Current state of the art and use case description on geofencing for traffic management

GeoSence

The project GeoSence elaborates on geofencing solutions aiming at improving urban traffic management and planning

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Summary

This report is a result of a literature review and document gathering focused on geofence use cases specific for road traffic management. It presents geofence use cases that are trialled or to be trialled, implemented use cases, as well as conceptual and potential future use cases, showing for which type of transport they are used and how geofence zones are applied or to be applied. The report was conducted in the project GeoSence – Geofencing strategies for implementation in urban traffic management and planning. It is a Joint programme initiative (JPI) Urban Europe project funded by European Union´s Horizon 2020, under ERA-NET Cofund Urban Accessibility and Connectivity and gather project partners from Germany, Norway, Sweden and UK. The goal is to present the current state of art, and describe use cases, based on the working definition of geofencing in the project, where geofence is defined as a virtual geographically located boundary, statically or dynamically defined. The study shows that for implemented and real-traffic trial use case, geofencing has been applied within private car transport, shared micro-mobility, freight and logistics, public bus transportation and ridesourcing. For the future use cases, geofencing has been tested or conceptually developed also for automated vehicles and shared automated mobility, among others. The report summarises main use cases and find them to answering to especially four challenges in traffic management: safety, environment, efficiency, and tracking and data collection. Some of the use cases however answer to several of these challenges, such as differentiated road charging, and the use cases in micro-mobility. Further, the system and functionality of the trialled and/or implemented use cases, show different types of regulation geofence use cases can be used for, from informing, assisting, full enforcement, incentivising and penalisation. Guidelines and recommendations so far form national authorities show that the existence of joint regulation or guidelines for the use of geofencing for different use cases is low – with some exceptions. Digital representation of traffic regulation will be crucial for enabling geofencing.

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1. Introduction

This report is part of the first task in work package 1 in GeoSence – "Geofencing strategies for implementation in urban traffic management and planning", where the objective is to define the current state of the art for geofencing and its applications. This includes a literature study of scientific publications, and project documentation and ongoing initiatives identified by the partners in GeoSence, with a specific focus on use cases – how geofencing is and can be used, and the context around it. Geofencing can be, and has been, used for many purposes, for instance for aircrafts or animal herding. However, for this project, we are interested in geofencing used for traffic management and planning.

The report is structured as follows: In section 1 we introduce geofencing including defining geofencing for traffic management and planning, before presenting our method in section 2. The results from the literature study are presented and divided into implemented and real-traffic use cases, conceptual use cases, ongoing projects and upcoming trials, and other uses cases in section 3. Section 4 consists of the analysis, discerning use case topics by purpose, followed by section 5, titled "Learning from implemented and trialled use cases - experience and evaluations", presenting the positive societal effects, some challenges with implementation and lessons learned from authorities.

1.2. Defining geofencing for traffic management and planning

The literature refers to similar but not completely alike definitions of geofence. For example, geofence can be understood as "a virtual barrier that geographically traces the different zones in which a certain agent can move into and within"(Maiouak and Taleb 2019). This is similar to the understanding of geofence in the ReVeAL-project as "a virtual perimeter for a real-world geographic area. A geofence could be dynamically generated as in a radius around a point location, or a geofence can be a predefined set of boundaries such as school zones or neighbourhood boundaries" (Sadler 2021). The "virtual" is essential, as another definition clarifies: "Geofences are virtual perimeters that mark locations in the physical world. Unlike their indoor cousins (beacons), geofences do not require the deployments of any physical hardware" (Statler 2016: 308). Another early definition, from Nait-Sidi-Moh et al. (2013: 127) is the following: "a positioning technique where spatial and temporal occurrences are detected using the real-time position of a mobile object (e.g., vehicles, containers, or people) and its position relative to a given geographical reference area, usually a zone represented by a virtual, often dynamic, perimeter. Intercepting the perimeter, or presence within the zone, is registered and processed by the geofencing system itself and by the in-vehicle equipment, or by both". However, we would add that it is recognised that tracking position is not always the case for all applications of geofence. Further the Civitas Eccentric-project refers to geofence as: "A defined virtual perimeter for a real-world geographic area, used to capture information signals sent within the borders of the zone" (LOTS 2020).

The "working definition" of geofencing for traffic management and planning guiding this literature review was defined as follows: *Creation of a geofence for monitoring, informing, and controlling* *traffic (mobile objects/vehicles) located within, entering or exiting the geofence, using electronic communication technologies or pre-defined geofences embedded into the mobile objects/vehicles*, where a geofence is defined as: *a virtual geographically located boundary, statically or dynamically defined*. These definitions are inspired by the CEN technical committee on Intelligent Transport System (CEN 2019) published standard CEN/TS 17380:2019, Intelligent transport systems - Urban-ITS - 'Controlled Zone' management for UVARs using C-ITS.

2. Method

The purpose of this study is to do a literature review on use cases of geofencing for traffic management and planning, based on the working definition of the project. The review has been focused on both scientific research articles, as well as published reports, city proceedings and documentation of ongoing projects.

2.1. Scientific and grey literature review

A literature review of the period between 2005 to 2018 has been conducted within the GeoSUM-project "Geofencing for smart urban mobility" (Foss, Seter and Arnesen 2019), so to limit our search period we choose to build on this recent work and focus the review on implemented, trialled, experimental or suggested use cases in published reports and journal articles in the time frame from 2018 until about middle of 2021. Scopus and Google Scholar searches were carried out to find relevant literature, based on the working geofence definition of GeoSence, given above. For Scopus the search terms use were: TITLE-ABS-KEY (geofenc* OR geo-fenc* OR "virtual boundary" OR "virtual zone" OR "virtual fenc*" AND transport* AND vehicle OR "traffic management"). The search, limited from 2018 to start of April, gave 29 document results. For Google Scholar, we used: vehicle OR transport OR "traffic management" AND geofence OR "virtual boundary" OR "virtual zone" OR "virtual fence" as our search terms. The search, limited from 2018 to medio May 2021, gave 207 document results. Further, we excluded all literature not related to transport and vehicles, as well as the literature covering aircraft geofencing. Of the papers, 22 were considered the most relevant and included in this study. The study was further supplied with reports from ongoing projects and governmental and city proceedings on geofence for traffic management, mainly across Europe, provided by the GeoSence partners.

