

# Spatial information for safer bicycling

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## Abstract

The need for sustainable modes of transport is obvious, especially in urban areas. Because of the large number of trips within cities and distances lesser than 5 km, the bicycle is regarded as optimal mode of transport, both for utilitarian and leisure trips. Nevertheless, safety concerns are among the most relevant factors that hamper an increasing bicycle usage. Geographical information systems (GIS) with their ability to model and analyze road infrastructure and users in an explicitly spatial context can significantly contribute to meet these safety concerns. They can be employed in all stages of better understanding bicycle safety as a spatio-temporal phenomenon and provide the basis for informed decisions in the context of planning, information provision and cycling promotion.

After a short introduction about why it is necessary to address safety issues in the promotion of the bicycle as sustainable mode of transport, the benefits of a spatial perspective on the road space and its users are described. The main argument is that road traffic, and with this road safety, are spatial phenomena by their very nature and thus GIS can significantly contribute to various applications that foster safety improvements for bicyclists. In order to demonstrate how spatial information can be incorporated in various contexts, several application examples and case studies, where spatial modelling and analysis are key features, are given. Based on this overview a final section provides a brief outlook of current and future research topics that aim to further make use of spatial information for safer bicycling.

## 1 The bicycle as sustainable mode of transport

Numerous negative impacts of motorized traffic – from air pollution [1] to economic externalities [2] and social inequities [3] – have led to a growing demand for sustainable modes of transport; especially in densely populated, urban environments. This development has increasingly brought the bicycle, as sustainable and cost-efficient mode, into the focus of researchers, planners and decision makers [4]. Masterplans for bicycle traffic and bicycle promotion initiatives from local to transnational levels are indicators for this (re-) discovery of the bicycle [5].

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### ***1.1 Bicycle traffic and safety concerns***

Due to extensive bicycle promotion initiatives, many cities in Europe have successfully built or extended their bicycle infrastructure. This has significantly contributed to a constantly rising number of bicyclists on the roads [6]. But still, there are some influential factors which keep people from using the bicycle for their utilitarian mobility needs, above all safety concerns [7, 8]. Although sound exposure data are rare [9], there are indications from literature and official statistics, that cycling is healthy, but dangerous related to the travelled distance [10]. These findings are in line with a recent report by the European Commission on road safety. There, the EC points to the fact, that contrary to the overall trend, the number of killed bicyclists has been increasing during the last couple of years [11]. Thus, it can be stated, that perceived and object safety is a key issue in the context of promoting the bicycle as sustainable mode of transport [12, 13].

### ***1.2 Improving bicycle safety***

In order to improve safety for bicyclists, at least three issues (“safety pillars”, adapted from [14]), which are interrelated, need to be addressed on various levels:

- First of all, the infrastructure and regulative interventions need to be designed in a way that potential risks for bicyclists are minimized [15]. This can be done, for example, by separated bike lanes, controlled intersections or actions to reduce motorized traffic and speed [16].
- Secondly, the bicyclist’s physical condition, experience, compliance with road traffic rules and the technical condition of the vehicle must be taken into account. Although “individual” factors do not fully explain all incidents, it is noteworthy, that – depending on the source – 5-30% of all fatal injuries to bicyclists are caused by single-bicycle crashes [17]. However, targeting the mentioned individual risk factors requires an integrated approach comprising actions from traffic control to awareness initiatives.

- As a third aspect, bicycle safety can be improved by context-sensitive information about the environment, such as high-resolution, near-future weather data and specific information offers about optimal (safe) routes [18]. Such routing recommendations aim to minimize the bicyclist's exposure to risk factors, such as primary roads with a high traffic load or roads without any bicycle infrastructure.

