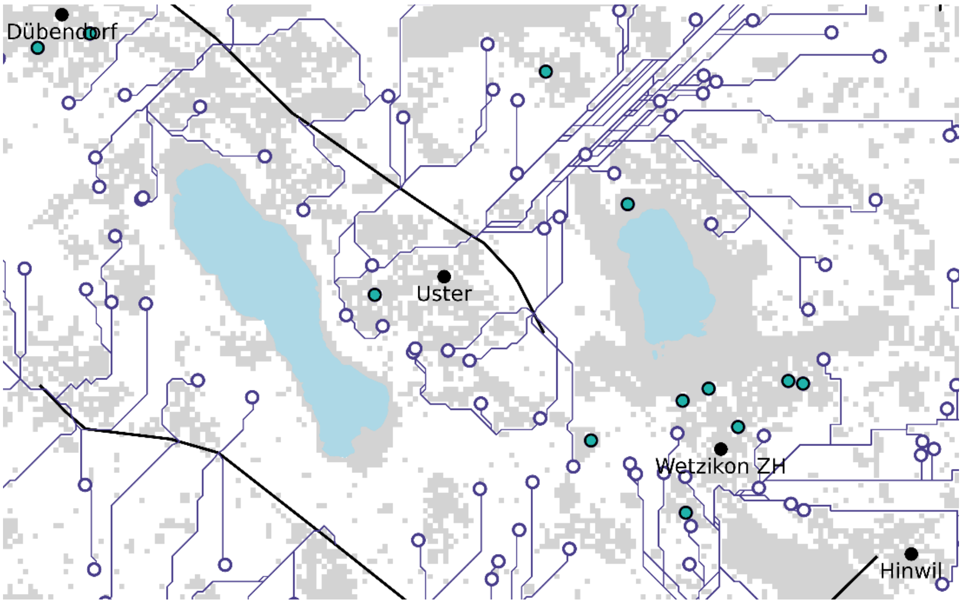

Implementing early-stage highway planning support in Dübendorf-Hinwil considering uncertain land-use and mobility demand

Fabrice Marggi, Arnor Elvarsson & Bryan T. Adey

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Abstract

This paper shows a case study for a tool introduced by Elvarsson et al. (2024) identifying potential for more efficient and effective infrastructure planning, emphasizing foresight in accommodating societal changes. The tool is used to generate and assess infrastructure developments. The assessment mirrors the societal needs of individual stakeholders showing in a transparent manner how some infrastructure developments can be favoured over others fostering consensus-building in participatory settings. Illustrated through a case study on the Swiss A15 highway corridor, the tool is used to naively generate a large number of variants within the solution space, enabling evaluation of the variants. The study addresses uncertain land use and mobility scenarios used to assess additional highway access points in multiple futures. These variants are furthermore compared to making no change. The evaluation considers costs and benefits such as construction and maintenance cost, travel time, and environmental factors across the different scenarios, based on population growth. This scalable, open-data-reliant framework empowers regional planners to strategically allocate resources, prioritize areas, and make evidence-based decisions, fostering transparent consensus-building. The results show that the methodology and framework can be used to streamline early-stage planning, guiding further study of specific variants, and facilitating efficient infrastructure improvements.

Keywords

Highway infrastructure; decision-support tool; infrastructure generation; future scenario, uncertainty, societal needs

Preferred citation style

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1 Introduction

Highway infrastructure planning demands a forward-looking approach to efficiently address future societal needs. Infrastructure is planned and then constructed and/or modified to accommodate societal needs. These societal needs are expressed by different stakeholders within society. While some stakeholders, e.g., infrastructure owners, may strive for minimal construction and maintenance costs others, e.g., the infrastructure users will prefer minimised travel time, may require a larger infrastructure supply and consequently an increase in construction and maintenance costs. Accommodating the diverse, sometimes conflicting needs is a challenge, particularly because over the long planning time, societal needs may change in an unforeseeable way because of new developments, e.g., deployment of automated electric vehicles or change in commuting behaviour due to working from home. Throughout the planning process, uncertainty is prevalent, with a wide range of potential solutions to continually accommodate societal needs (Panopoulos et al., 2022). In the early stages of planning, planners face critical questions about accommodating future demands, such as avoiding travel delays due to high traffic and directing spatial development to accommodate these future needs.

This paper presents an example how the method presented by Elvarsson et al. (2024) can be used to quickly identify and assess the impact of changes to the infrastructure and its environment. The results can support planners in making transparent, evidence-based decisions related to the next step in the planning process with sufficient level of detail more quickly. After introducing the method in Section 2, the case study of the Swiss A15 highway corridor from Dübendorf to Hinwil in Canton Zurich is described in Section 3. Section 4 discusses our findings, providing insight and analysis derived from our application of the method. The paper concludes with Section 5, discussing the implications and suggesting directions for future research.

2 Method

The method is based on independently generating development variants and future scenarios as per Elvarsson et al. (2024). The variants are scored based on costs and benefits, which are impacted by the future scenario they are embedded in. These three fundamental components are further explained as follows:

- Generation of potential infrastructure developments: This step involves creating spatially explicit changes to current infrastructure. This includes naively generated infrastructure developments in a continuous space. The use of naïve random generation is crucial to explore a wide range of potential solutions without any preconceived biases, before the solutions are filtered by feasibility.
- Generation of scenarios: Multiple scenarios are defined to represent future changes of the environment of the infrastructure (e.g., population) and its uncertainty. These scenarios are detailed on a geographic scale, indicating specific locations and areas, making them spatially explicit. This approach is crucial for predicting how changes in the environment e.g. demographics might impact the demand and topological design of highway infrastructure.
- Scoring of developments in multiple futures: Lastly, the proposed developments are assessed within the context of the crafted scenarios. The costs and benefits considered are a representation of the societal needs. A planner is tasked to accommodate societal needs and ensure that the planning outcomes are both relevant and beneficial to all stakeholders.

As part of the scoring, the net benefit of each development is quantified and compared to the net benefit of retaining the current state of infrastructure.