3. Results - Geofencing for traffic management

The following section present results with use cases divided into 1) implemented or real-traffic trials of use cases, by transport mode, 2) conceptual uses cases by modelling or simulation, 3) ongoing projects or upcoming trials, and 4) other use cases, suggested in project documentation.

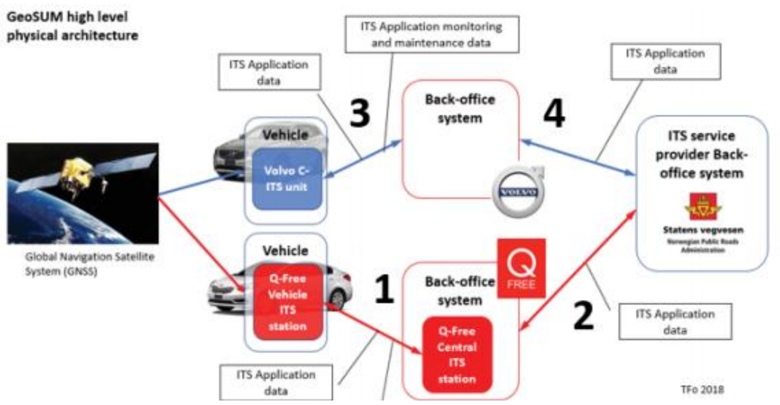
3.1. Implemented and real-traffic trial use cases

3.1.1. Private car transport

In the research project GeoSUM, pilots were developed and tested for hybrid vehicles, with geofenced low emission zones (LEZ) and school zones (SZ) (Arnesen, Seter, Foss et al. 2020), both for an integrated and for a retrofitted system.

See text box "GeoSUM pilot description" for more information about the set-up of the pilots. Dahl, Arnesen and Seter (2020), have presented the first results from the retrofitted system for both the LEZ and the SZ use cases, while the more recent paper of Arnesen, Seter, Tveit and Bjerke (2021) solely focused on the LEZ in regard to road user charging. Both studies combined pre-/post-survey data and technical vehicle data with high temporal resolution such as speed and position to investigate behaviour change as a result of introducing the geofences. For instance, the drivers were presented with information on distance-based road pricing, thus presenting an alternative to fixed tolling points (Arnesen et al. 2021). Both technical data and survey data showed changes in travel behaviour and user's acceptance of the systems. Further, an integrated system for geofence use cases was piloted in collaboration with

GeoSUM pilot description: *In the retrofit pilot*, the equipment consisted of an external OBU (Samsung Galaxy A 10 smartphone) with GPS, connected to outputs from OBD-II connected via Bluetooth: The equipment read zones from the National Road Data Base (NVDB) in Norway, and using the display to communicate with the driver. This equipment was developed by Q-Free and installed into the vehicles. For recruitment of participants, internal information channels in SINTEF, The Norwegian Public Roads Administration (NPRA) and Q-Free was used. The test fleet for this retrofit pilot ended on 46 cars, consisting of Mercedes, Mitsubishi, Volvo and Volkswagen, with a total of 80 subjects, as each car could register up to two drivers. 28 cars were located in Trondheim, and 18 in Oslo. The SZ was defined using a radius of 150 m around each school in both cities, while the LEZs were defined in 2 levels in Trondheim, and 3 in Oslo, using the current tolling areas for inspiration. The pilot lasted for 8 weeks after installation. The two first weeks were however "black mode" with no information in the display. After these two weeks, the display showed map-based information about LEZs and SZs. The drivers were given an initial reward sum of 1000 NOK, which would decrease if the drivers drove on fossil fuel in LEZs. *The pilot with integrated equipment*, was conducted with one single vehicle provided by Volvo and took place in Trondheim only. Here a pre-defined test route with both LEZ and SZ was driven by volunteered participants. Some of the participants from the retrofit pilot was recruited here, in addition to employees from the NPRA. The total number of subjects was approximately 50. The car was a Volvo V90 T8 petrol hybrid, equipped with a prototype DIM (display) to provide information to the driver, developed for NordicWay 2. The car also included a measurement computer to log a large variety of variables from the driving sessions and a GPS. The following figure summarizes the physical architecture of the GeoSUM pilots, with the main objects, actors, ITS stations and major information flows:



Volvo. The drivers drove the vehicle with this integrated solution for one predefined test-track in the city and were notified through HMI in the display of the car about the upcoming zones (Seter et al. 2021). Here the switch from gasoline to electricity was managed automatically based on the LEZ. For the SZ, the car gradually decelerated by automatically reducing the speed using the electric motor for braking and adjusting the configuration of the accelerator to require more effort from the driver to override the functionality (Seter et al. 2021). Survey data answered before and at differet locations during the test track made the basis for the evaluation of the acceptance system, and the results are summarised in section 5, with a comparison also to the retrofit pilot results. See Seter et al. (2021) for more details.

In NordicWay2 (NordicWay2 2020), a pilot for dynamic environmental zones was also tested in the City of Gothenburg. This pilot is similar to what was done in GeoSUM, however in this project the city authorities took a more active role through a city innovation platform (CIP). This CIP delivered a joint mean for data exchange and storage from a smart city perspective, with exchange of controlled zone information, restrictions, status etc. through this platform. Test software in the vehicle (Volvo) ensured that the vehicle automatically ran on pure electric within the zone. The central data exchange was based on the Ericsson Interchange Node, which offers a common platform for information exchange between business and governmental systems.

In Germany a smartphone app was developed in 2017 at the University of Landshut (Hilpoltsteiner et al, 2018) in cooperation with BMW and the Ministry of Interior to provide drivers with information for building a rescue alley for emergency vehicles approaching traffic congestion. The system is based on information from police traffic information centers and GPS location data. A temporarily limited geofence is created by the system to define the region of the congestion. There is no evaluation report available, however, a similar system was later implemented as a software update to BMW cars equipped with ConnectedDrive solution (BMW-Group, 2018) but it is not reported, whether this service relies on geofencing technologies too.

