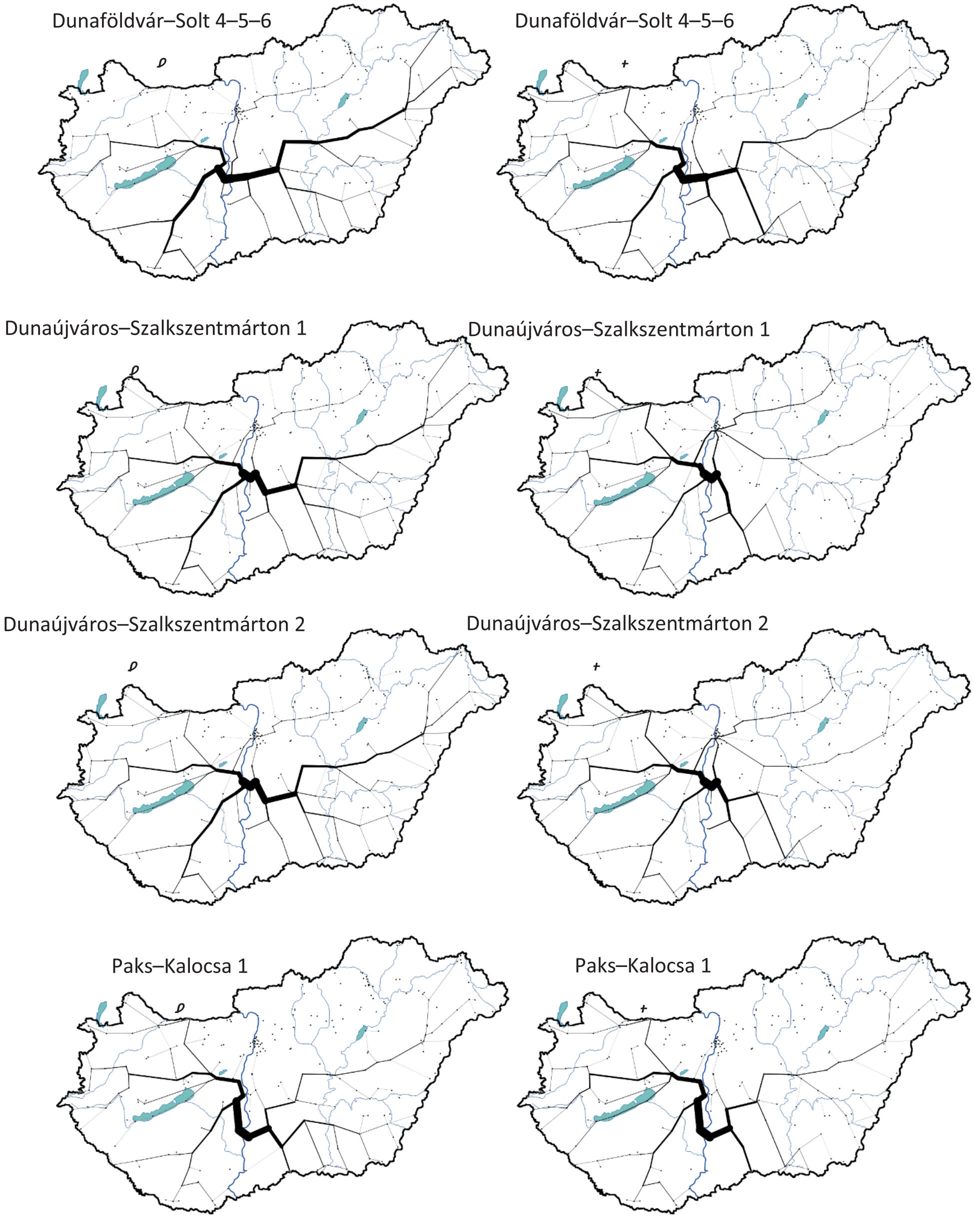
We can see that the Szob–Esztergom bridge (due to its location) only carries traffic between the northeastern and northwestern parts of the country, the paths that have their origin or destination more to the south still mostly use the Southern Railway Bridge for both minimum path length and minimal travel time.