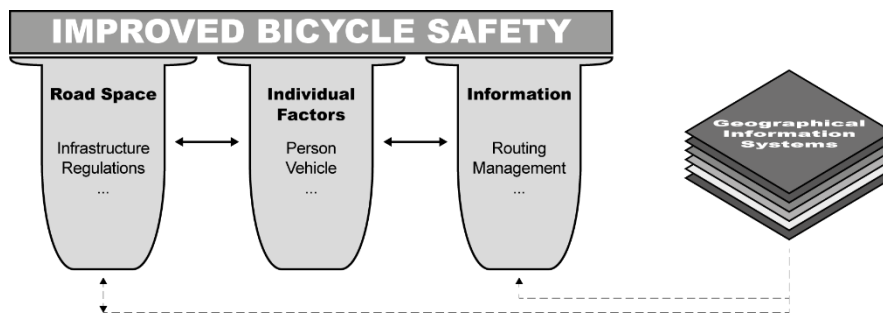


Fig. 1. Three approaches for the improvement of bicycle safety, adapted from [14].

Individual factors which potentially contribute to an improved bicycle safety cannot be directly targeted by geographical information systems. But GI systems allow for a systematic, digital representation of the road space, including the physical and legal characteristics. Additionally the spatial location can be used as a common denominator for multiple perspectives on the road space. Thus GIS can facilitate an interactive communication about the physical space in a digital, map-based environment [19, 20]. Existing authoritative, commercial or crowd-sourced data can subsequently be managed, modeled and analyzed in geographical information systems and in turn serve as basis for innovative planning and information applications. Thus GIS can be – and is – employed in various planning contexts, from status-quo analysis to simulation, in the management and improvement of existing infrastructure systems, for participatory settings, such as feedback portals, and for user-specific information applications.

In the following sections it is briefly argued why and how geographical information systems can contribute to a better understanding of bicycle safety and how these insights can be used for informed planning and management decisions and information applications. As safety concerns and evident safety threats hold back potential bicyclists, tackling these aspects

from several sides should be part of any integrated effort to promote sustainable mobility, especially in urban environments.

## 2 What GIS can offer

Bicycle safety is a complex spatial and temporal phenomenon with multiple influential factors, such as the built infrastructure, the traffic volume, weather conditions and the individual bicyclist as an entity in physical space and time. In order to better understand this multi-faceted phenomenon with all dependencies and relations, an integrated perspective which brings together any kind of information about the road space and its users is required. Geographical information systems allow for such a perspective as the road space, any events and users are spatial by their very nature or can be spatially related (geo-located). Thus they can be digitally captured, related, analyzed and mapped.

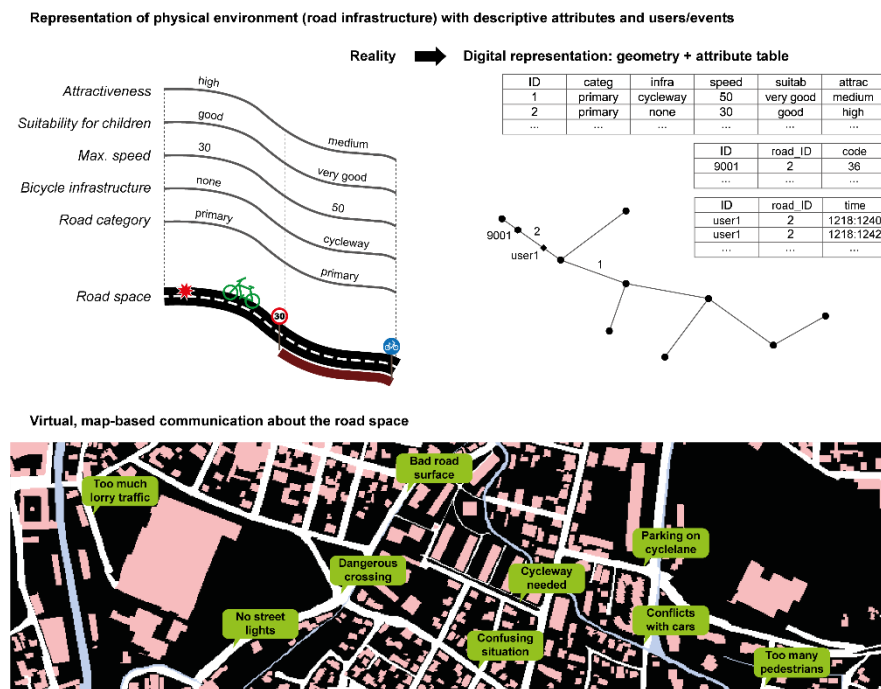
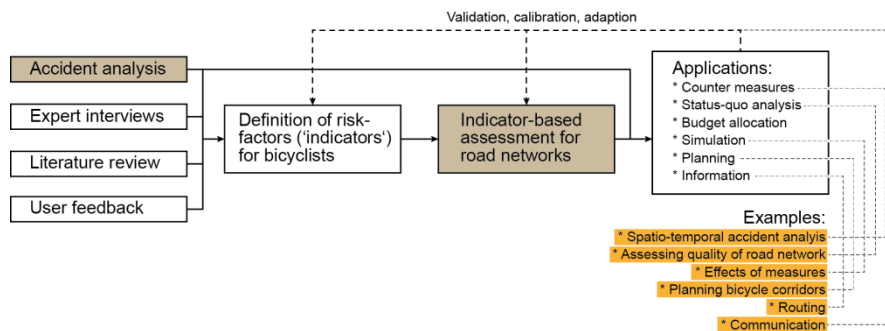