3 Case Study

3.1 Overview and data requirements

The case study is the highway corridor northeast of Zurich, Switzerland (see Figure 1). This area is delimited by the communes Dübendorf and Hinwil. The corridor contains an existing highway section, planned in 1965, that has been unchanged since 1988 despite plans to further develop it (Kanton Zurich, 2015; Kanton Zurich, 2023).

The current highway network was the basis upon which infrastructure developments were built. The current network was defined by a table of nodes and edges (Fröhlich, 2008). This data was enriched by classifying the nodes of the network graph e.g., access points, intersections. The data used for infrastructure, scenario generation and scoring is reported in appendix A. It included data on population and employment distribution, railway location, local road network, water body location, administrative boundaries, ground elevation, land use and land cover.

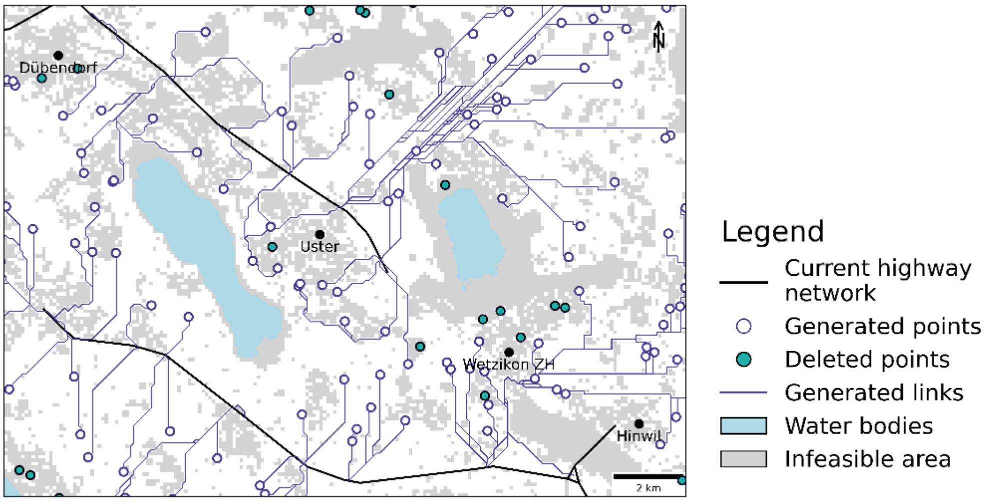
Figure 1: Overview of the study area, with the main highway running from Uster to the north of Dübendorf in dark blue

Source: Bundesamt für Landestopographie Swisstopo (2024)

3.2 Generate highway developments

In our case study, adding a new access point and linking it to the nearest existing access point were studied as highway developments. First, 1’000 points were randomly generated within the area of study. Second, the points were filtered by land cover, protected areas and proximity to the existing highway, to make sure that points were not within those areas e.g. settlements, or lakes. Third, each filtered point was connected to its closest existing highway access point. Fourth, the shortest route that does not intersect protected areas was investigated. An example of generated nodes and links is shown in Figure 2.

Figure 2: Generated highway developments in the area of study consisting each of one new access point with a connection to the closest existing highway node



3.3 Generate scenarios

The scenarios correspond to population and employment predictions for 2050, which have been identified by others as significant drivers for highway infrastructure (Glover and Simon, 1975; Levinson and Karamalaputi, 2003; Levinson and Chen, 2007; Rayaprolu, and Levinson, 2024).

A scenario combines the current state and a prediction of the growth until 2050. The population growth was predicted only where the space and legislation allowed for future growth, as per the Communal and Cantonal Zoning ordinances (Raum+, 2024). The potential was estimated per parcel and was aggregated onto a hectare raster. As the total population growth was smaller than overall potential, the ratio of exploitation of the parcels varied in each scenario (see Figure 6 in appendix C). The employment distribution was assumed to follow the observed evolution between 2011 and 2021 shown in Table 9 in Appendix C. Employment growth rates were specified per cantonal district and multiplied with the current employment distribution data.

3.4 Score infrastructure developments in future scenarios

The infrastructure developments were scored as a function of how much they reduced costs to stakeholders, who are categorised by the following stakeholder types: the owner, users, directly (DAP) and indirectly affected public (IAP) and their needs (cost components) as in Table 1. Each cost component was calculated for each development and under each scenario, with the equations and exact values used for monetisation listed in appendix B.

Table 1: Relevant stakeholders and cost components for highway infrastructure

Stakeholder type	Cost component	Description
Owner	Construction costs	Costs related to constructing a new link and access point were based on its elevation profile and on obstacles to be crossed, such as rail lines and rivers as well as tunnels that must be built.
	Maintenance costs	Maintenance costs were approximated based on empirical values over the life-time
User	Travel time delay	Travel time delay on the highway network considering the OD matrix including changes in mobility demand due to changes in population and employment

	Access time to highway	The accumulated travel time from a raster cell to access a highway for all users based on travel-time based Voronoi tessellation
Directly affected public	Added noise pollution	Cost of residents near new highway links, based on Bangmann (2020) influenced by proximity and sound level (Nielson and Laursen, 2005; Althaus et al., 2009; Illinois Department of Transportation, 2017) and different population scenarios.
Indirectly affected public	Ecological disruption	The cost of added fragmentation of the landscape and a loss of habitat for wildlife. The calculation follows Ecoplan and Infras (2014).
	Land use consumption	Agricultural, hydrological, and carbon storage losses based on prevailing land use. Corresponding estimations for ecosystem service values were adopted from Liu et al. (2023) and Kumar et al. (2019).
	Greenhouse gas emissions	Carbon dioxide (CO2) emissions associated with the expansion of the highway infrastructure, excluding additional CO2 emissions due to induced demand based on estimates from Martinez Caraballo et al. (2013).