The Dunaföldvár–Solt bridge is extensively used by almost all paths that run on the main lines to cross the Danube. However, in case of Alternatives 1, 2 and 3, it appears that the traffic on line No. 150 is high in case of a minimum path length, while, in case of minimal travel times, due to the low line speed, they run on line No. 150 even when the line speed is not increased. This situation changes fundamentally for Alternatives 4, 5 and 6, as these routes become optimal even for minimal travel times. In this case, line No. 5 also connects significant directions, because then it is better to travel in this direction than through Kelenföld station where a change of direction is necessary. However, partly because of this, there are only a few routes from the northeastern part of the country as they use mostly the Southern bridge.

The Dunaújváros–Szalkszentmárton bridge is the one that essentially serves the whole country, as routes pass through it from all regions of Hungary. In case of the two alternatives, the geographical distribution of the paths are practically the same, except for the calculation taking into account the travel due to the effect of lines No. 152 and the Greater Burma line.

The Paks–Kalocsa bridge, being the southernmost crossing, is used by routes connecting the southern regions of the country. However, the calculations show that even some paths from Hegyeshalom and Záhony, the northwestern and northeastern "gates" of Hungary use it, which indicates that even this bridge can be a real alternative to the Southern Railway Bridge. The reason for this is the higher line speed of the connecting lines through which the new bridge can be reached quickly.




Dunaföldvár–Solt 4–5–6
Dunaföldvár–Solt 4–5–6
Dunaújváros–Szalkszentmárton 1
Dunaújváros–Szalkszentmárton 1
Dunaújváros–Szalkszentmárton 2
Dunaújváros–Szalkszentmárton 2
Paks–Kalocsa 1
Paks–Kalocsa 1

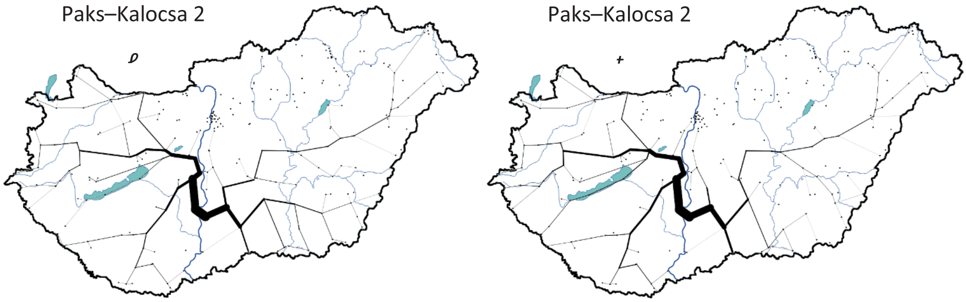


Figure 11: The geographical distribution of the paths passing through each new Danube bridge alternative for minimal path lengths (left column) and minimal travel times (right column)

Note: The thickness of the lines is proportional to the number of paths. The number of paths passing through the new bridge is taken to be 100%.

Source: Compiled by the authors.

However, examining the number of paths passing through the new bridge in each alternative the picture becomes different (Table 1): only 1.5% of all paths pass through the Paks–Kalocsa bridge in both alternatives, which is a very small ratio. It means that only those paths choose this crossing that connect the stations in the immediate vicinity of the bridge with the more remote regions of the country on the opposite bank of the Danube.

