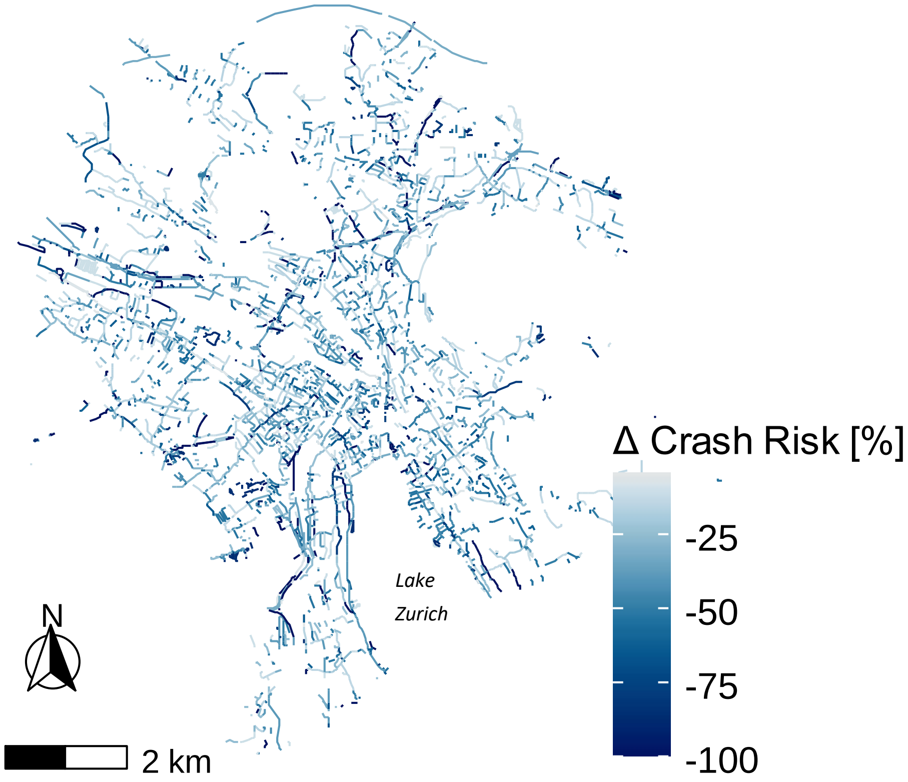


# Creating network-wide overviews of road infrastructure costs and crash risk in early planning stages

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## Abstract

Many cities aim to transition their mobility systems toward more sustainable and safer active modes, such as cycling. This involves modifying road space to improve safety and attractiveness for cyclists. However, gaining an overview of the costs and benefits of such modifications is challenging due to limited spatially explicit data about road infrastructure. These data are labour-intensive to collect across entire urban networks. Decision makers rely on such data for evidence-based planning, especially in early planning stages. This paper aims to address part of this challenge. The paper presents an approach that provides a preliminary network-wide overview of existing road space, road space modification costs, and crash risk. Using Zurich City as an example, the approach combines: (1) a machine learning model to analyse aerial images and generate a spatial overview of road space; (2) cost estimates for infrastructure modifications based on this overview; and (3) crash risk changes associated with the proposed modifications. The approach offers planners and decision-makers an overview to quickly assess potential trade-offs and benefits of road network transitions, considering costs, safety, and available road space. By providing this overview early in the planning process, the approach promotes sustainable and evidence-based mobility development in urban areas.

## Keywords

Road space; machine learning; cycling; road safety; construction cost; cost estimate; aerial imagery; remote sensing

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# 1 Introduction

Urban areas face growing pressure to promote sustainable transport modes like cycling. This is driven by rising populations (United Nations, 2019), climate change mitigation needs (Shukla & Skea, 2022), and the ambition to eliminate traffic fatalities/serious injuries under "Vision Zero" strategies (European Commission, 2011). Encouraging people to cycle requires road infrastructure that is safe and appealing for all users, including children, older adults, and inexperienced cyclists (Rérat & Schmassmann, 2024). Urban planners and policymakers are thus confronted with the task of implementing the transition away from car-based transport to transportation by active modes.