Thus, the total net benefit (*NB*) for a highway development *i* under scenario *j* was obtained as follows:

$$NB_{ij}^{total} = C_i^{construction} + C_i^{maintenance} + C_{ij}^{travel\ time\ delay} + C_{ij}^{access\ time} + C_{ij}^{external\ factors}$$

Whereby the costs of external factors include:

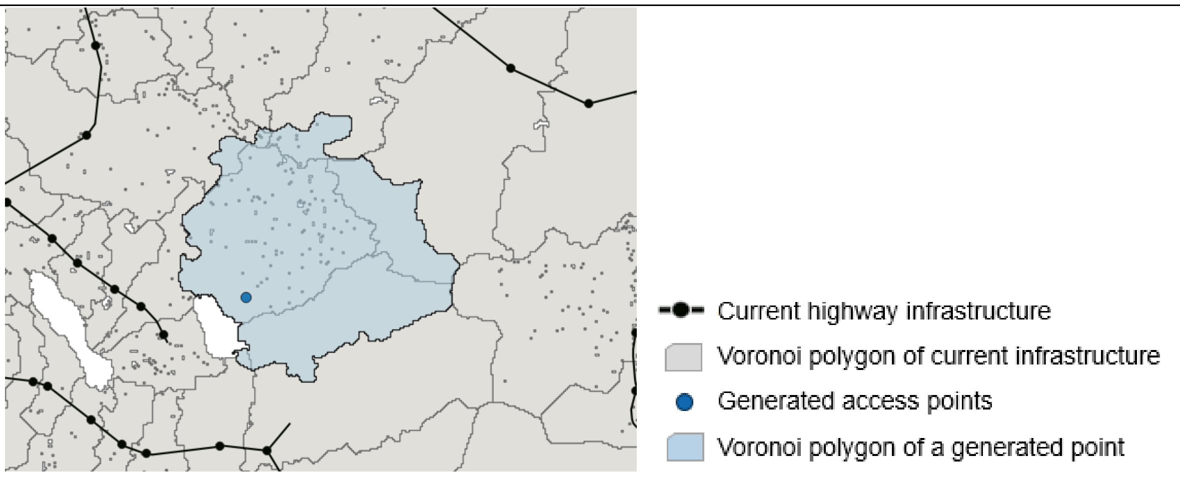
$$C_{ij}^{external\ costs} = C_{ij}^{noise} + C_i^{ecological\ disruption} + C_i^{climate\ effects} + C_i^{land\ consumption}$$

The costs were reported in comparison to the status quo. Consequently, the net benefits of each development were determined in relation to a base case comprising the current infrastructure in the given scenario.

Only travel time delay, access time and noise pollution varied with the scenarios. The total net benefits consisted of one-off (construction) and periodic elements. Monetary values for periodic benefits were reported for the year 2050, according to the scenarios, and then extrapolated over the following 50 years. This simplification and the omission of discounting can be justified by the intended use of the tool in the early stages of planning, which are already affected by significant uncertainty.

To capture the spatial effects of building infrastructure in one location instead of the other, the travel demand derived from population and employment distribution was allocated to infrastructure through Voronoi tessellation. Voronoi polygons are the result of each of such a tessellation, whereby every point inside a polygon is located to its own polygon's centroid than any other centroid (Voronoi, 1908; Aurenhammer, 1991). The space was tessellated by travel-time (instead of Euclidean distance) whereby the highway access points acted as centroids. The travel-time tessellation consisted of importing the current local road network from Open Street Map (OSM, 2023), rasterizing it allocating the travel time required to cross each cell and finding the shortest path from each cell to its closest existing access point. Accordingly, the tessellation was different when evaluating developments with new access points. Figure 3 shows a grey travel-time-based Voronoi tessellation graph where the polygons boundaries are defined by the travel time to the highway access point centroids. The introduction of a new access point in blue would result in a modification of the tessellation graph, with the creation of a transparent light blue polygon and the alteration of the borders of all adjacent polygons.

Figure 3: Voronoi tessellation graph with the inclusion of one additional access point



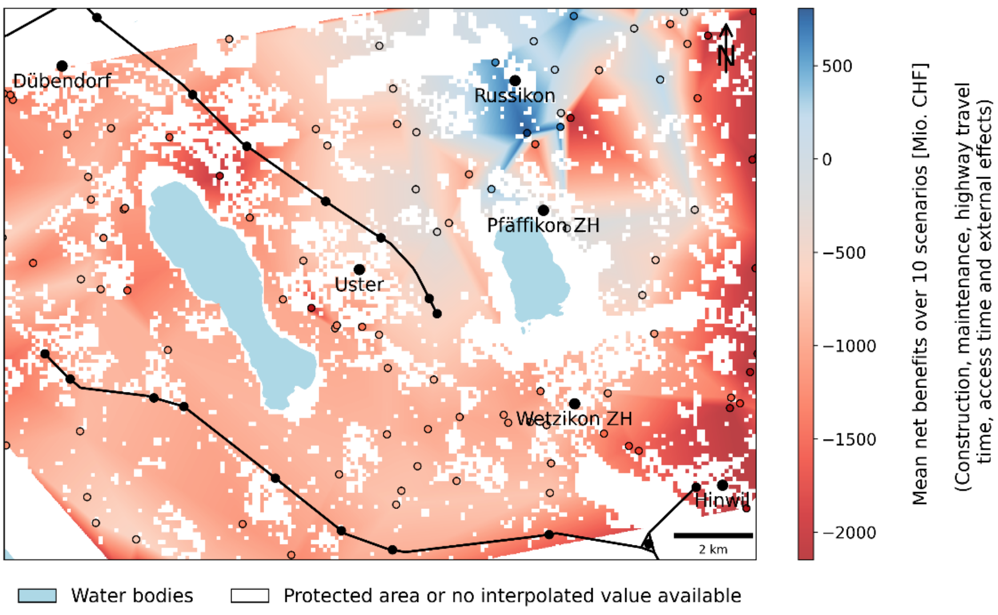
To approximate future travel demand, current travel patterns were extrapolated from the cantonal origin-destination (OD) matrix (Amt für Mobilität des Kantons Zürich, 2023) and were adjusted based on the population and employment growth within the respective areas. The approximated future travel demand from the OD was allocated to network links based on a stochastic user equilibrium routing algorithm (Nogal et al., 2016). The travel time on each link was estimated using the BPR function (US Bureau of Public Roads. 1964). With a new link, underserved parts of the population may be better served than without the link.