3.1.2. Shared micro-mobility

There is a growing literature on the use of geofencing for shared micro-mobility regulation, especially e-scooters, but also e-bikes. Geofencing technology in micro-mobility is already implemented or on the way to be implemented in several cities in the EU and the US. E.g., Moran, Laa, & Emberger (2020) studied the use of geofences in Vienna, Austria, where geofences were applied to show the outer zone boundaries, e.g., where parking must end, and to locate no-parking zones, through a smartphone application. Different no-parking zone eforcements were applied, one by not letting the riders end the trip within a no-parking zone, and penalization, with financial penalty for ending a scooter ride within a no-parking zone or outside the geofence. Moran (2021) studied geofence use for shared bikes and e-scooters in San Francisco, where use cases of no-parking zones were applied by one of the operators. Further, a report by DRISI, Caltrans (The California Department of Transportation) Division of Research, Innovation and System Information (DRISI 2020) studied the use of geofencing for e-scooters and e-bikes in several US cities. The report refers to how geofenced zones have been applied for preventing access to specific roadways, trails or geographic areas, limiting device speed in geographic areas, reducing riding on sidewalks, and designating approved or prohibited parking areas. E.g., one of the operators stated that scooters will be programmed to decelerate to a stop within a quarter mile of the designated no-ride zones. Riders then will receive an in-app notification informing them about the no-ride zone and redirect them to permitted areas to ride. Geofencing is also applied in some areas in Trondheim, Norway. The municipality has also developed guidelines for using geofencing, where the municipality defines the zones (Trondheim kommune 2020). Similar systems have been implemented in Stockholm and Gothenburg where the cities can define zones for parking and speed reduction of the e-scooters in an interface connected to the operators within voluntary agreements (Drive Sweden, 2020).

In 2019 geofencing was used by the city of Munich, Germany (Landeshauptstadt München, 2019) to implement time limited access and parking restrictions for shared e-scooter users during the "Oktoberfest" in a broader area around the Oktoberfest district. More specifically, there was a no-driving and no-parking zone at the central Oktoberfest area. Furthermore, an area with temporary restrictions for rental and another area with time limited renting and driving restrictions during 5pm and 6am were implemented in the bordering quarters. One of the main goals was to prevent drink and drive by guests leaving the area by e-scooter after their visit. An official evaluation is not available, however, despite this regulatory effort, the police reported over 400 cases of drunken e-scooter users during this period justifying the relevance of the project for traffic safety.

Another project is currently implemented by the city of Hamburg (Bezirk Altona, 2021). Here geofencing was used to establish four parking zones on the outer boundaries of the "Schanzenviertel" district, while parking within the district was officially prohibited. The project was primarily intended to defuse conflicts on the sidewalks caused previously by irregularly parked e-scooters. The project is currently under evaluation. It was initialized by the Altona district advisory council in cooperation with the Altona district office, traffic and police authorities, and the e-scooter providers. In line with the official agreement between the city of Hamburg and the e-scooter providers, the no-parking zones and the parking zones were defined by the district authorities. E-scooter providers were requested to implement the new regulation in their systems. However, despite this new regulation, issues with irregularly parked e-scooter seem to continue as a recent report in the newspaper "taz hamburg" suggests (Door, 2021, 1 July).

3.1.3. Freight and logistics

The Smartfusion project (Leonardi, Allen, Brenna et al. 2015) evaluated a real-traffic trial in Berlin for logistics management. This use case featured geofencing or "zoning management" as it was called, which was tested with a hybrid truck Volvo FE. Using geofencing, the objective was to determine a number of electric mode "sensitive" zones along a certain route. When crossing into this zone, the objective, here the Volvo truck, would only be allowed to drive in full electric mode. The zones were defined along the main Berlin delivery route, with the information entered into the navigation and route planning software, making it possible for the driver to get information about the zones when entering, and the chance to start hybrid mode via an onboard switch tool. The system was tested both with the zone management system turned on and off, to see how the system influenced fuel consumption.

Another system (von Roth, 2019) was implemented by Audi at its plant in Ingolstadt (Germany). To deal with high complexity and increasing traffic demands at its production site, a self-monitored delivery process for traffic at the plant's truck control station was implemented. Three geofencing zones were used (with perimeters of 1km, 20km and 50 km) to track access of trucks when entering the region and to estimate arrival times precisely. Trucks reaching the plant are automatically booked into the system and thus can drive directly to the place designated for unloading goods without having to stop at the plant's control station anymore. Deviations from the schedule due to delayed trucks are automatically corrected. As a result, truck throughput times were reduced substantially. Geofences are also implemented within the cloud-based information and communication system smartPORT run by the Hamburg Port Authority in Germany (Hamburg Port Authority AöR, 2015). Among other functions it aims to avoid delays and congestions at the port, use available space effectively, reduce truck downtimes, and provide an accurate picture on traffic for better decisions. Geofences are used to provide truck drivers with vehicle-specific information based on their geographical position. It provides information on traffic congestion, road construction sites and closures, and currently available parking space.

Other examples of geofencing for freight and logistics have also been trialled in other cities, such as in Cologne in Germany, where Ford has been testing a geofencing solution for nine hybrid delivery vans operated by municipal authorities. Cologne has a low emission zone and the geofencing system is thought to alleviate the problems of not knowing when and where you can drive your vehicle. Restrictions of the zone can change dynamically. Similar tests have been done by Ford in London and Valencia (Eckardt 2019). With this system, electric propulsion automatically activates when entering the zone and switches off when leaving it. The distances travelled in different modes can be stored using a blockchain solution and can be accessed, analysed and shared anonymously among relevant parties including city authorities and the vehicle or fleet owners (Green Car Congress 2019).

Another pilot worth mentioning, is from the NordicWay2 project, where geofencing is used for dynamic access control to designated road lanes (NordicWay2). Scania developed an interface making it possible to send a request for access and receive messages for approved or denied access through an interchange node. The messages were initiated at the traffic management centre, which contained systems from Technolution for exchange with the interchange node, interaction with the traffic operator and the central databus for traffic data. The pilot tested quality of service in terms of latency.

The mission of the Civitas Eccentric Project (LOTS 2019), in Stockholm in 2019, was to measure the impacts of replacing daytime diesel truck deliveries of goods in urban areas with nightly deliveries, called “off-peak deliveries”. This was done using vehicles that could run on electricity. The test took place using six centrally located McDonald’s restaurants as delivery points, starting from a warehouse in the outskirts of Stockholm operated by the transport company HAVI Logistics. The test vehicle, a plugin hybrid electric vehicle (PHEV), was supplied by Scania[1]. The PHEV switched to electricity when entering a pre-determined zone border to the inner-city. The same zones were also used to limit the speed to 40 km/h in the inner city.