However, reallocating urban road space to encourage cycling is challenging. Space is limited, reallocations often necessitate space reductions for other modes (Ballo et al., 2024), and public resistance to change is common (Wicki & Kaufmann, 2024). Additionally, many cities lack a comprehensive, easily accessible overview of current road infrastructure, making early-stage planning difficult (Liu et al., 2021; Wysling & Purves, 2022). Estimating costs and benefits of network-wide changes is particularly labour-intensive, often requiring manual measurement and local data that may not be available . In this context, any reallocation of road space is connected to trade-offs of costs and benefits that need to be considered at the network level.

To support effective and efficient planning, cities need tools that allow for transparent, early-stage assessment and communication of road reallocation options, especially when justifying investments and seeking political support (Elvarsson et al., 2025). The capability to appraise the costs and benefits of reallocating space in a transport network in early planning stages is thus important for making informed decisions and implementing the best possible options.

This paper presents an approach to support such assessments. Machine learning (ML) and aerial imagery are used to estimate available road space. Transition options for different road types are used to calculate both construction costs and changes in crash risk. The method enables planners to explore design trade-offs early in the planning process at the network scale. The approach is demonstrated using a case study in Zurich, Switzerland, as part of the E-Bike City (EBC) project (Ballo et al., 2023).

# 2 Background

This work is part of the EBC project, which investigates the impact of reallocating urban road space for micromobility, including bicycles, scooters, and cargo bikes. Two key considerations in such infrastructure modifications are the financial investment required and the resulting change in cyclist crash risk. The objective is to provide a transferable approach for quickly estimating these impacts at the network level and enabling cost-safety trade-offs.

## 2.1 Costs of road space modifications

Estimating modification costs requires unit costs and quantities. Unit costs refer to the price of elements such as painting bicycle lanes or installing physical dividers, yet empirical cost data are limited. Cycling infrastructure is often bundled within broader roadworks, making the cost attribution ambiguous, and post-project cost summaries in Switzerland are rarely public or detailed (Zani & Adey, 2025).

Quantities depend on how much infrastructure is needed, which requires a comprehensive view of the existing road network. While data on road geometry, traffic conditions, and infrastructure are available in Zurich, similar datasets are not accessible in many cities. To support transferability, this study uses resources widely available and scalable to other locations to estimate road space: aerial imagery and ML (see Antwi et al. (2024) for an example of applying ML with aerial imagery for urban road analysis).

## 2.2 Estimating crash risk

Cyclist crash risk depends on various factors, including traffic volumes, the presence of designated cycling infrastructure, speed limits, and road user behaviour (see Salmon et al. (2022) for a recent overview). Estimating crash risk across a network is complex due to the interdependencies among these variables. One approach is to compare the modified EBC network to a reference city with similar characteristics, though this limits the ability to evaluate specific road space reallocation options.

Instead, this work quantifies crash risk changes at the road level, i.e., the expected change in crash rates and crash severity after a road is redesigned. This is based on infrastructure attributes and crash records, allowing for spatially detailed analyses of risk changes resulting from different road transition options.

## 2.3 Relevance in early planning

Cost and safety estimates are most useful when available during early planning stages (as opposed to the individual project appraisal level). However, in current practice, such analyses typically occur late in the process, once specific projects are already selected (Ackermann et al., 2014). This limits the ability to compare road design options at the network level or to make systematic decisions based on comprehensive trade-offs (Liu et al., 2021). An early-stage overview of network-wide costs and benefits supports more effective decision-making and communication with stakeholders.

Based on this background, this work presents the following in order to estimate the costs and change in crash risk of implementing an EBC: 1) A ML model to estimate available road space; 2) Bottom-up, empirical cost estimates for implementing cycling infrastructure; 3) Spatially explicit estimates of cyclist crash risk; 4) An approach to quickly estimate the trade-offs considering costs of implementing an EBC and the resulting change in crash risk in early planning stages based on the data in points 1-3.