Access time to highway was assessed by combining the number of trips to the closest highway access that each raster cell generated within each Voronoi polygon and the according travel time. To approximate the number of trips, the current average number of trips per capita, derived from empirical observation (BFS and ARE, 2023), were multiplied with the population in each raster cell in each scenario.

3.5 Results of early-planning development scanning

The early-planning scanning tool was implemented in Python. Running one scenario with 127 developments (result of filtering 1'000 development alternatives) on a laptop equipped with 16GB of RAM took approximately 9 hours. Figure 4 shows, for one scenario, the expected net benefits of each feasible development. The net benefit is the sum of the costs and benefits of a given development in comparison to the status quo. The net benefit is shown in the colour of the point. The colour of the area in between the points is based on the interpolated values between the point values.

Figure 4: Spatial representation of the expected mean net benefits over 10 scenarios



The map indicates the general area in blue to consider in further planning steps. For the studied area around the A15, Figure 4 shows the following: 1) a cluster of locations in blue depicting where a new access point might provide higher positive benefit. 2) new access points close to the existing infrastructure do not provide significant positive benefit, 3) the eastern, rather hilly region shows overall higher negative benefits and 4) some generated access points within proximity exhibit disparate values, especially around points between Russikon and Pfäffikon.

Out of all the developments, 11 showed a positive net benefit. Table 2 displays the six developments with the highest average net benefit, represented by the dark blue points in Figure 4. The ranking of the developments informs planners which alternative is worth investigating in more detail and provides an approximation of the expected net benefits. In addition, the variation in the net benefit of a development under different scenarios as shown in Figure 7 in appendix D, illustrates the robustness of the alternatives to uncertain futures and can provide as additional information to planners.

Table 2: Ranked list in order of highest average net benefit of developments across 10 scenarios

ID	**Average net benefit [Mio. CHF]**	**Standard deviation [Mio. CHF]**	**Approximate location of new access point**
2	809	26	1 km south of Russikon
103	638	28	1.5 km south-east of Russikon
249	557	30	2 km north-east of Russikon
895	534	24	In Russikon
201	411	31	3 km north-east of Russikon
775	410	33	1.5 km north-west of Uster

4 Discussion

With this method, early-stage planners can be supported in identifying where infrastructure development may lead to societal benefits. Figure 4 shows, for one scenario, a cluster of locations around Russikon depicting new access points providing higher positive benefit. This is explained by their vicinity to bigger rural settlements as Pfäffikon that currently have high access times to the highway so large accessibility gains can be made. On the contrary, new access points close to the existing infrastructure do not provide significant positive benefit. Meanwhile, the eastern, rather hilly region shows overall higher negative benefits that can be drawn from higher construction costs due to long distances and the need for high construction costs, including bridges and tunnels. Planners benefit from a spatial visualisation, like in Figure 4 and may also extract a list of favourable developments as in Table 2, allowing for a decision to study some developments further depending on the evaluated robustness of the developments across the developed spatially explicit scenarios (see appendix D). The spatial variability of the results indicates that the influence of local environmental characteristics is significant. Consequently, further analysis of this variability should be conducted in subsequent planning stages.

Furthermore, it can be seen that the current planned connection between Uster East and Betzholz, south of Hinwil, is not the most highly scored. This may be related to the fact that the method currently only looks at the generation of one access node and a link to connect it to one current highway, whereas the planned connection would connect the two highways together. This improvement of the development generation module is in progress.

5 Conclusions

This paper presents an example of how the method from Elvarsson et al. (2024) can support decision makers in the planning of highway infrastructure. Naively generated infrastructure developments were evaluated over an ensemble of possible future scenarios using a scoring function that minimizes uncertain future costs and benefits, i.e., best satisfies uncertain future societal needs. The method uses for the first time estimates of demand using a travel time based Voronoi tiling, which allows the allocation of traffic demand to access points depending on the location of the generated highway developments. The method allows an indication of the suitability of an alternative and its robustness to future uncertainties. This enables evidence-based decision support in the early stages of highway planning.

The approach is expected to be helpful in early planning stages, emphasising fast execution at the expense of some simplifications, mainly in scoring. The method and the programmed tool can be easily adapted to other types of infrastructure, modified scenario generation, scoring or even new case study corridors.

6 Acknowledgement

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A Data overview and data sources

Appendix A provides a comprehensive overview of the datasets used in this case study and their sources. All data are generally freely available. All sources are listed after the table. For each source, it is indicated in which part of the implementation it was used.

Figure 5: Overview of the data used for the implementation of the case study

Data description	**Source**	Generating infrastructure	point filtering	link filtering	Construction costs	Voronoi tiling	Access time benefits	Travel time delay	Plot	Scenario
Highway network	(Fröhlich, 2008)	■								
Road network	(Boeing, 2017; OpenStreetMap Contributors, 2023)					■	■			
Railway	(Bundesamt für Landestopografie Swisstopo, 2023a)				■					
Rivers	(Bundesamt für Landestopografie Swisstopo and Bundesamt für Umwelt BAFU, 2022)				■					
Lakes	(Stadt Zurich, 2023b)								■	
Population (STATPOP)	(Bundesamt für Statistik BFS, 2023)									■
Employment (STATENT)	(Bundesamt für Statistik BFS, 2023)									■
Elevation model	(Bundesamt für Landestopografie Swisstopo, 2023b)				■					
Population growth scenario	(Kanton Zurich, 2023a)									■
Emplyoment development (2011 - 2021)	(Statistisches Amt des Kantons Zurich, 2022)									■
Administration boundaries	(Geoinfromation Kanton Zürich, 2023)							■		■
origin-destination (OD) matrix canton of Zurich	(Amt für Mobilität des Kantons Zürich, 2023)							■		
Land use and land cover										
Federal Inventory of Landscapes and Natural Monuments (BLN)	(Bundesamt für Umwelt (BAFU), 2017c)		■	■						
Wildlife corridors	(Geoinfromation Kanton Zurich, 2021)		■	■						
Low moor	(Bundesamt für Umwelt BAFU, 2021)		■	■						
Federal inventory of raised bogs and transition moors	(Bundesamt für Umwelt (BAFU), 2017b)		■	■						
Federal inventory of wetlands of national importance	(Bundesamt für Umwelt (BAFU), 2017a)		■	■						
Inventory of nature and landscape conservation objects	(Stadt Zurich, 2023a)		■	■						
Dry meadows and pastures	(Stadt Zurich, 2022)									
Forest	(Kanton Zurich, 2023b)		■							
Crop rotation area	(Kanton Zurich, 2022)		■							
Swiss Land Use Statistics	(Bundesamt für Statistik (BFS), 2023a)			■	■					

