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# **An ArcGIS analysis of Stand-alone GPS quality for Road Pricing**

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## **Abstract**

The paper presents the methods and some of the result maps from a study of GPS quality in relation to road pricing in a dense urban area. Data from 500 cars were collected over a two-year period in the Copenhagen region (Denmark). The data was analyzed in ArcGIS in order to determine whether the GPS quality and reliability is adequate for implementation of a road pricing system. The GPS log files was imported into ArcGIS and analyzed in relation to the digital road network and the density of the high rise areas in order to examine where the high buildings and narrow street canyons causes too many gaps in the position logs. The results showing that the satellite availability is not sufficient were illustrated on different maps showing the satellite availability in relation to the road network and the density of the high rise areas.

## **Keywords:**

Geographic Information System, GIS, Global Positioning System, GPS, Road pricing, ITS.

## **1. Introduction**

Road pricing is one among several approaches for reducing congestion on the streets in larger cities. GPS based road pricing is considered one of the best approaches for some cities. Drivers can be charged based on where, when, and how much they drive in the streets. However, for a GPS based system to work it must be reliable, and that can be a problem in the city centres in older cities, where the streets are narrow and the buildings are tall. A sufficient number of GPS signals might not reach the receivers in the vehicles causing lack of position registrations, and in the end problems with the charging schemes.

The AKTA experiment, as described in the following section, was carried out in 2001-2003, where 500 cars were equipped with GPS receivers. The GPS data was logged when the vehicles were in motion, and a very large and complete data set was collected. The GPS data has formed the basis for a throughout ArcGIS analysis of the GPS availability in Copenhagen, and the results of this analysis are given in the following. The GIS analysis shows that there are streets in Copenhagen where GPS based road pricing are not feasible because of limited satellite availability. First a general introduction to the field experiment, before we look at the analyses.

## **2. An Introduction to the Experiment**

The Copenhagen AKTA-experiment (the Danish abbreviation for alternative driving and congestion charging) tested such a system on 500 cars over a two-year period [1]. AKTA tested a kilometre-based rush hour charging scheme, a scheme with all day charges (but double charge in the rush hours) and a scheme with cordons (refer to Figure 1)

GPS data were collected for 500 cars over a period of 2 years. The database includes approx. 250,000 trips and 120,000,000 GPS observations. The GPS receivers calculated and stored the car's position every second. For each car, different information was registered by the GPS receiver for every trip made. The most important information, besides time and date, is the X coordinate, the Y coordinate, the number of visible satellites, HDOP (Horizontal Dilution of Precision), distance and speed. The united database with this information was imported into ArcGIS, where different types of analyses were performed on the data.

The accuracy of every GPS based observation depends on the number of satellites in view, the quality of each signal (HDOP) and the direction the satellites are located by in respect to the vehicle and its movement. The receiver needs minimum 4 satellites in view to estimate x, y and z as well as the time, which is used to estimate the position of the satellites. A HDOP value less than 4 indicates a good signal quality and hence a good measurement. Usually, reliable uninterrupted positioning can only be realized under an open sky or with minimum obstructions. However, GPS must provide sufficient availability and reliable service for road pricing even if the performance of the existing system may decrease under difficult operational conditions. The signal reception is therefore specifically sensitive in built-up areas since the signal problems often are caused by high buildings that cut off the signals.

These signal problems are also seen in wooded areas and while driving through tunnels and under bridges.