The US Department of Transportation reports on the case study for improving work zone safety in two states in the US (Luna, Chajka-Cadin, Gissel et al. 2020). Roadway work zones pose numerous hazards to drivers, workers, and pedestrians. In the study the goal was to alert drivers in advance of upcoming work zones so they can pass through safely or select an alternative route. In the pilot in Kentucky, work zone information is activated by geofencing technology, and when the commercial vehicles were entering a work zone the truck drivers received a message through an application on an in-vehicle device. These work zones are available in an open-source format, which is available to software vendors and developers who can integrate the data into their software. Transmitted data also includes traffic congestion, active work zones, speed limits, and lane closures.

3.1.4. Public bus transportation

In Gothenburg in Sweden, the Project ElectriCity started in 2013 on public transport. The buses are equipped with a Zone Management System with static geofences. Inside the zones, the buses automatically follow or drive below posted speed limits, as well as only use electric propulsion in certain areas sensitive to noise and emission The zone borders are downloaded to the vehicles when parked overnight, meaning these are static zones, where the vehicles are not connected dynamically to the local authority services otherwise (ElectriCity 2016). The system is reported to work well, and the drivers appreciate driving the buses on this bus line. Since the introduction of the system, the speed limits are better enforced.

3.1.5. Ridesourcing

Another use case applying geofencing is related to ridesourcing by transportation network companies (TNCs) (Ranjbari, Luis Machado-León, Dalla Chiara et al. 2020). Increased use of ridesourcing leads to increased pick-up and drop-off activity, which again might slow traffic or cause delays as vehicles increase curb use and conduct pick-up and drop-off. In the study of Ranjbari et al. (2020) the purpose was to investigate how cities can keep travel lanes operating smoothly and efficiently, by analysing strategies within the city of Seattle in the US. One of the strategies was geofencing applied to direct drivers of TNCs, such as Lyft and Uber, and passengers, to designated pick-up and drop-off locations on a block, and to passenger load zones (PLZ). Data was collected with road tube counters on specific locations on the roads.

3.2. Conceptual uses cases by modelling or simulation

There are several papers exploring conceptual use cases integrating geofencing capabilities into existing simulation or modelling tools and methods.

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[1] It used HVO as source of energy when driving outside the inner-city. HVO is an acronym for hydrotreated vegetable oil and is a form of renewable diesel produced from both animal and vegetable oils and fats

3.2.1. Private car transport

Razzaq, Subih, Khatoon et al. (2020) present a larger system for informing and predicting available parking space at a parking lot, geofencing being one of the sub-components in addition to IoT, cloud computing and prediction models based on sensors and available data sources. The system is not tested in real traffic, but simulations are executed for a real-world parking lot in Pakistan for several scenarios. The aim of the system is to provide information of available parking spaces, and if not available, provide prediction whether a parking space will be available shortly (waiting time). Vehicles would need a two-way communication protocol for this system to be implemented, i.e., connection to and from the vehicle to the system cloud.

Hawas, Thandavarayan and Basheerudeen et al. (2019) define geofences at intersections, allowing only vehicles inside the geofence to communicate with each other, reducing communication complexity. The geofences can be dynamic with respect to for instance traffic volume, lesser cars in traffic calling for larger geofences, while in congested cases the geofences can be smaller to scale with the number of vehicles. The setup is tested in real life in Ain city in United Arab Emirates, where the main focus is on optimalization of message exchange with 2.4 GHz V2V (vehicle-to-vehicle) communication.

3.2.2. Public bus transportation

Ruiz, Arias, Massobrio et al. (2020) investigated geofences for automatic electric drive of plug-in buses in zero emission zones (ZEZ). The focus is on constructing an algorithm for optimizing battery usage inside and outside the zones, by finding the best strategy for a bus to operate with minimum emissions and upholding zero-emission zones. The strategy is shown to work well within a simulation environment in Uruguay.

3.2.3. Automated vehicles

Several cases are related to automated vehicles or self-driving vehicles (AVs). E.g., Wijbenga, Vreeswijk, Mintsis, et al. (2019) present the issue of mixed traffic periods, in the early introduction phase of AVs. During that period, there will be areas on the road where the higher levels of automation cannot be allowed due to issues with sensors, complex situations, human factors etc. AVs will be changing their automation levels in these "Transition Areas". Here, geofence is briefly mentioned to be used for "no automated driving" zones. Conversely, Coicheci and Filip (2020) refer to geofenced areas where vehicles can operate in self-driving mode only within certain areas. This is in line with the reference to AVs on SAE level 4 as “fully autonomous within a geofence, so within an area [with a] high-definition map” (statement by Jackie DiMarco, chief engineer for autonomous vehicles at Ford in Crosbie 2017)[2].

[2] SAE level 4: The American Society of Automotive Engineers (SAE) defined the application level 4 for autonomous driving as High Driving Automation, where vehicles are capable of dealing with disruption and issues, but allows manual overriding. This automation level 4 requires that this type of vehicles can only ride within designated areas limited by geofences. https://www.synopsys.com/automotive/autonomous-driving-levels.html

3.2.4. Shared automated mobility

Huang, Kockelman, Garikapati et al. (2020) presented a conceptual paper where geofenced areas, called automated mobility districts (AMDs), are used. These areas define where SAV (Shared automated mobility) can be used for last/first mile of person transport. The geofence areas (AMDs) correspond to high mobility districts. The researchers use a so-called SUMO (Simulation of Urban Mobility) toolkit to examine shared fleets of fully automated vehicles to replace first-mile last-mile connections to transit stations in the city of Austin, Texas, U.S. See also Zhu et al. (2020) for a simulation use case of geofenced AMDs in Greenville, South Carolina, U.S., where the results show positive mobility and sustainability impacts of the vehicle solutions and planning tool applications. However, some scenarios also show more mileage overall.

Another study (Twumasi-Boakye, Cai, Joshi et al. 2021) refers to using geofencing in high trip density areas for dispatching shared autonomous vehicles. This could help improve fleet performance if shared mobility and shared autonomous vehicle operations become more used.

3.2.5. Fleet tracking

Jagwani and Kumar (2018) tests a prototype fleet tracking system, including geofencing. Here, alerts can be triggered when vehicles are entering/leaving areas and data such as speed and location can be logged by the system both inside and outside the zones. The system is verified to work through experiments done in Delhi, India, but is currently a prototype.