# 3 Methods

The approach comprises several sequential steps designed to estimate construction costs and crash risk changes associated with network-wide road space modifications[1]. These steps are described below.

### Estimate available road space

Aerial imagery from swisstopo (10 centimetre resolution) (swisstopo, 2024) was used to estimate current road space. A pretrained segmentation model (YOLO11n-seg) (Jocher et al., 2023) was fine-tuned using 1,000 labelled image pairs from Zurich. After image segmentation, geometric post-processing was applied to derive road width estimates. These were validated against 100 manually measured samples and benchmarked against alternative road space estimation methods.

### Estimate crash risk

Crash risk was calculated using police-reported cyclist crashes resulting in injuries or worse (to avoid underreporting bias, as up to 90 % of cyclist crashes in Switzerland are not reported to police (Hertach et al., 2022; Ringel et al., 2023)). Each crash was assigned to the nearest road link. Annual cyclist kilometres per link were estimated using cyclist counts (Volkswirtschaftsdirektion des Kantons Zürich, Amt für Mobilität, 2024) and link lengths[2]. Crash rates were then derived as crashes per million kilometres cycled.

Road characteristics (e.g., speed limit, infrastructure, on-street parking) were used in Poisson regression and random forest models to identify significant predictors of crash rates. Severity

[1] While this paper presents the results of costs and crash risks for different road types, the approach works in the same way for intersections. The results for intersections are not shown in detail in this paper.
[2] For the present work, traffic volumes were not changed between the current state and the EBC. I.e., any mode shift effects were not considered, since this work aims to quantify the difference between the city in its current version and if it had the EBC infrastructure.

distributions were applied to estimate crash consequences per road type, which were combined with crash rates to compute total crash risk (in monetary units per million kilometres cycled).

### Define transition options

Each road type was assigned a target state based on the EBC strategy. For instance, narrow residential roads could be converted into cycling streets, while wider roads might receive protected contraflow bike lanes. Transition definitions were based on previous EBC research by Ballo and Cardoso (2025).

### Estimate construction costs

Empirical cost estimates were gathered from Swiss communes and cantons, including planning and labour components. Where available, ex-post cost data were used to validate estimates. Each road transition was linked to specific interventions (e.g., painting, installing barriers), which were monetized based on the available unit cost data. For example, converting the narrow residential street into a cycling street only requires the painting of the road surface at a cost of 90 Swiss Francs (CHF) per square meter (excluding overhead/planning costs).

### Estimate crash risk change

For each transition, the change in crash risk was calculated by comparing current and future risk estimates. For example, a residential street with no cycling infrastructure and on-street parking might have a crash rate of 2.0 per million kilometres and injury rate of 66%, while the transitioned version with cycling infrastructure and no parking would have a crash rate of 0.8 and injury rate of 50%.

### Summarise changes at the network level

The costs and crash risks were aggregated across the entire road network, enabling comparisons between different transition options. This allowed for city-wide appraisals of cost-safety trade-offs in early planning stages.

Table 4 in the appendix shows an overview of the data and models used in this work.

# 4 Results

The results of the previously defined steps are presented in the following subsections.

### Estimate available road space

The ML model was validated using known road widths, and was able to outperform other methods of estimating road widths (see Table 1).

Table 1: Comparison of accuracies of different methods for estimating road widths

| **Method** | **Mean average percent error of estimated road width [%]** |
|---|---|
| Machine learning model with aerial images | 18 |
| Land cover data | 22 |
| OpenStreetMap lane numbers | 25 |
| Expert knowledge | 35 |

Source: Adapted from Zani and Adey (2024)

The ML model performs worst on large roads over 15 meters wide (which usually contain medians), likely due to bias in the training since wide roads are relatively rare in Zurich. However, the effect of this is small, since there are relatively fewer wide roads (by length) in Zurich's road network: out of about 705 kilometres of roads, 459 kilometres are residential (around 6 meters wide) and only about 35 kilometres are primary roads (around 10 meters or wider).