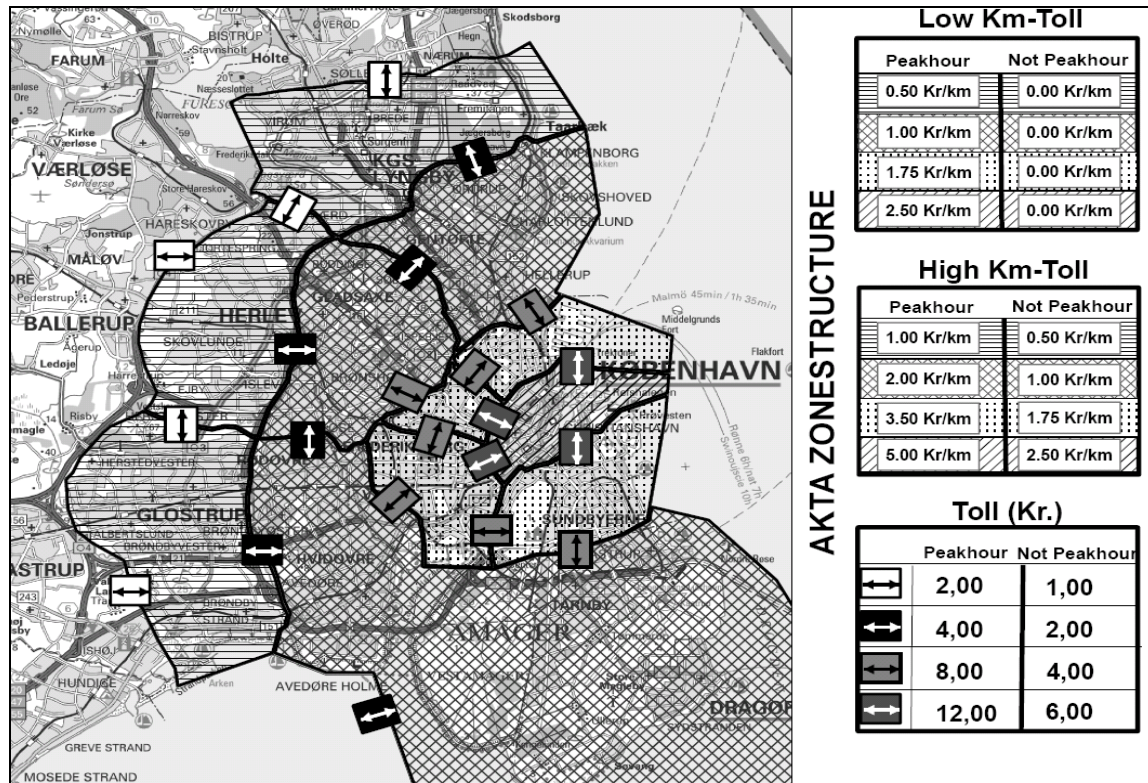


Figure 1: Different pricing schemes in AKTA (Background map from KMS, Copyright Kort & Matrikelstyrelsen G X-03, [www.kms.dk](http://www.kms.dk)).

The GPS points are not directly related to a digital roadmap. In many cases it might be ambiguous which road the point “belongs to”. Therefore a map-matching algorithm had to be created in order to relate the GPS points to the network. This algorithm is described by Nielsen and Jørgensen [2]. One of the advantages of map-matching is that sections of trips without GPS observations are estimated using the most efficient path principle. Therefore, it was not only possible to analyze the quality of the GPS observations, when there were sufficient observations to estimate a location, but also to analyze the occurrence of missing observations by use of GIS.

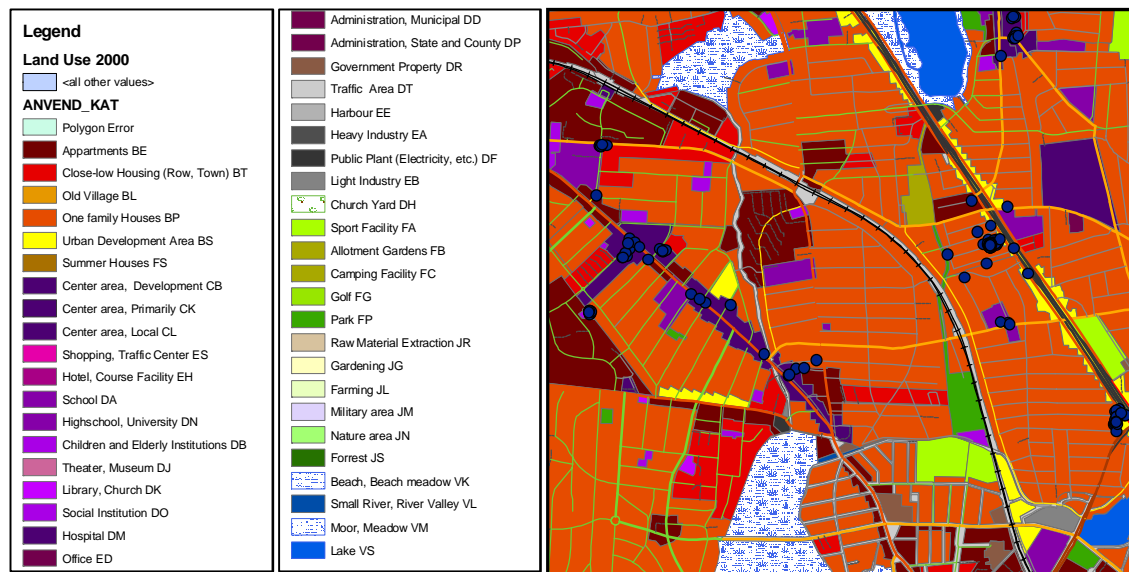
### 3. Data

Due to the fact, that each car’s data was stored in separate files, a united database was created in order to be able to perform overview analyses on the data. The log-files were imported into the database which consisted of 42,000,000 observations. Due to such a problematic large database in relation to Windows limitations, different sets of data were created as subsets from the united database by use of SQL. The subsets were all created with randomly chosen data and created within different categories, such as a subset of all data and a subset of the data from Copenhagen only, etc.