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Geoinfromation Kanton Zurich. (2021). *Wildtierkorridore*. https://opendata.swiss/de/dataset/wildtierkorridore1

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Bundesamt für Umwelt (BAFU). (2017a). *Bundesinventar der Auengebiete von nationaler Bedeutung*. https://opendata.swiss/de/dataset/bundesinventar-der-auengebiete-von-nationaler-bedeutung

Stadt Zurich. (2023a). *Inventar der Natur- und Landschaftsschutzobjekte von kommunaler Bedeutung*. Open Data. https://opendata.swiss/en/dataset/inventar-der-natur-und-landschaftsschutzobjekte-von-kommunaler-bedeutung

Stadt Zurich. (2022). *Trockenwiesen und -weiden Nachkartierungen 2022 (OGD) (kantonaler Datensatz)*. https://www.stadt-zuerich.ch/geodaten/download/567

Kanton Zurich. (2023b). *Waldareal (OGD) (kantonaler Datensatz)*. Open Data. https://www.geolion.zh.ch/geodatensatz/show?gdsid=111

Kanton Zurich. (2022). *Fruchtfolgeflächen*. Open Data. https://www.geolion.zh.ch/geodatensatz/1484

Bundesamt für Statistik (BFS). (2023a). *Arealstatistik: Geodaten*. https://opendata.swiss/de/dataset/arealstatistik-1979-aktuell

B Monetization

Appendix B presents the calculation methods and the values used to monetise societal needs for the scoring function. For construction, maintenance and external costs, the values are listed in tables showing which cases e.g. type of infrastructure or land use have been distinguished. The corresponding sources for each monetary value are listed alongside the values.

B.1 Construction costs

The construction costs are a summation of the costs associated with each individual infrastructure component, namely open highway, on/off ramps, bridges and tunnels, as outlined in the following equation:

$$C_i^{\text{construction}} = C_i^{\text{open highway}} + C_i^{\text{ramp}} + C_i^{\text{bridge}} + C_i^{\text{tunnel}}$$

where the length of each highway component is multiplied by the related unit construction costs listed in Table 3:

$$\begin{aligned} C_i^{\text{construction}} &= C_{\text{open highway}}^{\text{unit}} \cdot L_i^{\text{open highway}} \\ &+ C_{\text{ramp}}^{\text{unit}} \cdot n_{\text{ramp}} \\ &+ C_{\text{bridge}}^{\text{unit}} \cdot L_i^{\text{bridge}} \\ &+ C_{\text{tunnel}}^{\text{unit}} \cdot L_i^{\text{tunnel}} \\ \text{where} \quad L_i^{\text{link}} &= L_i^{\text{open highway}} + L_i^{\text{bridge}} + L_i^{\text{tunnel}} \end{aligned}$$

Table 3: Unit cost of construction of infrastructure elements: highways, ramps, tunnels, and bridges

Infrastructure element	Unit cost [CHF/m] C_{source}^{unit}	C_{2023}^{unit} [a]	Source
Open highway	11'000	15'200	(Neue Züricher Zeitung, 2005)
On and off ramps (per unit)	100 M	102 M	(Martani et al., 2022)
Bridge	57'200 [b]	63900	(Tiefbauamt Kanton Zürich, 2019)
Tunnel	300'000	416'000	(Neue Züricher Zeitung, 2005)

[a] adjusted through the Swiss construction price index (Bundesamt für Statistik (BFS), 2023b)
[b] Assuming a bridge width of 22m and costs of 2600 CHF/m² (Tiefbauamt Kanton Zürich, 2019)

Bundesamt für Statistik (BFS). (2023). *Baupreisindex*. https://www.bfs.admin.ch/bfs/de/home/statistiken/preise/baupreise/baupreisindex.html

Martani, C., Eberle, S., & Adey, B. T. (2022). Evaluating highway design considering uncertain mobility patterns and decision flexibility. *Infrastructure Asset Management*, *9*(3), 135–155. https://doi.org/10.1680/jinam.21.00018

Neue Züricher Zeitung. (2005). *Warum 1 Meter Autobahn 300 000 Franken kosten kann*. Neue Zürcher Zeitung. https://www.nzz.ch/articleDEMU1-ld.371895

Tiefbauamt Kanton Zürich. (2019). *Umfahrung Uster West*.

B.2 Maintenance costs

For maintenance costs a distinction was made between structural (SM) and operational maintenance (OM) for a duration D of 50 years, according to the following equation:

$$C_i^{\text{maintenance}} = D^{\text{maintenance}} \cdot (C_i^{\text{sm}} + C_i^{\text{om}})$$
$$C_i^{\text{s m}} = r^{sm} \cdot C_i^{\text{construction}}$$
$$C_i^{\text{s m}} = C_{\text{open highway}}^{om} \cdot L_i^{\text{open highway}} + C_{\text{bridge}}^{om} \cdot L_i^{\text{bridge}} + C_{\text{tunnel}}^{om} \cdot L_i^{\text{tunnel}}$$

The costs for yearly structural maintenance were assumed to amount to a share of the construction costs. Operational maintenance was monetized similarly as constructions costs, based on unit costs of the different infrastructure components. The values used for monetization are highlighted in Table 4.

Table 4: Unit costs for operational and structural maintenance

Structural maintenance (sm)			
r^{sm} [% of the infrastructure per year]		1.2	(ASTRA, 2019)
Operational maintenance (om)			
Infrastructure component	C_{2004}^{om} [CHF/m/a]	C_{2023}^{om} [CHF/m/a]	Source
Open highway	63.5	89.7	(Lüking et al., 2008)
Bridge	63.5	89.7	
Tunnel	261.1	368.8	

ASTRA. (2019). Netzbestandsbericht Der Nationalstrassen 2018.