3.2.6. Other conceptual use cases

Nayak, Mugali, Rao et al. (2019) present a project that provides safety-related notifications such as approaching vehicles in and around accident-prone areas, and blocked road ahead. For the first case, accicent-prone areas, two geofences are defined on each side of the area, and the vehicles are communicating via mobile network if they are inside any of the two geofences. A back-office system keeps track of the status of the zone (no car inside or car inside) and alert of approaching vehicles if both geofences have vehicles inside. The system was tested with an experiment using smartphone application and audio to communicate the alerts. See Kim, Yoo, Eom et al. (2018) for similar system.

Another similar case is the ITS-serivce emergency vehicle approaching (EVA) where positioning and geofencing is used to alert vehicles within a certain peraminter when the emergency vehicle is approaching, via cellular and cloud communication. This has been tested in the NordicWay 2 project.

Another case, however, not related to geofencing for vehicles, but for people, is being developed for construction sites. Here apparel and personal protective equipment (PPE) is being equipped with wearable tech including sensors, GPS and location trackers. Geofencing allows site or safety supervisors to establish restricted or hazardous areas that will alert workers with a combination of alarms and light if they enter these areas. "The system can also be integrated to work with actuators on heavy equipment that will trigger the machine to shut off or slow down when a worker wearing a tag is nearby". Such wearable tech with geofencing however needs further research and testing (Jones 2017).

In the paper by Eom, Hwang, Lee et al. (2020) CMVF systems (Connected Mobile Virtual Fence) are used to limit the broadcast of V2V messages to only surrounding vehicles. I.e., a geofence is defined around each vehicle, following the vehicle as they are driving. Only geofences intercepting and under certain other restrictions (directions etc.) are set to communicate V2V messages such as BSM (Basic Safety Message) and CAM/DENM (Cooperative Awareness Message/ Decentralized Environmental Notification Message) to each other. Real world experiments are conducted using smartphones installed into vehicles. This study is using the mobile network for transmitting messages. Moreover, see reference therein for more previous papers on CMVF systems and Kim et al. (2018).

Coconea, Mizaras, Türetken et al. (2019) present two use cases of geofencing: Geofence suggested for re-routing, by presenting the driver with a pop-up message, and geofence for alerting nearby parking and public transport information, based on real-time occupancy data. These two use-cases are envisioned in a traffic management system for MaaS.

Chen, Zhang and Li (2018) presents a conceptual paper about letting drivers share their driving data voluntarily to enable collection of trip chain data (a sequence of trips that starts and ends at the "home" location"), in exchange for less waiting time for example at crossing using what they call a Traffic Voting System (TVS) to extend green light. This means, that if they are willing to share their travel data, they get the right to vote, and depending on the results of the vote, traffic signals can be accommodated to improve traffic efficiency. In this system the travellers set up the geofence around her/his trip destinations, typically at home and at work, to register their trips and get the benefits of the TVS.

3.3. Ongoing projects or upcoming trials

"Agreed geofencing zones" for buses

The project "Digitalized Infrastructure Zones" (DIZ2) started in 2019 and is among other a cooperation between The Traffic Department in Gothenburg and AB Volvo. The zones defined in DIZ2 refer to distances / areas and attributes for these (e.g., lower speed limit, electric drive). The project concerns agreed geofencing, i.e., zones with stricter traffic rules, which are applied by certain vehicle fleets (buses). In this case, the speed is lower than the speed limit, and there is a requirement for electric operation in certain areas. The project sets up a technical solution to provide the agreed rules and describe the requirements for the fleet of vehicles and working methods for handling agreed geofencing. The geofence was used on a specific route, part of ElectriCity (mentioned above), until December 2020 when this route was discontinued. The results of the project will enable heavy goods vehicle (HGV) drivers to drive safely and with lower emission levels in Gothenburg, but also make it easier for other road authorities to create conditions for increased road safety and lower emission levels.

In the region Dalarna, Sweden, there is currently an ongoing full-scale trial with geofencing for public buses. 14 Keolis buses, have geofencing, making the buses themselves keep the speed limits around vulnerable areas and schools (Hansson 2019).

High-capacity transport vehicles in sensitive areas

One of the pilots that will be tested in the NordicWay3 project is a geofencing service for high-capacity transport vehicles (HCT[3]). In this pilot the aim is to develop the intelligent access control technology one step further and use geofencing to control speed in sensitive areas such as over bridges and in urban areas where the combination of speed and weight could cause damage on both the infrastructure as well as in surrounding buildings. If feasible this could allow the road operator to expand the network for HCT without or with less reinforcement of the infrastructure, thus demonstrating how digital solutions can be an alternative to infrastructure investment. The pilot focuses on high-capacity transport (HCT) in rural areas, however, it could be relevant also for urban areas, e.g., as mentioned with lowering speed. Other upcoming real traffic-trials related to high-capacity transport, is the HCT-City project, with pilots in Stockholm and Varberg municipality. The project will use geofencing for digital support, by giving access in sensitive zones based on permits (Wandel 2021).

Road pricing

GeoFlow is another research project supported by the Research Council of Norwegian focusing on road charging pricing schemes with on-board units (OBU) using geofencing. This is an ongoing project with planned pilot start in November 2021, recruiting 200 vehicles in the city of Trondheim to test and evaluate a GNSS distance-based road charging system, using a close to market ready OBU. Geofences will be defined and used to represent charging zones with different rates. Both technical data for verification and investigating driving behaviour and questionnaires for user acceptance will be collected.

Voluntary-low emission zones

As part of NordicWay3 (NordicWay3 projectplan), there is an ongoing project between the Norwegian Public Roads Administration in Norway, The Swedish Transport Administration in Sweden, and BMW, testing voluntary low-emission zones in the cities of Oslo, Stavanger, Bergen and Trondheim in Norway, and the following cities in Sweden: Stockholm, Gothenburg, Malmö and Uppsala. The PHEVs of BMW, registered in 2019 and 2020, have recently updated their software, making the car switch automatically from fossil fuel to electricity within these low emission zones – but with the chance for the drivers to switch off the functionality. The drivers of these cars are currently being surveyed about their experience.