The data analysis was supported by different digital land use maps (described in the following), which showed the land use category or density for every area; hence the GPS conditions can be seen in relation to the surroundings

## Land Use Map

The land use map of Copenhagen is very detailed (see Figure 2), since it include 44 different land use categories. The map contains approximately 12,000 polygons and covers the greater Copenhagen area. This Land Use Map made it possible to analyse some special relationships, e.g. the land use relationship to forest etc.



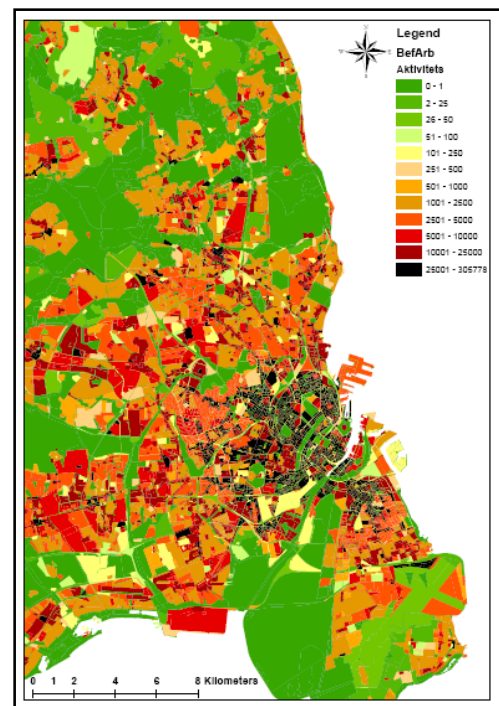
**Figure 2: Land use map (based on map from the Copenhagen Regional Development Council, HUR, [www.hur.dk](http://www.hur.dk)).**

## Density Map

The Density Map of Copenhagen contains information on the density of people and workspaces per square kilometre.

The map consists of 32,000 polygons which all have a land use category and an estimated factor for the density of the buildings. This urban density was estimated from both the population density and the workplace density for Copenhagen. (See Figure 3)

This Density Map made it possible to analyse the connection between the satellite availability and the density of the buildings.



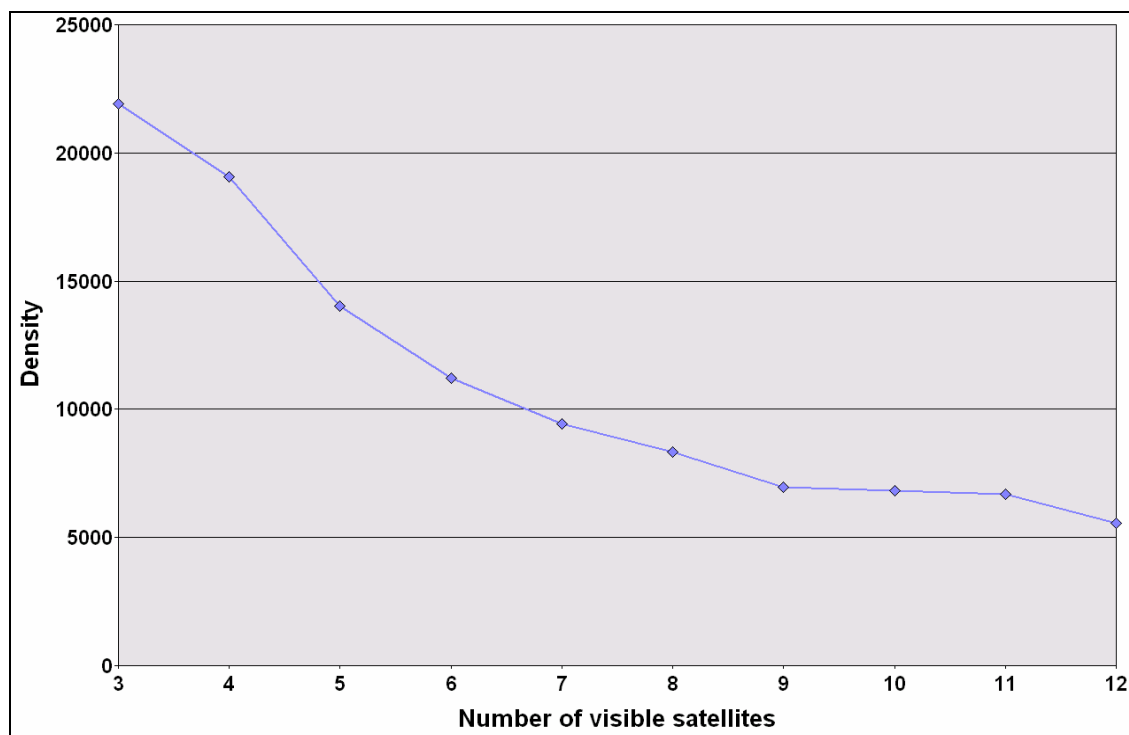
**Figure 3: Estimated density of the buildings.**