Fig. 2. GIS as integrated platform for multiple perspectives on the road space.

GIS is used for the digital representation of the physical environment with an (theoretically) unlimited number of descriptive attributes, for users and events in this environment and for the virtual, mainly map-based communication about this digitally represented space (see figure 2). Using the geographical location as common denominator many more information layers can be related to the digital representation of the road space as such. Through overlay techniques queries and analysis can be done over multiple layers and finally visualized in maps.

Whereas established domains dealing with mobility and transportation – such as traffic engineering, telematics or planning – have a specific, rather “technical” view, geographical information systems can beyond that serve as integration platform where multiple perspectives – “technical” as well as qualitative – on the road space can be merged. GIS thus allows for a holistic approach towards a better understanding of bicycle safety and facilitates innovative applications for several domains.

Providing a sound data basis in the context of the promotion of safe cycling is of great importance for informed decisions. The consideration of explicit spatial characteristics is especially valuable in the analysis of bicycle accidents and in the assessment of the road network’s quality in terms of bicycle safety, which in turn serve as basis for several applications (for a general introduction to GIS in the context of road safety see [21]).



**Fig. 3. Multi-stage workflow to provide sound data and analysis results for informed decisions in the context of bicycle safety. The employment of GIS especially allows for additional insights in accident analysis and assessment approaches (light brown, see [22]). The result of an integrated spatial analysis approach can then form the basis for various applications (yellow).**

In order to show the potential of an explicit consideration of space in the analysis of bicycle safety and in the promotion of safe cycling as sustainable transport mode, multiple examples are provided in the following sections. These examples can be related to or are the outcome of a multi-stage workflow which comprises several tasks that rely on GI technology and tools (see figure 3).