Heavy goods transport

The ongoing Swedish project "Smart Urban Traffic zones", is concerned with the increased urbanization and the intensifying competition for urban space between different vehicle types. The project includes two demonstrations for heavy goods vehicles in Stockholm and Gothenburg using geofencing. The first, is to create solutions for granting access to certain vehicle classes in environmental zones, divert other vehicle classes, and allow for adapting speed and powertrain on

[3] Freight transport that is carried out by longer and/or heavier vehicle combinations than what is normally permitted by government's regulations or typical allowance (Lindqvist and Salman 2019). However, we remark that what HCT can differ between countries. For example, the term "European Modular System" (EMS) is used more and more.

freight transport. The demonstrator has the goal of showing how geofencing can be used to make transport more efficient in vulnerable areas. The other demonstration is about "moving geofences" for a safer urban environment, where the intention is to connect an intelligent sensor, an intelligent heavy vehicle and a communication platform to warn unprotected road users. A construction site exit will be used to demonstrate technology that warns about risks, with sensors in the vehicle (Vinnova 2019).

The Horizon 2020 EU project ReVeAL "Urban vehicle access regulation" started in 2019 (ReVeAL 2019) and is among others about regulating access for heavy goods vehicles and speed and zero-emission zones (ZESs). One of the trials will concern assisting access with speed regulation in Helmond in the Netherlands, while the other trial will be about assisting access in ZEZs in London, UK.

3.4. Other use cases (e.g., suggested in project documentation)

A report from a workshop in GeoSUM (Meland et al. 2020) presents several ideas of geofencing use cases related to traffic safety, environment, traffic management or regulation, driver support and connecting it to other areas of mobility as a service. The workshop included actors from the transport area, divided into public management and planning, and practitioners, where transport is an important part of their daily business. For traffic safety, it was suggested to use geofencing as speed control in areas with many speed violations, or dynamic speed zones based on friction and weather conditions. For environmental purposes, geofencing was suggested for encouraging to not use the car when local pollution is heavy, or to enforce restrictions of idle engine use. Regarding traffic management and regulation, it was suggested to use geofences for temporary events, such as festivals/"Summer Street", similar to the "Oktoberfest" case mentioned above, and use geofencing for planning "smart routes".

4. Analysis - Defining overarching use cases

Overall, the literature and projects applying geofencing in traffic management can be defined into overarching use cases that fit into the following challenges or purposes: Safety, environment, efficiency, and tracking and data collection. Table 1. summarises the use cases based on the main challenge/or purpose. However, it must be noted that some use cases span across several of these purposes.

Safety as a purpose includes use cases of geofencing such as speed zones. This includes speed zones such as vulnerable areas or school zones for private car transport (Dahl et al. 2020, Arnesen et al. 2021; Seter et al. 2021), speed zones for public buses (ElectriCity 2016), speed zones in micro-mobility (e.g., DRISI 2020), and speed regulation for heavy goods vehicles (Sadler 2021; VINNOVA 2019). It also included accident zones, such as notifications about approaching vehicles in and around accident-prone areas (e.g., Hilpoltsteiner et al. 2018), and safety information like a blocked road ahead (Nayak et al. 2019). Lastly there are work zones, when for example vehicles enter the virtual geographic area designated for work zone, users can receive messages through the apps on in-vehicle device (Luna et al. 2020) or through wearable tech (Jones 2017).

Environment as a purpose, includes the general use case of low- or zero emission zones. This means low-emission zones in private transport (Dahl et al. 2020, Arnesen et al. 2021; Seter et al. 2021; NordicWay2; NordicWay3 projectplan), for zero-emission and low-noise zones in goods delivery (LOTS 2019; Leonardi et al. 2015; ElectriCity 2016), access in zero-emission zones (Sadler 2021) and zero-emission zones for heavy goods transport (Sadler 2021; VINNOVA 2019). It also includes the case of battery optimization within zero-emission zones (Ruiz et al. 2020).

Efficiency is the third purpose which includes several different use cases. One is pick-up/drop-off zones. Here geofencing was applied to direct drivers of transportation network companies (TNCs) and passengers to designated pick-up and drop-off locations on a block, or passenger load zones (Ranjbari et al. 2020). Another was intersection zones, with communication between vehicles in the zone (Hawas et al. 2019). Information of available parking space (Razzaq et al. 2020) is another use case fitting here. There are also access related use cases, such as allowed access zones, based on permits for e.g., high-capacity transport (Wandel 2021). Related to this, geofencing is also used for optimizing truck traffic management at ports und factories, including self-monitored scheduling solutions and better information supply for truck drivers (parking, congestion, road works) and control authorities (van Roth 2016, Hamburg Port Authority AöR, 2015). Conversely, to prevent access to certain areas was another use case, as shown in the micro-mobility cases (e.g., DRISI 2020), as well as no-parking zones (e.g., Moran et al 2020; DRISI 2020). Several cases covered use of geofencing for automated vehicles, such as geofencing applied for indicating automation level for AVs with "no-automation zones" (Wijbenga et al. 2019), or conversely, self-driving zones (Coicheci and Filip 2020). Or the use of shared automated vehicle zones (e.g., Huang et al. 2020; Zhu et al. 2020) such as for high density-trip areas (Twumasi-Boakye et al. 2021). Differentiated road charging (e.g., Arnesen 2021; GeoFlow project) is yet another use case fitting into efficiency as a purpose. Although demonstrated with LEZ, this specific use cases can serve several purposes. Further, mobile or moving geofences is another use case that could fit to efficiency (Eom et al. 2020; see also Kim et al. 2018; VINNOVA 2019).

Tracking and data collection is the fourth catgeory, which can be be argued to more of an instrument or tool for the other three purposes. It covers for example different fleet tracking systems (e.g., Jagwani and Kumar 2018). However, it can be noted that this system is quite similar to already existing fleet management systems. Further, the use case with the trip chain collection in exchange for extended green light, is relevant here, using geofences around trip destinations (Chen et al. 2018). The use case differentiated road charging (Arnesen 2021; GeoFlow project), is also a possible fit here, although as stated, as it serves many purposes.

Table 1. Use cases defined by main challenge/purpose:

Challenge/purpose	**Use cases**
Safety	Speed zones
	Accident zones
	Work zones
Environment	Low- or zero emission zones
	Battery optimization zones
Efficiency	Pick-up/drop-off zones

	Intersection zones
	Parking available
	Allowed access zones
	Prevent access
	No-parking zones
	AV zones
	Shared automated zones
	Differentiated road charging
	Mobile geofences
	Scheduling truck traffic and unloading
Tracking and data collection	Fleet tracking
	Trip chain collection
	Differentiated road charging

A closer look at the trialled and/or implemented use cases, show how they present different ways of using geofencing – both by the hardware and software systems applied, and the functionality they provide (Table 2). For the hardware and software systems, there is a variance between mobile device/app only, mobile device/app and an on-board unit, integrated, and integrated with interface. The functionalities differ between being informing, incentivising, informing and incentivising, penalizing assisting, and fully enforcing. As such, geofencing is a technique that can be used for different purposes, with different hardware/software systems, and with different functionalities based on purpose and system.