For Alternatives 4, 5 and 6 of the Dunaföldvár–Solt bridge and of the Dunaújváros–Szalkszentmárton bridge, 5.5% of all train paths pass through them in case of minimal travel times. What seems surprising at first is the case of Alternative 3 of the Dunaföldvár–Solt bridge, as its traffic is almost 8%. The reason for this is to be found in the increase in the line speeds of the connecting lines: as long as the line speed of lines No. 150, 44 and 5 are unchanged, the paths prefer to use the Dunaföldvár bridge to avoid the slow line No. 150 in approaching Budapest. But as soon as it is possible to travel faster on these lines, the Southern Railway Bridge becomes preferred again. In case of the Dunaújváros–Szalkszentmárton bridge, the connecting lines were already taken into account at a higher speed, which means that in terms of traffic, this bridge is essentially the same as the Dunaföldvár–Solt bridge, regardless of its more northern location.

At the same time, 8.5% of all paths pass through the Szob–Esztergom bridge. This means that though it provides faster and shorter connection only between the northern parts of the country, it could play a key role in rerouting the northwestern–northeastern traffic and could have the role that the Újpest railway bridge and the connecting lines lack as a northern bypass route.

The bridges of Dunaújváros–Szalkszentmárton and Dunaföldvár–Solt play a similarly significant role in rerouting the traffic of the Southern Railway Bridge. In case of Alternative 2 of the Dunaújváros–Szalkszentmárton bridge, in case of minimal travel times, the traffic of the Southern bridge at Budapest would decrease by 9% and by 19% in case of minimal path lengths. In cases of Alternatives 4–6 of the Dunaföldvár–Solt bridge, these numbers become 11 and 19%, respectively. This means that only half of the shortest routes would be faster using this bridge than the Southern bridge in Budapest, i.e. the significant increase in the path length can only be partially compensated by the increase in the line speed.

The Szob–Esztergom bridge shows another behaviour: paths with minimal length cause a 7%, while paths with minimal travel time cause a 17% in the traffic of the Southern Railway Bridge. 60% of the paths that are faster via this bridge, are longer in kilometres, which means that the development of the connecting lines causes significant decrease in the travel times while similarly make the paths to bypass Budapest.

So far, however, the short and long, and slow and fast routes have been treated equally. But making short and slow routes faster is not as significant for the network as a whole, as it would be to achieve a reduction in travel times in all routes of a region connected only by slow paths. To measure this property, we calculate the decrease in the presence and absence of the new Danube bridge by summing the length or the travel time of all the shortest paths between all pairs of stations.

As the results show, both alternatives of the Dunaújváros–Szalkszentmárton bridge and Alternatives 4–6 of the Dunaföldvár–Solt bridge are outstanding: they cause a decrease of more than 0.8% in the total network path length and more than 0.6% decrease in the total network travel time. One of the reasons for this is the behaviour seen above: since many routes previously passing through Budapest cross these two bridges, the reduction in length and travel time caused by them is added together.

Alternative 2 of the Dunaföldvár–Solt bridge and the Szob–Esztergom bridge cause only a moderate decrease in the total network path length and the total network travel time, about 0.4%, despite the fact that the traffic of these bridges are roughly the same or even slightly higher than the previous ones. This means that the traffic-reducing effect does not necessarily lead to a significant reduction in journey times. Alternatives 1 and 3 of the Dunaföldvár–Solt bridge and both alternatives of the Paks–Kalocsa bridge result in only a minimal reduction about 0.2%, which is not surprising at all considering the traffic load of the bridges.