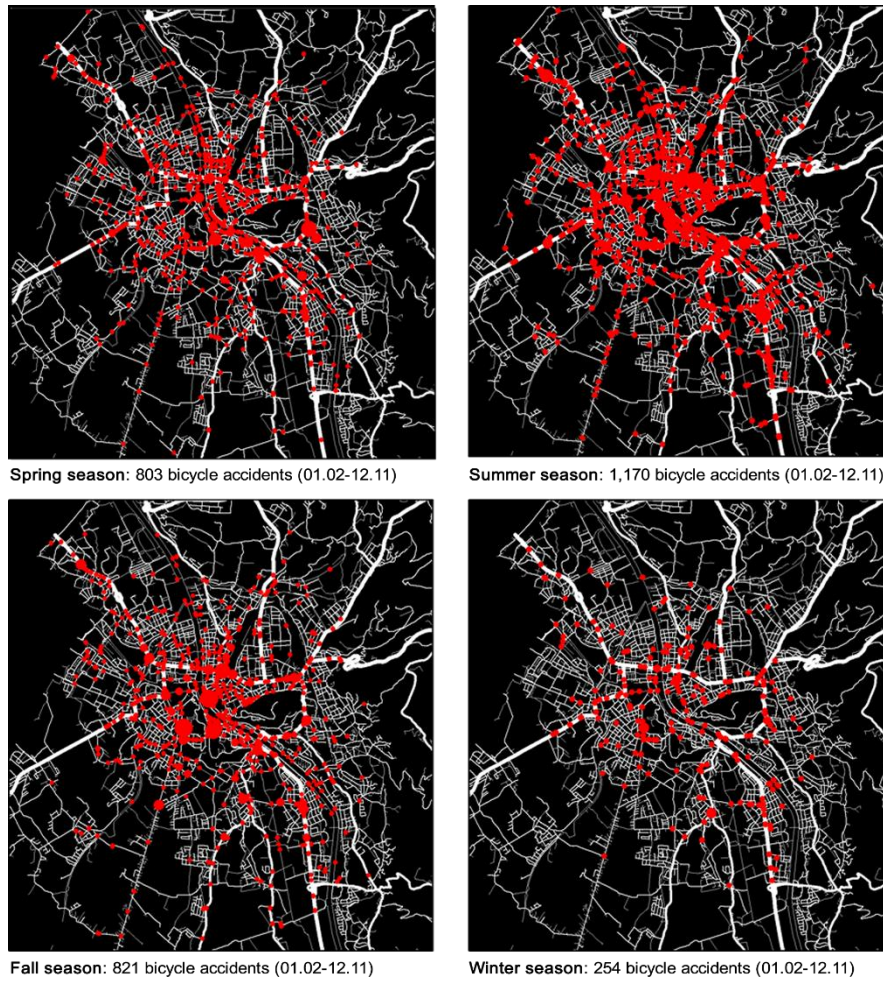
### ***2.1 Spatio-temporal accident analysis***

Analyzing bicycle accidents with GIS helps to better understand where, when and under which physical conditions accidents did or are more likely to occur.

Currently, mainly two, explanatory approaches are applied in order to better understand the mechanisms behind bicycle accidents. Firstly, epidemiological approaches (see [23] for a methodological overview) aim to calculate risk factors that lead to bicycle accidents with a certain probability. For this, mainly aggregated accident data are related to a statistical population: [24] use census districts as aggregation level for a multivariate statistical analysis. [25] calculate the risk exposure for person kilometers travelled, based on estimated distances per census districts. Secondly, in-depth analyses of detailed accident reports seek to identify individual, contributing risk factors. In an extensive study [15], for example, relate accident reports, including socio-demographic variables of involved persons to different route types. In doing so, physical conditions that increase the risk for bicycle accidents (e.g. downhill grade, major streets with on-street parking) could have been identified. Findings from such analyses serve as important input for further assessment approaches (see section 2.2 and figure 3).

Apart from essential issues concerning the data quality and methodology (discussed in detail in [26]), the two mentioned approaches do not explicitly put single accident occurrences into a spatio-temporal framework. Thus spatial and/or temporal autocorrelations are rather seen as biasing factor than as a fundamental characteristic of accidents. But for targeted counter measures the explicit consideration of the spatial and temporal setting of

accidents is decisive. Thus exploratory analysis approaches, such as [27], are required in order to analyze the spatio-temporal distribution of accidents.



**Fig. 4. Spatial distribution of bicycle accidents in the city of Salzburg (Austria) for each season. Preliminary results from an ongoing study.**

In an ongoing study we have found, that bicycle accidents are highly clustered within the road network and that the temporal variation – in several scales – is significant. First results of a case study indicate that during the summer months bicycle accidents in the investigated city are, contrary to the “safety in numbers phenomenon” [28, 29], a function of the bicycle

volume. Significantly more accidents than expected from a random distribution occur on major bicycle connections without any motorized traffic and an excellent bicycle infrastructure. In contrast to this, more accidents (than expected from random distribution) happen on radial connections with less or no bicycle infrastructure during the winter months (figure 4 shows the single locations of bicycle accidents for each season).

Counter measures, such as infrastructure adaption, traffic management or road surveillance, can be planned much more effectively when the spatial and temporal hot spots are known. In order to find the most suitable measure for individual hot spots, an in-depth analysis of the respective incidents is required. Through the preceded analysis, which functions as filter, these detailed investigations can be done much more efficiently than in a global setting.