Lüking, J., Herrmann, T., Krauer, K., & Eckstein, P. (2008). Kosten des betrieblichen Unterhalts von Strassenanlagen. In Forschungsauftrag VSS 2000/463.

B.3 Travel time delay

This scoring component quantifies the changes in travel time on the highways in a development compared to the status quo during the peak hour of one day and is then extrapolated to a duration of 50 years. The computation of the travel time for one development independently of the status quo and for one day was computed following the following formula:

$$C_{ij}^{\text{travel time delay}} = VTT \cdot \sum_{\substack{s \in \\ \text{Highway sections}}} veh_{sij} \cdot TT\left(\text{capacity}_{si}, \text{ traffic demand}_{sij}^{peak}\right)$$

where $TT\left(\text{capacity}_{si}, \text{ traffic demand}_{sij}^{peak}\right)$ is the travel time as a function of capacity and peak hour traffic demand on a specific section s in development i and scenario j
veh_{sij} is the amount of vehicles on section s

the calculation of travel time combines the number of vehicles (veh_{sij}) and the travel time (*TT()*) in each section of the highway during peak hours. Using the values of travel time (VTT) of 32.2 CHF/h (Schmid et al., 2021) the travel time is then converted into monetary values.

Value of travel time	VTT_{2020}	VTT_{2023}	Source
[CHF/h]	30.6	32.2 [a]	Schmid et al. (2021)

[a]adjusted through the inflation Swiss national consumer price index (CPI) (Bundesamt für Statistik (BFS), 2023)

To compute the travel time in each section of the highway, the predicted traffic demand based on observed current traffic patterns and future scenarios was allocated onto the links of the network. An approach from Nogal et al. (2016); was used. Essentially, traffic demand is allocated across all network links until the user optimum state is achieved, which occurs when all travellers moving between the same OD pair experience equal travel times. The travel times on these network links are determined using the BPR function:

$$\text{Final travel time}_l = fftt_l \cdot \left(1 + \alpha \cdot \left(\frac{V_l}{C_l}\right)^{\beta}\right)$$

for each link l

where $= fftt_l$ is the free flow travel time on link l

V_l is the estimated traffic volume in vehicles per hour

C_l is the capacity of link l in vehicles per hour

The resulting travel time depends on the free flow travel time, the capacity, and the demand on the link. We use α = 0.25 and β = 2.4 (Vrtic et al., 2018). These values are derived from empirical studies specific to Switzerland.

Nogal, M., O'Connor, A., Caulfield, B., & Martinez-Pastor, B. (2016). Resilience of traffic networks: From perturbation to recovery via a dynamic restricted equilibrium model. *Reliability Engineering and System Safety*, *156*, 84–96. https://doi.org/10.1016/j.ress.2016.07.020

Vrtic, M., Weis, C., Rindsfüser, G., & Matthews, W. (2018). Kalibrierung von Capacity-Restraint-Funktionen. In *Schriftenreihe* (Issue 1628).

Schmid, B., Molloy, J., Peer, S., Jokubauskaite, S., Aschauer, F., Hössinger, R., Gerike, R., Jara-Diaz, S. R., & Axhausen, K. W. (2021) *The value of travel time savings and the value of leisure in Zurich: Estimation, decomposition and policy implications*, Transportation Research Part A: Policy and Practice, 150(June), 186–215. https://doi.org/10.1016/j.tra.2021.06.015

B.4 Access time to highway

The calculation of the total access time to highway for all users in one development und scenario per day was made according to the following formula:

$$C_{ij}^{\text{access time}} = VTT \cdot \sum_{\substack{c \in \\ \text{cell}}} TT_i^{c,p} \cdot N_j^{c,p}$$

where $TT_i^{c,p}$ is the travel time from the cell c to its closest access point p for development i
$N_j^{c,p}$ is the amount of trips from cell c to its closest access point p in scenario j
VTT is the Value of Travel Time

In order words, it is a summation over all raster cells of the perimeter of study. The respective travel time from each cell to its nearest access point was multiplied by the number of trips from that cell to the nearest access point. The overall travel time was monetized using the Value of Travel Time.

The according value represents the expected monetary value of the access time in one development and one scenario for one day. It is then compared to the current infrastructure in the corresponding scenario and the difference e.g. the benefits are extrapolated to the duration of 50 years.

B.5 External factors

The external costs are a summation of noise pollution, nature and landscape, climate effects and land consumption. It can be formulation as follows:

$$C_{ij}^{\text{external costs}} = C_{ij}^{\text{noise}} + C_i^{\text{nature and landscape}} + C_i^{\text{climate effects}} + C_i^{\text{land consumption}}$$

B.5.1 Noise pollution

The calculation was based on a straightforward approach by Bångman (2020). This consisted of creating a buffer based on the routing of a link. To each of these buffers, the costs generated per affected person were attributed. Therefore, total costs were obtained by overlaying the buffer with the population distribution of all scenarios and the respective per capita costs. The following equation shows the formal definition of noise emission costs with the corresponding values for monetization in Table 5.

$$C_{ij}^{\text{noise}} = D \cdot \sum_{b \in buffer} \left(C_{\text{b}}^{\text{noise}} \cdot P_{ij}^{\text{affected},b} \right) \quad (12)$$

where D is the duration to consider the noise costs (50 years)
b indexes the buffer to the infrastructure (e.g., $10m, 20m, \ldots$)
$C_{\text{b}}^{\text{noise}}$ represent the costs due to noise per affected inhabitant and year in buffer b
$P_{ij}^{\text{affected},b}$ the number of inhabitants affected in buffer b for development i under scenario j

Table 5: Buffer distances to a highway link with the corresponding noise level L_{eq} defining the costs per affected inhabitant

Distance [m]	10	20	40	80	160	320	640	1280	2560
L_{eq} [dB]	73.5	70.5	67.5	64.5	61.5	58.5	55.5	52.5	49.5
$C_{\text{b}}^{\text{noise}}$ [CHF/p/a] 2017 [a]	6874	5247	3843	2665	1705	965	442	124	19
$C_{\text{b}}^{\text{noise}}$ [CHF/p/a] 2023 [b]	7254	5536	4055	2812	1799	1019	467	130	20