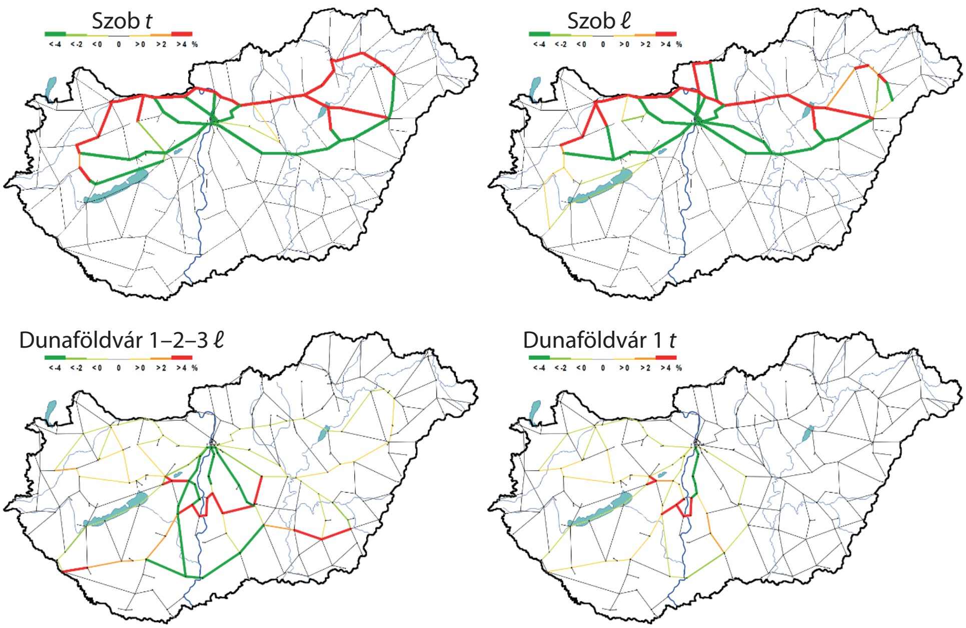
Table 1: The percentile change in the measures used to describe the alternatives

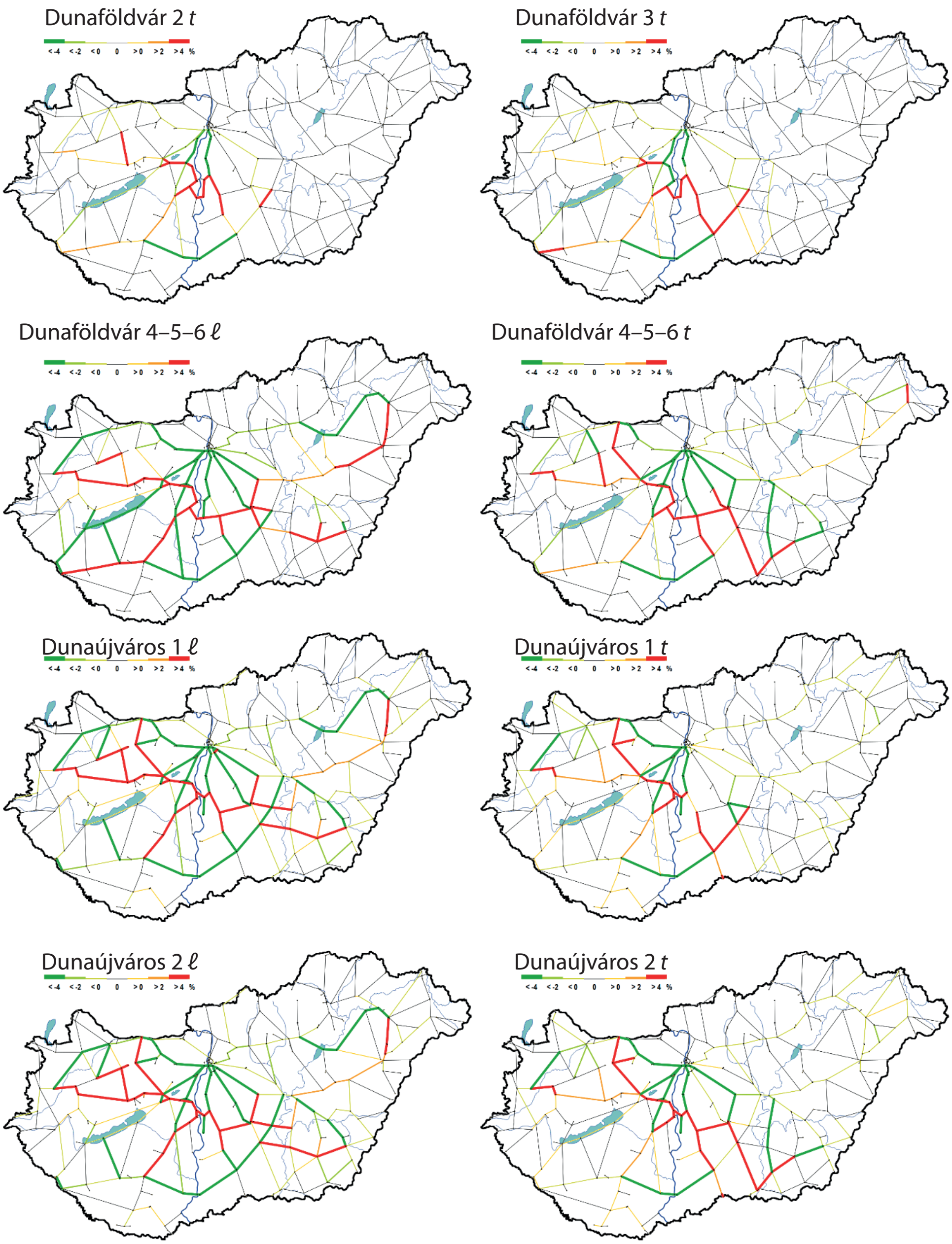
	Szob–Esztergom		Dunaföldvár–Solt									
	distance	time	distance				time					
Alternative			1–3	4	5	6	1	2	3	4	5	6
Decrease in the total network path length/travel time if the new bridge is implemented (%)	0.57	0.80	0.41	0.88	0.92	1.02	0.12	0.41	0.12	0.70	0.84	0.87
Decrease in the traffic of the most heavily loaded line section if the new bridge is implemented (%)	6.86	17.47	6.16	18.88	19.49	19.68	1.22	6.16	1.22	10.95	11.72	11.64