## ***2.2 Assessing quality of road network in terms of safety***

Based on findings from accident analyses, literature reviews, expert interviews and extensive user feedback, indicators that contribute to a potential safety threat for bicyclists, both perceived [30] and objective [31], can be identified and compiled in a weighted, global assessment model. As it is indicated in figure 3, the setup and calibration of the assessment model is an iterative process. Hence the result of the quality assessment depends on the indicator selection and definition of the single weights.

Compared to other assessment routines, such as in-situ expert assessment, the indicator-based assessment model has several advantages [22]: Firstly, the composition of the assessment result can be traced back to the smallest building blocks of the model. This transparency ensures a straight-forward interpretation, independent from the user. Secondly, the model is adaptable. This means that the indicator set and the weights can be adapted in a way that they reflect the actual situation as optimal as possible. Thus the model allows for example for a differentiation between rural and urban environments where the risk factors for cyclists tend to be different [32]. Thirdly, the model generates comparable outputs and facilitates comparison tasks between different regions or time slices, based on standardized



inputs and analysis procedures. Related to this, the results can be reproduced and the model can be applied multiple times. Accordingly the model is perfectly suitable for simulation purposes (see next section). The assessment of a whole road network in terms of bicycle safety is the starting point of any further planning activity. It helps to gain an overview of the overall quality of the network, identifies missing connections and makes weak points in the system obvious.

### *2.3 Spatial simulation for safety improvement*

Geographical information systems are not only suitable to accurately represent the current situation of the road space, but also to simulate future or alternative scenarios [33]. Simulations in this context can either focus on the environment or the road users and their behavior and demands. Both aspects are being dealt with in the following.

The first application context of spatial simulation is built on models such as the aforementioned indicator-based assessment model. Here the model is used to extrapolate the effect of changes in the road space, which is reflected in the model as indicator. For example it can be simulated with which measures the quality of a given segment could be increased. An arbitrarily selected segment has, for example, an index value of 0.63, whereas the neighbouring segments have index values of 0.31 and 0.36<sup>2</sup> respectively. The index value – and thus the quality in terms of bicycle safety – could be changed in the following way:

- Bicycle lane, no other change: 0.44
- Physically separated bicycle way, no other change: 0.37
- Calmed road, no other change: 0.49

This example illustrates the benefit of a model-based simulation, implemented in a geographical information system. Such simulation results can serve as basis for informed decisions in the process of planning or budget allocation, as they comprehensibly test the effect of measures before in-

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<sup>2</sup> The index value is standardized between 0 (excellent) and 1 (poor) and depends on the model parametrization.

vestments are made. Combining the simulation of measures with additional decision factors, such as the legal scope or monetary costs, results in a multi-criteria optimization problem which is to be finally solved by decision makers. Spatial simulation and analysis provides the basis for informed decision making processes.

A second simulation approach, which should be briefly discussed in the context of bicycle safety, focuses on the road users (either grouped or individually) in a given network. Here the amount and quality of traffic (e.g. bicycle flow, socio-demographic composition of road users etc.) is estimated for different spatial units and time intervals. Knowing when and where how many and which bicyclists are on the road is important to know for several reasons. Firstly, bicycle incidents need to be related to a statistical population in order to calculate risk functions properly. Secondly, to eliminate potentially dangerous bottlenecks in the system, the capacity of existing infrastructure needs to be adapted adequately to the demand. And thirdly, the decision on building new infrastructure should be based on expected needs and demands, in order to ensure a maximum effect at reasonable costs. Based on an example from Denmark, [34] point to the fact, that such an evidence-based approach is rather unusual in the planning of bicycle infrastructure.



**Fig. 5. Agent-based model simulation of bicycle traffic: randomly distributed origin-destination relations with agents (left) and most frequently traversed segments in the network (right). Preliminary results from an ongoing study.**

Well established methods for simulating the current or future amount of traffic for different settings and level of details already exist. They range from traffic demand models [35] to cellular automata [36], game theory [37], flow model simulation [38] and agent-based models [39]. All these

methods were primarily developed for car traffic and partly for public transport. For active modes of transport only very few examples exist (e.g. [40] for pedestrians in a main station). This is mainly due to the lack of data, since there is, for example, no obligation to register bicycles and counting stations are hardly ever distributed representatively in the network.