[a] Exchange rate of 2017 used for the conversion: 100 SEK to 11.5347 CHF (Schweizerische Nationalbank (SNB), 2024)
[b] adjusted through the Swiss national consumer price index (CPI) (Bundesamt für Statistik (BFS), 2023)

Bångman, G. (2020) *English summary of ASEK Guidelines (Vol. 6)*. https://bransch.trafikverket.se/contentassets/4b1c1005597d47bda386d81dd3444b24/asek-2021/19_english_summary_a7.pdf

Bundesamt für Statistik (BFS). (2023). *Price level indices*. https://www.bfs.admin.ch/bfs/en/home/statistics/prices/international-price-comparisons/price-level-indices.html

Schweizerische Nationalbank (SNB). (2024). *Devisenkurse – Jahr*. https://data.snb.ch/de/topics/ziredev/cube/devkua?fromDate=2014&toDate=2023&dimSel=D1(SEK100,CNY100)

B.5.2 Ecological disruption

The construction of a highway leads to a fragmentation of the landscape and, simultaneously, to loss of habitat for wildlife. Calculating these costs follows the approach proposed by Ecoplan and Infras (2014). The determining factor is the length of open highway of a new link which is multiplied by the respective unit cost according to the following formula.

$$C_i^{\text{nature and landscape}} = L_i^{\text{open highway}} \cdot (C_{\text{fragmentation}}^{\text{unit}} \cdot D_{\text{fragmentation}} + C_{\text{loss of habitat}}^{\text{unit}} \cdot D_{\text{loss of habitat}})$$

with the unit costs for fragmentation and habitat loss specific to highway infrastructure listed in Table 6.

Table 6: Unit cost of a highway construction to nature and landscape

	Unit cost [CHF/m/a] C_{2014}^{unit}	C_{2023}^{unit} [a]	Duration D [years]	Source
Fragmentation	155.6	165.6	50	(Ecoplan and Infras, 2014) [b]
Loss of habitat	31.6	33.6	50	

[a] adjusted through Swiss national consumer price index (CPI) (Bundesamt für Statistik (BFS), 2023)
[b] p. 342

Bundesamt für Statistik (BFS). (2023). Price level indices. https://www.bfs.admin.ch/bfs/en/home/statistics/prices/international-price-comparisons/price-level-indices.html

Ecoplan, & Infras. (2014). Externe Effekte des Verkehrs 2010, Monetarisierung von Umwelt-, Unfall- und Gesundheitseffekten.

B.5.3 Climate effects

The total costs for the climate impact were based on the length of the individual infrastructure elements of the respective routing of the development considered according to this equation:

$$C_i^{\text{climate effects}} = L_i^{\text{open highway}} \cdot C_{CO_2\text{ emission, open highway}}^{\text{unit}} + L_i^{\text{tunnel}} \cdot C_{CO_2\text{ emission, tunnel}}^{\text{unit}} + L_i^{\text{bridge}} \cdot C_{CO_2\text{ emission, bridge}}^{\text{unit}}$$

Martinez Caraballo et al. (2013) has recorded the cost of carbon emissions incurred during construction, maintenance and restoration over a 50-year cycle. These can be recorded as unit costs per length of highway constructed as listed in Table 7.

Table 7: Unit cost of climate effects for the infrastructure elements: open highways and tunnels

Infrastructure element	Emission [t CO2/m/50a]	$C^{unit}_{CO_2\ emission}$ [a] [CHF/m/50a]	Source
Open highway	18,6	2'780	(Martinez Caraballo et al., 2013)
Tunnel	25.1	3'750	

[a]with 149.5 CHF/t CO2 in 2023 (adjusted through Swiss national consumer price index (CPI) (Bundesamt für Statistik (BFS), 2023), initial value 140.9 CHF/t CO2 in 2020 (Bundesamt für Raumentwicklung, 2023))

Bundesamt für Raumentwicklung. (2023). *Externe Kosten und Nutzen des Verkehrs in der Schweiz. Strassen-, Schienen-, Luft- und Schiffsverkehr 2020*. http://www.are.admin.ch/dokumentation/publikationen/00015/00557/index.html?lang=de

Bundesamt für Statistik (BFS). (2023). Price level indices. https://www.bfs.admin.ch/bfs/en/home/statistics/prices/international-price-comparisons/price-level-indices.html

Martinez Caraballo, E., Redruello, I., Gonzalez, M. J., Muench, S., & García Navarro, J. (2013). Quantity of CO2 emissions in the life cycle of a highway infrastructure. In *International Journal of Environmental Sustainability* (Vol. 8, Issue 3, pp. 81–94). https://doi.org/10.18848/2325-1077/cgp/v08i03/55028

B.5.4 Land consumption

These costs arise from land consumed by the construction which means loss of agricultural production, reduction in water balance, reduction in CO2 storage capacity, etc. This can be monetized by means of ecosystem services as shown in Table 8.

Table 8: Unit values of ecosystem services provided by forest, crop rotation area (*Fruchtfolgeflächen*) and dry meadows

Landcover / landuse	Ecosystem service value [CHF/m²/a]	Source	Duration until rehabilitation [years]
Forest	0.8890 [a]	(Liu et al., 2023)	50 (WSL, 2008)
Crop rotation area Dry meadow	0.1014 [b]	(Kumar et al., 2019)	50

[a]70'698 CNY/hm²/a (Liu et al., 2023) with the exchange rate used for the conversion: 0.125733 CNY to CHF (Eidgenössische Steuerverwaltung ESTV, 2023), [November 2023])
[b]Economic contribution of India's agri-ecosystem services 68'180 (INR/ha/year) in 2017 (Kumar et al., 2019), exchange rate of 2019 used for the conversion: 0.01411 INR to 1 CHF (Schweizerische Nationalbank (SNB), 2024))