### Estimate crash risk

The models show that the presence of cycling infrastructure, speed limit, presence of parking, and motorised vehicle volume have the most impact on crash rates. Other variables (such as road slope) are therefore not further considered in this work. Note that presence of trams also had a very strong effect on crash risk, but since the EBC does not alter any of the tram routes, this variable was not considered. Crash rates ranged from 0.45 crashes per million kilometres cycled per year (residential streets with cycling infrastructure, 20 kilometre per hour speed limit, without parking) to 11 (collector roads without cycling infrastructure, 50 kilometre per hour speed limit, without parking). Note that crash rates were truncated at 11. Only 15 road types (out of 282) had higher crash rates (up to 152) due to being relatively rare combinations of road factors.

### Define transition options

Ballo and Cardoso (2025) identify the possible transitions for different road types in the EBC. The transitions range from relatively cheap to expensive – with the approach shown here, planners would be able to choose which design is to be implemented, based on the estimated costs and crash risks (along with other considerations, such as ease of implementation, subjective safety, changes to accessibility, etc. These considerations are not included in the present work but in other parts of the EBC project).

### Estimate construction costs

Since each road type can be transitioned in several different ways, the results here show the average of all possible transitions and the minimum possible costs per road type (Table 2).

Table 2: Overview of the costs of transitioning each road type

| **Road type** | **Length of network [kilometres]** | **Costs to transition [thousand CHF per kilometre]** | |
|---|---|---|---|
| | | Average of all design options | Lowest cost design option |
| Residential | 459 | 423.5 | 48.5 |
| Secondary | 149 | 601.6 | 73.3 |
| Secondary with tram | 59 | 165.1 | 67.1 |
| Primary | 29 | 856.6 | 112.1 |
| Primary with tram | 9 | 149.3 | 81.4 |
| Entire network | 705 | 453.7 | 58.3 |
| Total cost | | 320 million CHF | 41 million CHF |

Note: Costs are indexed to the year 2024 and include overhead/planning costs (20 %). The road types shown here are the ones defined by Ballo and Cardoso (2025). CHF = Swiss Francs.

Implementing the EBC will thus likely cost around 320 million CHF for reallocating road space (excluding intersections), but could cost as little as 41 million CHF if the cheapest design options are selected. The large difference between the average costs and lowest costs can be explained primarily by the use of red paint. In most transition design options, all bicycle surfaces are painted red. This amounts to over one million square meters of red paint across the city. At over 100 CHF per square meter, this becomes the dominating cost item for the “average design option cost” in Table 2, while providing little crash risk reduction beyond the physical separating elements between bicycle and car lanes (red paint mainly serves to increase subjective safety and cyclist comfort, which is not considered in the present work). Omitting the red paint results in significantly lower costs, as shown by the “lowest cost design option” in Table 2. This shows there is a trade-off between construction cost and (mainly) subjective safety that should be considered when choosing road transitions. Roads with trams are less expensive to transition since the tram lines cannot be moved, resulting in relatively less construction and therefore lower costs than when the road has no tram lines. Note that the re-design of intersections for the EBC would cost about an additional 315 million CHF. There are about 3,100 intersections in the city, 400 of which include traffic lights. Re-design of a small intersection costs around 10,000 CHF. The re-design of a larger intersection including reprogramming its traffic lights costs around 500,000 CHF (see Appendix B).

### Estimate crash risk change

Implementing the transitions for each road type reduces the average crash rate (all severities, across all road types) from 3 crashes per million kilometres cycled per year to 2.3 (23 % reduction). For the entire network, the crash rate is reduced from 2.58 to 1.54 (40 % reduction). The number of expected crashes resulting in injuries is reduced from 551 to 331 per year (40 % reduction), and the number of serious injuries and fatalities is reduced from 6.5 to 2 (71 % reduction) (Table 3). The rate of crashes with (serious) injuries or fatalities is therefore reduced more than the rate of crashes without any injury. These changes in crash risk were monetised using norm-based crash consequence costs (VSS, 2019).