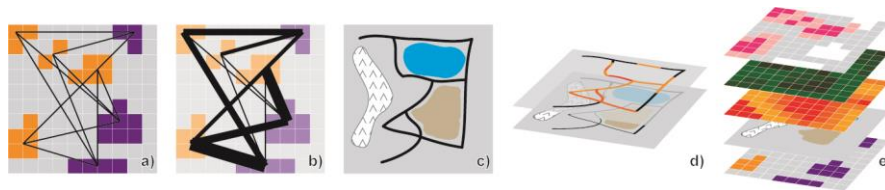
Nevertheless, there are promising attempts to estimate bicycle flows on a macroscopic level. In an ongoing study we combine GIS with agent-based model techniques in order to simulate bicycle flows in an urban road network with a total length of roughly 800 km (see figure 5). Major advantages of this approach are the possibility to simulate different behaviors (e.g. mode choice preferences) and interactions with the road environment and other external factors (e.g. weather, other road users) while putting the agents in an explicit spatial context (e.g. characteristics of road network, location of residential and commercial areas). Beside an estimation of the number of bicyclists for the whole network, potential bottlenecks, hot-spots and central (= frequently traversed) segments can be identified. Such insights help to provide a basis for the abovementioned issues and partly tackle the problem of a significant data shortage [9]. Given the availability of real-time data of traffic flows, incidents, temporal construction sites etc., these data could be managed in a spatial data base and provided for adaptive simulation settings.

## ***2.4 Planning bicycle corridors***

Based on status-quo analyses of the network in terms of safety and a sound estimation of the spatio-temporal distribution of bicyclists, further analyses for the establishment of straight connections with high capacity (“bicycle highway”) can be conducted. These connections play a key role in the establishment of the bicycle as sustainable mode of transport for daily commuters in urban agglomerations where the distance travelled and the travel time are frequently disproportionally related [41]. Apart from being a cost-efficient and sustainable alternative to motorized traffic, infrastructure which is dedicated to bicyclists contribute to a higher level of de-facto and perceived safety [42].

The planning of bicycle corridors requires several spatial analysis steps, which can be put into practice with common GIS software (see figure 6):

- Identification of major relations (functional connections) between origin and destination locations (see previous section), step a).
- Prioritization of OD-relations based on demand, planning strategy, target group etc. step b).
- Generation of ideal connections, either independent from and/or based on existing road network, step c).
- Identification of existing segments which could be part of a straight connection, based on their suitability (capacity, safety, accessibility etc.), step d).
- Optimization of multi-criteria problem (available space, monetary cost, legal scope etc.) to build missing bicycle infrastructure, step e).



**Fig. 6. Systematic planning approach for bicycle corridors. GIS is employed in all steps with spatial query, filter, overlay and network analysis functionalities.**

These steps can be applied in any environment and scale level. But generally, the designation of bicycle routes with high-capacity infrastructure is most efficient in urban agglomerations with overall bicycle promotion strategies. Current examples can be found in Copenhagen<sup>3</sup> or London<sup>4</sup>.

## 2.5 Routing

Addressing the third safety pillar (figure 1) routing portals play a central role in the user-specific information of bicyclists. Routing services – espe-

<sup>3</sup> <http://www.supercykelstier.dk/concept> (accessed Dec. 23<sup>rd</sup> 2014)

<sup>4</sup> <http://www.tfl.gov.uk/modes/cycling/routes-and-maps/barclays-cycle-superhighways> (accessed Dec. 23<sup>rd</sup> 2014)

cially when they are enriched with additional information that is relevant to bicyclists – contribute to the attractiveness of the bicycle (see e.g. [43] and [44] for the aspect of information and culture in the context of bicycle promotion) and are a perfect medium to recommend safe connections. The following brief case study demonstrates the contribution of such a routing service to an overall strategy of (safe) bicycle promotion and shows the potential of GIS as toolset and platform for several steps in a multi-stage workflow (see figure 3).