The calculation of the related costs combined the affected area and the unit costs introduced above. The affected area was defined to be the lateral distance of 25m to a built highway link. The occurnig landuse within this buffer is considered as lost area. Overlayed with land cover data one can allocated to the unit costs to each development as follows:

$$
\begin{aligned}
C_i^{\text{land consumption}} = {} & A_i^{\text{forest}} \cdot C_{\text{forest}}^{\text{unit}} \cdot D_{\text{forest}} \\
& + A_i^{\text{crop rotation area}} \cdot C_{\text{crop rotation area}}^{\text{unit}} \cdot D_{\text{crop rotation area}} \\
& + A_i^{\text{dry meadow}} \cdot C_{\text{dry meadow}}^{\text{unit}} \cdot D_{\text{dry meadow}}
\end{aligned}
$$

Eidgenössische Steuerverwaltung ESTV. (2023). *Aktueller Monatsmittelkurs*. Fremdwährungskurse. https://www.estv.admin.ch/estv/de/home/mehrwertsteuer/mwst-abrechnen/mwst-fremdwaehrungskurse/mwst-monatsmittelkurse/mwst-aktueller-monatsmittelkurs.html

Kumar, L., Manjula, M., Bhatta, R., Venkatachalam, L., Kumar, D., Devi, P., & Mukhopadhyay, P. (2019). Doubling India’s farm incomes paying farmers for ecosystem services, not just crops. *Economic and Political Weekly*, *54*, 43–49.

Liu, S., Dong, Y., Liu, H., Wang, F., & Yu, L. (2023). Review of Valuation of Forest Ecosystem Services and Realization Approaches in China. *Land*, *12*(5). https://doi.org/10.3390/land12051102

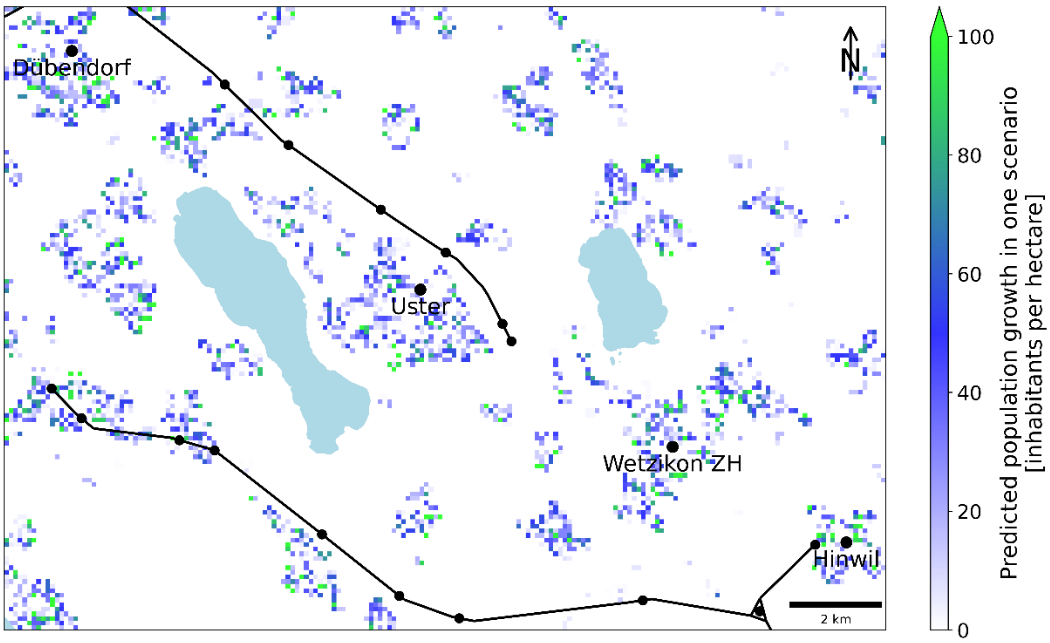
Schweizerische Nationalbank (SNB). (2024). *Devisenkurse – Jahr*. https://data.snb.ch/de/topics/ziredev/cube/devkua?fromDate=2014&toDate=2023&dimSel=D1(SEK100,CNY100)

WSL. (2008). *Häufige Fragen und Antworten zu den Folgen der Stürme Vivian und Lothar*.

C Scenarios

Appendix C illustrates how the scenarios were defined for population and employment changes. Population growth varies for each hectare cell in each scenario. On growth scenario is shown in Figure 6, this was then added to the current population distribution, available in the same spatial resolution to get a predicted future population state. The exploitation of the development potential of each cell was made randomly in each scenario, accordingly the spatial distribution of the population growth would look differently in other scenarios compared to Figure 6.

Figure 6: Spatial representation of the predicted population growth until 2050 in one future scenario derived from the total development potential according to Raum+ (2024)



The development of the employment per hectare cell, is mapped based on the observed past growth between 2011 and 2021. These growth values are then extrapolated to 2050, the resulting growth rates per district of the canton of Zurich are listed in Table 9.

Table 9: Employment growth rate per district until 2050 extrapolated from observed growth between 2011 and 2021 (Statistisches Amt des Kantons Zurich, 2022)

District	Employment growth
Affoltern	1.33
Andelfingen	1.39
Bülach	1.33
Dielsdorf	1.17
Dietikon	1.51
Hinwil	1.22
Horgen	1.06
Meilen	1.16
Pfäffikon	1.34
Uster	1.06
Winterthur	1.33
Zürich	1.48

Statistisches Amt des Kantons Zurich. (2022). *Betriebslandschaft im Kanton Zürich mit dem Bestand und den Umzügen nach Branchen, Gemeinden und anderen Kantonen*. https://www.zh.ch/de/politik-staat/statistik-daten/datenkatalog.html#/datasets/2322@statistisches-amt-kanton-zuerich

D Results

Appendix D shows additional results of the case study.

To be able to make a qualified statement on the robustness of the development variants, the variation in the net benefits can be analysed. This can be depicted for single cost components or the total net benefit (see Figure 7). Planners aim for developments providing high benefit while performing similarly in different future scenarios. In terms of uncertainty, no major variations can be seen among the developments with positive net benefits.

Figure 7: Box plot of net benefits over 10 future scenarios for 15 developments with the highest mean net benefit