Table 3: Overview of the change in crash risk when modifying Zurich into an E-Bike City

| | **Status Quo** | **EBC[1]** | **Difference** |
|---|---|---|---|
| Number of cyclist crashes per year (all severities) | 750 | 614 | 136 |
| Cyclist crashes resulting in injury per year | 552 | 331 | 221 |
| Cyclist crashes resulting in severe injury/death per year | 7 | 2 | 5 |
| Crash-related costs per year (MCHF[2]) | 51 | 29 | 22 |
| Cost over 25 years (undiscounted, in MCHF) | 1272 | 731 | 541 |
| Cost over 25 years (discounted with 2%, in MCHF) | 993 | 571 | 422 |

[1] E-Bike City; [2] Million Swiss Francs

### Summarise change at network level

The network-level costs and crash risk changes were presented in the previous subsections. In this example, it becomes clear that transitioning Zurich’s roads to EBC-designs could cost as little as 41 million CHF, and result in yearly savings of about 22 million CHF in cyclist crash costs. A planner or decision-maker would now be able to change transition options at will to explore how costs and safety may be traded. This would not be possible if either costs or crash risk were estimated at a higher, aggregated level, as is often done.

# 5 Discussion

This work aimed to present several contributions to the process of appraising modifications of entire road networks. First, a ML model to estimate available road space was presented. It is based on pre-trained, open-source models. The ML method achieved accuracy for estimating road widths (18 % average error) that outperformed other methods, while also being unaffected by data scarcity that could affect other cities (since aerial imagery is widely available). This

ML-based approach is therefore promising to produce the required data on available road space when planners are appraising options for redistributing existing road space (or for any other task that relies on information about road space).

Second, an approach to making spatially explicit, empirically-based cost estimates for road modifications was introduced. Most studies that estimate costs and benefits of cycling infrastructure projects use aggregated unit costs for construction. For example, Paulsen & Rich (2023) use data from Nielsen et al. (2018), who report that "inner city finger routes" cost about 250,000 CHF per kilometre. Such an estimate is not able to account for any of the context of the actual road being modified, and changes in the design of an "inner city finger route" cannot be considered. While the demonstrated approach is likely not as accurate as an estimate made for a specific project, it is likely accurate enough to produce a realistic overview of network-wide costs. Usually, early-stage cost estimates for Swiss transportation projects deviate by +/-60 % (Zani & Adey, 2025) – some uncertainty is to be expected, especially considering the compounding uncertainty of actual road space. However, when averaged over an entire network, this approach is able to show how costs change when different road transitions are considered.

Comparing these estimates to other empirical cost data shows that the estimates are realistic. Various (anonymous) cantons and communes have provided data showing that cycling infrastructure projects can cost between 30,000 to 500,000 CHF per kilometre, based on the amount of interventions. This matches well with the values in Table 2. Current public cost estimates for expanding cycling infrastructure in Zurich are significantly higher (Ledebur, 2025). However, this is unsurprising considering that these public estimates include large, expensive investments (including bicycle bridges), while the EBC strategy is to prioritise low-effort/cost interventions that are still able to improve safety.

Third, an approach to estimating the expected change in crash risk across an entire network was shown. Combining several different types and sources of data, crash risk was estimated for various different types of roads. The data for bicycle traffic volume is the least accurate, as it is based on a four-step transport model. The overall yearly cycled kilometres matches well with values from other sources (PLANAR AG, 2023), but individual road volumes deviate from the values observed by counting stations by 65 % on average. However, the overall good calibration suggests that, over the entire network, these traffic volumes are valid for comparing possible road designs.