Salzburg – capital of the homonymous federal state, with approximately 150,000 inhabitants – has been following a sweeping strategy for bicycle promotion for more than two decades. A fixed sum is invested into infrastructure projects every year, resulting in a tight network of bicycle facilities with radial and tangential high-capacity connections. Through these substantial efforts, together with different accompanying actions, a modal split of approximately 20% for the bicycle could have been reached. In order to further increase the number of bicyclists, the responsible administrative bodies have expanded their promotion strategy and started to invest into user-specific information.

The central application of this information offer is a routing service which is available over the internet ([www.radlkarte.info](http://www.radlkarte.info)) for both, desktop and mobile devices. The service basically provides two route options, where one is the shortest connection between origin and destination and the other the most suitable (for legal reasons it's not labeled as safest route). The latter result is based on the already mentioned indicator-based assessment model. This model calculates the potential safety threat for each segment, expressed as an index value which is further used as impedance in the route optimization algorithm. Similar to the simulation use case, the system's architecture is open to implement real time data. Additionally the service, as it is built upon a spatial data base with GI capabilities, allows for the integration of any further, spatial information layer. The application provides for example a detailed profile (derived from high-resolution laser scan elevation model), calculates travel time and energy costs, shows up-to-date departure times of public transport stops and combines the route recommendation with current weather data in the map view. So, not only the route optimization, which is a core spatial analysis task, but also the

data preparation and the provision of additional information relies on GI technologies and tools. Especially the data pre-processing and the data modelling in a spatially enabled environment allows for an explicit consideration of bicycle safety and distinguishes the application from similar products [22].

The present routing platform is intended to be an additional building block of a comprehensive bicycle promotion strategy, which considers both, the infrastructure and the user-specific information offer. Such offer about safe routes aims to support everyday bicyclists in their route choice and raises awareness for the bicycle as sustainable (and safe) mode of transport.

## 2.6 Communication

The perception of the road space heavily depends on the transport mode of the road user [45]. In order to consider the specific perspectives and demands of bicyclists in citizen-centered, participatory applications, it is necessary to provide adequate communication tools.



**Fig. 7. Examples for different forms of location-based communication in the context of bicycle safety<sup>5</sup>**

Generally these tools use the geographical location as reference to ensure an effective communication. Location-based communication in the context of bicycle safety can take different conceptual, organizational and technical forms (see figure 7):

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<sup>5</sup> Sources (from left): <http://www.openstreetmap.org>, <http://radlkarte.info/>, <http://youtu.be/18eFQwsf8S4> and <https://radsicherheit.berlin.de/diskussion> (all accessed Dec. 29<sup>th</sup> 2014)

- Unidirectional, passive communication agent – server: bicyclists on the road are used as sensors [46] and contribute, for example, to the generation of real-time traffic flow visualizations. Bicycle flows can also be derived from unlabeled trajectories with segmentation algorithms [47].
- Unidirectional communication server – agent: from a server information about optimal or safe routes are communicated to the bicyclist's smartphone [18]. These recommendations are either built on models (as described in the previous section) or on crowd-sourced information<sup>6</sup>.
- Unidirectional feedback agent – server: the ubiquitous availability of smartphones and mobile internet connection enables bicyclists to give in-situ feedback concerning the quality of road space in terms of safety or to assess the plausibility of routing information. These feedbacks are collected on a central server and serve as valuable information for targeted infrastructure measures and other safety improvements or as inputs for the calibration of routing recommender systems (see figure 3).
- Discussion about road space: maps are ideal communication and negotiation platforms about space, either asynchronous or in real time [48]. In the context of bicycle safety maps could be utilized to present and discuss measures to improve the overall safety, for example where it is most urgent to build a new cycle way etc. The applicability of such an approach has been tested, just to name an example, for the installation of a new bus line by [49]. The reliability of citizen's judgments was investigated among others by [50].