Table 2. System and functionality of trialled and/or implemented use cases.

Use cases	**Hardware and software systems**	**Functionality**
Speed zones	OBU and mobile device	Informing (also referred to as passive enforcement by some projects)
	Integrated in vehicle	Assisting or active enforcement (e.g., vehicle slows speed within zone)
Work zones	In-vehicle devices and application programming interface	Informing
Low- or zero emission zones	OBU and mobile device	Informing and incentivising
	Integrated in vehicle	Assisting or active enforcement (actively switching a plug-in hybrid vehicle remotely to electric mode within zone)
Pick-up/drop-off zones	Mobile device/app	Informing
Prevent access including no-parking zones (micro-mobility)	Mobile device/app OR Integrated in vehicle	Informing
		Penalization
		Fully enforcing (e.g. vehicle stops operating within zone)

Differentiated road charging	OBU and mobile device	Informing and incentivising

5. Learning from implemented or trialled use cases – experience and evaluations

5.1. Positive societal effects

Several of the journal articles and project documentations report positive societal effects with the use of geofencing. Of those reporting on actual emission changes for example, it was found lower CO^2 emissions (LOTS 2019; Leonardi et al. 2015). It was also found an increased use of electricity, within low emission zones (Dahl et al. 2020; Arnesen et al. 2021). When it comes to school zones, the results varied somewhat more (Dahl et al. 2020; Arnesen et al. 2021). Also, concerning ridesourcing, traffic safety, by e.g., lower speeds, could not be observed (Ranjbari et al. 2020). However, they found that increased PLZ allocation and geofencing strategy reduced the number of pick-ups/drop-offs in the travel lane, reduced dwell times, increased curb use compliance, and increased TNC passenger satisfaction. Some studies reported on the positive acceptance of the drivers, e.g., regarding night time deliveries (LOTS 2019) and geofenced bus route (ElectriCity 2016). The study comparing acceptance for retrofit solution and integrated solution, found quite high acceptance for geofenced low emission zones for both systems. However, the integrated system had somewhat greater levels of satisfaction, usefulness and usability for low emission zones, than the retrofit solution. Further the study found greater levels of satisfaction and usefulness for SZ with integrated system than retrofit system (Seter et al. 2021). As argued in the study, these findings could reflect the increased level of convenience and comfort of an automated system, which one could expect would increase the level of acceptance among users (Hartwich et al. 2018).

5.2. Some challenges with implementation

The studies on use cases in micro-mobility refer to several challenges with implementation. Using spatial analysis, the study of Moran et al. (2020) tracked the e-scooter geofences and no-parking zones of six operators in Vienna. They found the bulk of no-parking zones to be located around parks, pedestrianized corridors, and cultural institutions. They also found that all six scooter operators modified their geofences during the course of this study (adding neighbourhoods and removing others), and this took place without any type of municipal approval or standardized disclosure to users. They conclude that there is a room here for the public sector to take on a stronger role, to provide oversight of the spatial dynamics of scootersharing, and by establishing incentives to ensure that outlying and/or transit-poor neighbourhoods are not excluded when planning geofences.

In the DRISI project (2020) several cities reported that the implementation of geofenced boundaries for micro-mobility in general worked well. However, in Los Angeles, it took the e-scooters longer time to recognize their location within a geofenced area, causing some of them to decelerate slower. Similar problems were also reported in Forth Collins, where the detection of geofenced areas was inconsistent due to GPS limitations, and in Portland, where geofencing technology functions were also reported to work inconsistently. It was argued that these issues could stem from difficulties with drawing the geofence boundaries given low or variable geographic system (GIS) accuracy. Two of the vendors also reported issues with the two-dimensional system of GPS – e.g., a geofencing boundary meant to prevent scooterriding on a highway overpass, would also affect streets, bike lanes and trails located below the highway because the geofence operates in three dimensions. Another issue reported was the problem of riders switching their phones to "Airplane mode" to avoid being detected in geofenced areas. Further it was suggested by the vendors to encourage cities to share their digital representation of desired boundaries to vendors, to increase consistency across the vendors, and that the cities work together with vendors to be able to reflect limitations in GPS technology.

Moran (2021) who studied the use of bike and e-scooter geofences in San Francisco, found that there was limited and inconsistent regulation of geofences. E.g., the neighbourhoods left out from geofence services in the period of study, were those with lowest densities and farthest from employment centres. As stated in the paper: "This tension is central to municipal regulation of micro-mobility, which highlights the conflicting aims of private operators (create a geofence which generates high ridership and reliable profits) and municipalities (ensure shared bikes and e-scooters reach as many residents as possible)". The case demonstrates that if operators/vendors are left with freedom in geofence design, they will emphasise the city's densest areas, thus becoming a barrier to social equity. Further this case showed how community organisations might support or oppose expansion of geofences.

Difficulties and challenges may arise when proposed implementations of geofences are in conflict with local laws and regulations. Two issues that are currently under discussion in Germany between municipal stakeholders and government authorities is shortly described here. One example concerns the implementation of new software/hardware functions in e-scooters to enable speed limits by geofencing for instance when entering inner city pedestrian areas. When questioned whether such technical changes are covered by current national laws, the Federal Ministry of Transport and Digital Infrastructure replied that due to the known limitations in GPS accuracy, implementing such functions in e-scooters have some serious concerns. For example, related to impairments for road safety as well as an impairment of the driving dynamic features of the vehicle. This would raise concerns whether such new functions can be covered by the currently valid operating license. Therefore, the Federal Motor Vehicle and Transport Authority and the Federal Institute for Highways have been commissioned with an investigation, including these issues (see Landeshauptstadt München 2020).

The second issue concerns the applications of speed limits on urban roads. This is ruled by the German road traffic regulations (STVO and other laws). Therefore, implementing speed limits on signed main roads below the limits suggested by law and regulations are (with some exceptions e.g., at school zones) almost not possible. There is a call by municipal agents and members of the German Association of Cities to adapt the current law to give them more flexibility for decision-making when implementing speed limits.