The estimated crash rate also matches rates communicated in other sources. The crash rate (involving cyclists and resulting in at least injury) in Zurich in 2023 was about 2.32 per million kilometres cycled. The estimate for Zurich (as-is, not the EBC version) based on the presented approach is 2.58 (11 % deviation). A top-down approach for estimating EBC crash risk changes via comparisons to other cities also shows that the approach in the present work produces plausible results. For example, in Amsterdam and Utrecht, the crash rate is about 0.6 and 1.1 (Zani et al., 2024), compared to the EBC estimate of 1.54. Comparisons to such cities would consider more holistically the complexity of urban mobility, including cultural factors that cannot be approximated by the approach presented in this work. Bern, a city in Switzerland known for strong progress in implementing cycling infrastructure, had a crash rate of about 1.77 in 2023.

Lastly, it was shown how the presented approach can aid planners and decision-makers when making trade-offs between costs and safety. Specifically, in the examples presented, it was shown that around 300 million CHF could be saved if bicycle lanes are not painted red. In this case, crash risk was not affected, but other effects could be considered to quantify a potential loss in benefits. Similarly, any combination of road space transitions can be compared to quantify the resulting changes in costs and crash risk, without much additional computational effort, and for the entire city.

# 6 Conclusion

This study presents an approach for rapid, network-level early-stage estimates of construction costs and crash risks when reallocating road space. By integrating ML-based road width estimation, empirical cost data, and crash risk modelling, it enables planners to evaluate cost-safety trade-offs effectively.

Limitations include data accuracy, particularly in traffic volume modelling, and potential ML model biases. Further improvements, such as microscopic simulations for traffic volumes (Wage et al., 2022) and enhanced cost data collection across Swiss governmental levels, could refine estimates. Survey-based methods to account for crash underreporting (Ringel et al., 2023) would also improve the results by quantifying the reduction in crashes that are often not reported to police. While applied to Zurich’s EBC case study, further validation against existing planning processes is needed to assess its impact on decision-making.

# 7 Acknowledgements

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# 9 Glossary

| | |
|---|---|
| CHF | Swiss Francs |
| EBC | E-Bike City |
| ML | Machine Learning |

# A Appendix

Table 4: Overview of data and models used in this work.

| Task | Data/Model | Source | Comment |
|---|---|---|---|
| Estimate road space | Aerial images | Swisstopo | 10 cm resolution |
| | Pretrained image segmentation model | Ultralytics | YOLO11n segmentation model |
| | Land cover class “road” | Swiss Federal Office of Statistics | |
| Estimate crash risk | Link-level traffic volumes | GVM Canton Zurich | Approximates actual volumes |
| | Reported cyclist crashes | ASTRA VUGIS | Years 2017-2020 |
| | Speed limit | GVM Canton Zurich | |
| | On-street parking | OSM | |
| | Road type | GVM Canton Zurich | |
| | Cycling infrastructure | OpenStreetMap | |
| Define construction costs | Empirical cost data | Swiss communes and cantons | Mix of cost estimates and ex-post costs |

# B Appendix

Table 5: Overview of intersection modification costs.

| Type[1] | Description | Count | Cost per intersection [KCHF][2] | Total cost [MCHF][3] |
|---|---|---|---|---|
| 1 | Residential x Residential | 1809 | 36 | 65 |
| 2 | Secondary x Residential | 693 | 10 | 7 |
| 3 | Secondary x Secondary | 54 | 124 | 7 |
| 4 | Primary x Residential | 118 | 120 | 14 |
| 5 | Primary x Secondary | 31 | 452 | 14 |
| 6 | Traffic Lights | 392 | 400 | 157 |
| Total (average) | | 3097 | (190) | 264 |

[1] According to Ballo and Cardoso (2025), [2] thousand Swiss Francs and [2] Million Swiss Francs, both excluding 20 % overhead/planning costs

Accounting for the 20 % additional overhead/planning costs brings the total to 316 million CHF. A cheaper option is possible for residential-residential intersections that costs about 8,000 CHF per intersection. This would bring the average cost down to 186,000 CHF per intersection, or a total of 213 million CHF (256 million CHF with 20 % overhead costs).