	Szob–Esztergom		Dunaföldvár–Solt									
	distance	time	distance				time					
Alternative			1–3	4	5	6	1	2	3	4	5	6
Ratio of paths passing through the new bridge (%)	8.52	8.47	7.92	7.80	8.02	8.75	7.46	7.92	7.46	5.19	5.53	5.52

	Dunaújváros–Szalkszentmárton				Paks–Kalocsa			
	distance		time		distance		time	
Alternative	1	2	1	2	1	2	1	2
Decrease in the total network path length/travel time if the new bridge is implemented (%)	1.01	1.01	0.65	0.73	0.28	0.28	0.29	0.31
Decrease in the traffic of the most heavily loaded line section if the new bridge is implemented (%)	19.29	19.15	6.58	9.00	3.28	3.29	3.14	3.14
Ratio of paths passing through the new bridge (%)	8.38	8.28	4.13	5.12	1.55	1.55	1.57	1.71

Source: Compiled by the authors.




Dunaföldvár 2 t
Dunaföldvár 3 t
Dunaföldvár 4–5–6 ℓ
Dunaföldvár 4–5–6 t
Dunaújváros 1 ℓ
Dunaújváros 1 t
Dunaújváros 2 ℓ
Dunaújváros 2 t
<-4 <-2 <0 0 >0 >2 >4 %