5.3. Lessons learned from authorities – guidelines and recommendations so far

The existence of joint regulation or guidelines for the use of geofencing for different use cases is low. However, there are examples of recommendations and guidelines, both at country and city level. In Sweden, the government has initiated an action plan for piloting and testing geofence use cases, called "Comprehensive action plan: Joint mobilization on digitalization for secure and smart urban environments" (Government assignment 2018). The action plan provides a list of seven points to assist in the implementation of the geofencing concept: 1. Set up a research and innovation (R&I) program with targeted research and innovation projects to prepare the required documentation for work with all points of the action plan. 2. Encourage legislation and regulations that support the implementation of geofencing. 3. Develop organizational and digital processes as well as data for geofencing zones. 4. Develop systems, procedures and processes for self-regulating systems and control in smart zones. 5. Investigate the socioeconomic and business potential. 6. Encourage national and international harmonization, and 7. Support and pursue demonstration and pilot projects. The project partners chose to focus on three practical applications of geofencing: urban environment (including air and noise), access and speed. Although it could be a measure, The Ministry of Infrastructure in Sweden pointed out that there is no regulation currently demanding geofencing. Therefore, they did a feasibility study analysing implementation of geofencing applications that not only build on voluntariness, but also general use. To be able to set up viable and harmonized processes for geofencing zones, they suggest responsible organizations must be identified or established that can ensure that information enabling the creation of both static and dynamic geofencing zones is made available digitally and is quality assured, and where these organizations can operate around the clock.

As part of GeoSUM (see section 3.1.1. on the GeoSUM pilots), a workshop was arranged with the Norwegian Public Roads Authorities which focused on how geofencing could contribute to the regulatory role of national road authorities. Workshop discussion summary and other project outputs related to regulations are available in NPRA (2021). The workshop presented both experience from the GeoSUM project, and information from the NPRA. A result from the GeoSUM project relate to how the creation of geofences in NVDB (National Road Database), must become more flexible to when rules are to apply. Geofencing is dependent of reliable communication channels and accurate positioning, and more cooperation with other sectoral authorities should therefore be initiated. A further challenge could be proprietary solutions in vehicles. Further, current standards are not able to capture the complexity which three dimensional zones offers.

In the workshop it was discussed what the legal basis for implementing low emission zones is, particularly with regards to introducing tax-zones. Voluntary zones were discussed as an interesting option, as it does not need a legal basis. Similar with speed zones around schools, it was discussed whether they should be mandatory or voluntary. With speed zones around schools, one issue that came up was the different levels of authority, where the NPRA in charge of road safety at the national level, and the municipality is the responsible level in the case of traffic safety around the local schools.

NPRA already has a unit in charge of road signage, a responsibility shared with the municipalities and counties, where road sign positions are stored digitally in NVDB. However, traffic regulation based on digital traffic rules will require a greater level of precision than the current system is able to provide. To utilize geofence for safer, more efficient, and more environmentally friendly road transport, the NPRA must take two steps (NPRA 2021):

- Establish geofence as an object type with associated attributes in NVDB according to European standardization.
- Establish an operating unit that can handle geofence regulations on behalf of the State Public Roads Administration, Nye Veier AS, counties and municipalities. This operating unit must further establish cooperation with various OEMs to get new cars to comply with regulations in Norway. Here, a broad collaboration from different professional environments is needed.

The report "Traffic rules in the era of automated and connected vehicles" by RISE (2018), initiated by the Swedish Transport Agency, also refer to the handling of local traffic rules and that reporting into a national database need to become smoother and more standardized. Further they point out that a natural next step would be to identify what may be needed to ensure that the local authorities have the right resources to meet this requirement, e.g., resources to take care of a detailed databank. They suggest further research should assess the feasibility of making this mandatory, as such mandating the government to regulate local authorities in this regard.

The ReVeAL project (Sadler 2021) has discerned several issues that lie at the national or even EU-level of authority to use geofencing for UVAR: UNECE or EU geofencing standard/type approval, that includes the fitting of the equipment, such as data access and transfer, override possibility and its logging, and data security. These were also issues found in GeoSUM. The need to resolve the legal basis for enabling geofencing, with digital representation of traffic regulation, is crucial.

6. Abbreviations

AMD	Automated mobility districts
AV	Autonomous or automated vehicles
BSM	Basic Safety Message
CAM/DENM	Cooperative Awareness Message/ Decentralized Environmental Notification Message
CIP	City Innovation Platform
CMVF	Connected Mobile Virtual Fence
EMS	The European Modular System. A solution that allows combinations of existing loading units – also called modules – into longer and sometimes heavier vehicle combinations to be used on some parts of the road network
HCT	High-capacity transport. Freight transport that is carried out by longer and/or heavier vehicle combinations than what is normally permitted by government's regulations or typical allowance.

HGV	Heavy goods vehicles
HMI	Human-Machine Interface
LEZ	Low emission zones
MaaS	Mobility-as-a-Service
NPRA	Norwegian Public Roads Administration
NVDB	National Road Data Base
OBU	On-board unit
PHEV	Plugin hybrid electric vehicle
PLZ	Passenger load zones
SAE	The American Society of Automotive Engineers
SAV	Shared automated mobility
SUMO	Simulation of Urban Mobility
SZ	School zones
TNC	Transportation network companies
TVS	Traffic Voting System
V2V	Vehicle-to-vehicle
ZEZ	Zero emission zones

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GeoSence elaborates on geofencing solutions aiming at improving urban traffic management and planning.

The overall objective of the project is to design, trial and evaluate geofencing concepts and solutions for specific cases in cities, within the project and from other previous and ongoing geofencing initiatives, and to propose new ways of successfully deploying geofencing technologies. Tools for implementation, as well as approaches to scale-up and spread the innovation further in Europe will be proposed including e.g. ways of integrating geofencing functionalities in the decision making, built environment and traffic management in cities.

The project is a Joint programme initiative (JPI) Urban Europe project funded by European Union´s Horizon 2020, under ERA NET call Urban Accessibility and Connectivity and gather project partners from Germany, Norway, Sweden and UK. GeoSence project period is April 2021 to March 2024 with a budget of approx 1,6 million euros.

Partnership: City of Gothenburg, City of Munich, City of Stockholm, Norwegian Public Roads Administration (NPRA), Chalmers University of Technology, RISE, SINTEF, Technical University of Dresden, University of Westminster & CLOSER.

Support partners: ALICE, City of Helmond, City of London, City of Madrid, London European Partnership for Transport (LEPT), POLIS, Swedish Transport Administration, Volvo Group.