Berlin launched an extensive, digital dialog about bicycle traffic in the late fall of 2013, following a community approach with options to comment, rate and discuss postings. Within only one month 3,300 registered users contributed 5,000 posts and 4,000 comments. Basically all contributions had to do with safety, either directly or indirectly (see [51] for details).

Independently from the design of the communication platform, all of them use GI technology at the system's backend or for the visual interface,

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<sup>6</sup> Numerous examples for these community projects can be found on the internet, e.g. <http://cms.meineradspur.at/machmit.html> or <http://www.naviki.org> (both accessed Dec. 27<sup>th</sup> 2014)

mostly maps. The spatial data generated this way are not only used for visualizations, but as inputs for analyses, modelling and planning purposes.

### **3 Conclusion and outlook**

The need for more sustainable mobility, especially in urban agglomerations, is evident. Because of the bicycle's numerous advantages in this respect, it has come into the focus of nearly all urban sustainability strategies. Mobility in general is a complex, highly dynamic system. The same holds true for any specific mode of transport, in this case the bicycle. Consequently bicycle promotion cannot consist of single, isolated measures but must follow a system approach [52], targeting various interests. Geographical information systems facilitate such an integrated approach, which is demonstrated in the context of bicycle safety. Referring to the threefold safety concept, sketched in figure 1, it could have been shown how GIS concepts, technologies and tools address and contribute to the planning and maintenance of safe bicycle infrastructure and to user-tailored information services. Spatial analysis and modelling are at the center of a better understanding of bicycle accidents as spatio-temporal phenomena, of integrated planning, information and communication applications. In all these applications, the geographical location serves as common denominator, allowing for a combination ("overlay") of multiple information layers.

An iterative workflow, built around the indicator-based assessment model proposed by [22], incorporates and links several of these modelling and analysis components. The assessment approach can either be employed in a more efficient way to plan and build infrastructure ("What's the effect of building a cycleway at a particular road?") and take regulative actions ("To what degree would the road become more bicycle-friendly, if the maximum speed is lowered?") or as basis for innovative information applications such as routing and communication platforms.

In order to further enhance the contribution of geographical information systems to the promotion of safe bicycling, the following topics should be addressed in further researches:



- **Personalization.** Currently bicycle route recommendations mostly address an average user, who factually does not exist. Bicyclists have a broad range of preferences: whereas daily commuters prefer direct routes, parents with young children might prefer safe connections with designated bicycle infrastructure [53]. In a configurable model environment, individual preferences and perspectives on the road space can be integrated in the pre-configured assessment model and consequently contribute to personalized information products. How individual peculiarities can be transformed to code-readable model inputs and how these inputs should be weighted is subject to research. [54] provide first results of an investigation of algorithms for personalized bicycle route recommendations.
- **Socialization.** All technical and organizational efforts that contribute to a more social environment where experiences, feedback messages and updates are shared among several instances (bicyclists, authorities, event organizers, public transportation operators etc.) could help to further increase the attractiveness of the bicycle as a sustainable and safe mode of transport. Current research topics would be, among others: inter-bicycle communication, participatory planning processes or the provision of safety-relevant real-time data (e.g. information about snow removal or temporal construction sites).
- **Contextualization.** Retrieving information about safe routes or giving feedback to a current situation in road space are context-sensitive activities. Frameworks for providing applications that adapt to the current context exist [55]. But to our current knowledge there is hardly any research done so far in the context of safety information for bicyclists. Again, the geographical location is highly suitable for indicating the actual environment. Through the current position context-building information, such as real-time traffic flow, weather conditions or positions of other bicyclists, can be linked, modelled, analyzed and used in the return flow to the user. Subject to research are, among others, the identification of relevant information depending on the context (e.g. providing departure times of PT stops when rain showers are expected) and the appropriate communication to the user (e.g. how to communicate the potential occurrence of black ice?).

What all these topics have in common is the explicit spatial reference. Here the power of GIS comes into play: it offers the ideal platform or framework for building relations between various instances and data and thus allows for the generation and retrieval of relevant information. In this sense, GI systems make spatial information accessible for the promotion of the bicycle as sustainable and safe mode of transport.

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