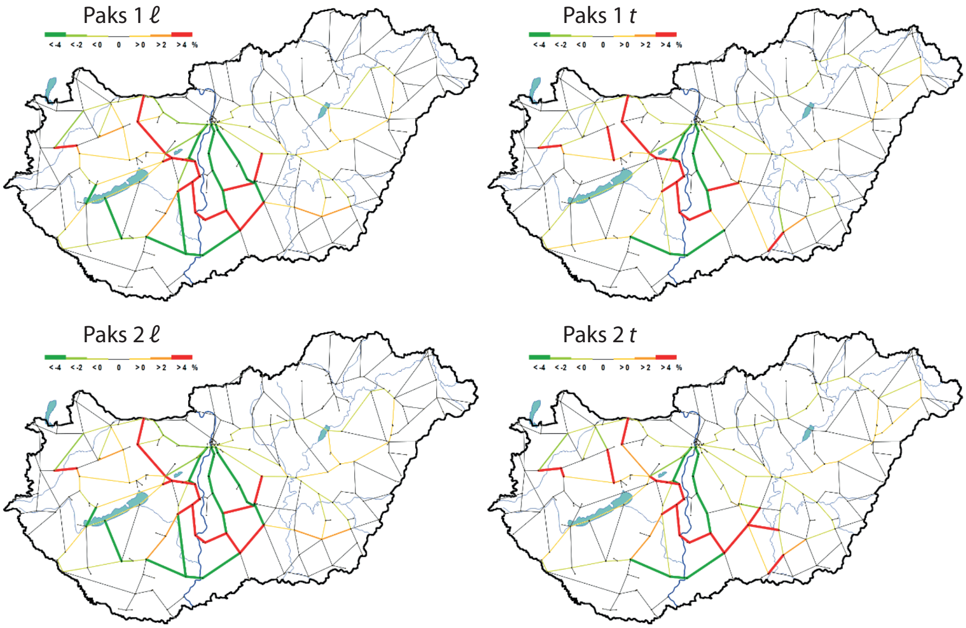


Figure 12: The change in traffic caused by each alternative of the new Danube bridge compared to the present situation

Source: Compiled by the authors.

Figure 12 illustrates the results of the study, the change in the traffic of each line section, and the rerouting effect on the traffic of each bridge. The Szob–Esztergom bridge "attracts" paths from lines No. 100 and 20 (Székesfehérvár–Szombathely) to lines No. 2, 4 and 80: it makes the paths to move north. However, while the impact of this bridge extends to remote regions, Alternatives 1–3 of the Dunaföldvár–Solt bridge make only the paths in the immediate vicinity of the bridge to reroute, the longer paths run on their current route. And this, as we have seen before, is not sufficient in any case to significantly reduce the total network travel time.

In contrast, Alternatives 4–6 of the Dunaföldvár–Solt bridge cause a significant reduction in traffic on the main lines leading to Budapest and also on the Baja bridge, mostly handling traffic between the southeastern and southwestern regions of Hungary. Thus, this bridge directs the routes to the central regions of the country: from line No. 1 to line No. 20, from line No. 80 to line No. 100.

Both alternatives of the Dunaújváros–Szalkszentmárton bridge have a similar effect, but due to the proximity to Budapest, it serves more as an alternative to northwestern–southeastern routes in bypassing the capital, and only slightly affects the traffic between the northeastern and southwestern regions of Hungary.

The two alternatives of the Paks–Kalocsa bridge only cause a local change in traffic. Due to the low traffic on the bridge, the decrease in the number of paths entering the capital is only symbolic, its effect only noticeable up to Komárom and to line No. 140 (Cegléd–Szeged).

Summary

The heavy traffic of the railway lines running through Budapest is continuously increasing due to the large suburban passenger traffic and the east–west freight trains, which in some periods already made the network overloaded according to the standards[31] set by the UIC.[32] This is especially true for the Southern Railway Bridge, the only double-tracked and electrified bridge over the Danube in Hungary which is already operating at the limit of its capacity; therefore, it is necessary to somehow reduce its traffic.

In this paper, we examined 4 bridge locations and a total of 11 route alternatives using mathematical modelling to determine the optimal place for a bridge to be built. Basically, brownfield developments were taken into account, i.e. where there is already the railway infrastructure on both banks of the Danube. Therefore, its costs can be significantly smaller than in case of a completely new line with more than 100 km of new tracks to be built as a greenfield development. Based on the calculations, the best place for the bridge to be (re) built, but on a more favourable route is between Dunaújváros and Szalkszentmárton, the former site of the TS floating bridge. Between Dunaföldvár and Solt, where there has been a railway bridge until 2000, is also a very favourable location.

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