## 4. Analyses and Methods

The data analysis was divided into two parts. In the first part, the satellite visibility and the HDOP values were examined individually with respect to the density of buildings and the surroundings, and in the second part, the streets' suitability for road pricing was examined based on average values calculated for every street.

### Part 1 – Analyses of satellite visibility

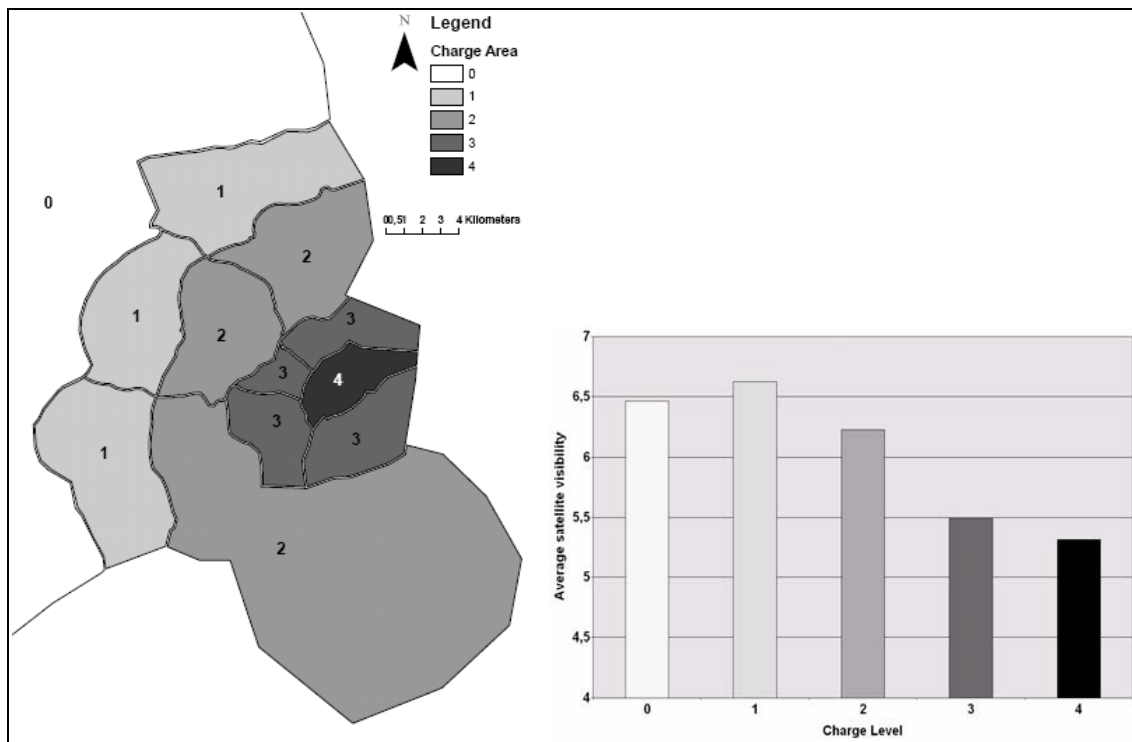
In order to determine the connection between the density and satellite visibility a buffer of 30 meters was made in ArcGIS on all the GPS logs followed by a spatial join between the buffers and the Density Map. An average of the density where then found for each GPS position. Figure 4 shows this average of the density plotted for each number of visible satellites. This illustrates that if the unit only has 3 satellites in sight, the urban density is then on average 22,000 (people + workspaces per square kilometre). If 12 satellites are in sight, then the average density is much lower (5,000). This emphasized how the satellite visibility is best when the building density is low and opposite worse in tight built-up urban environment.



**Figure 4: Relationship between the density of the buildings and the satellite visibility in Copenhagen on average.**

The urban density is here used as a proxy for the height and closeness of the buildings. However, it reveals a systematic bias in the accuracy of the signals (3 satellites are too few to estimate a position, 4 are just a minimum and are therefore quite uncertain, 5 and 6 provide

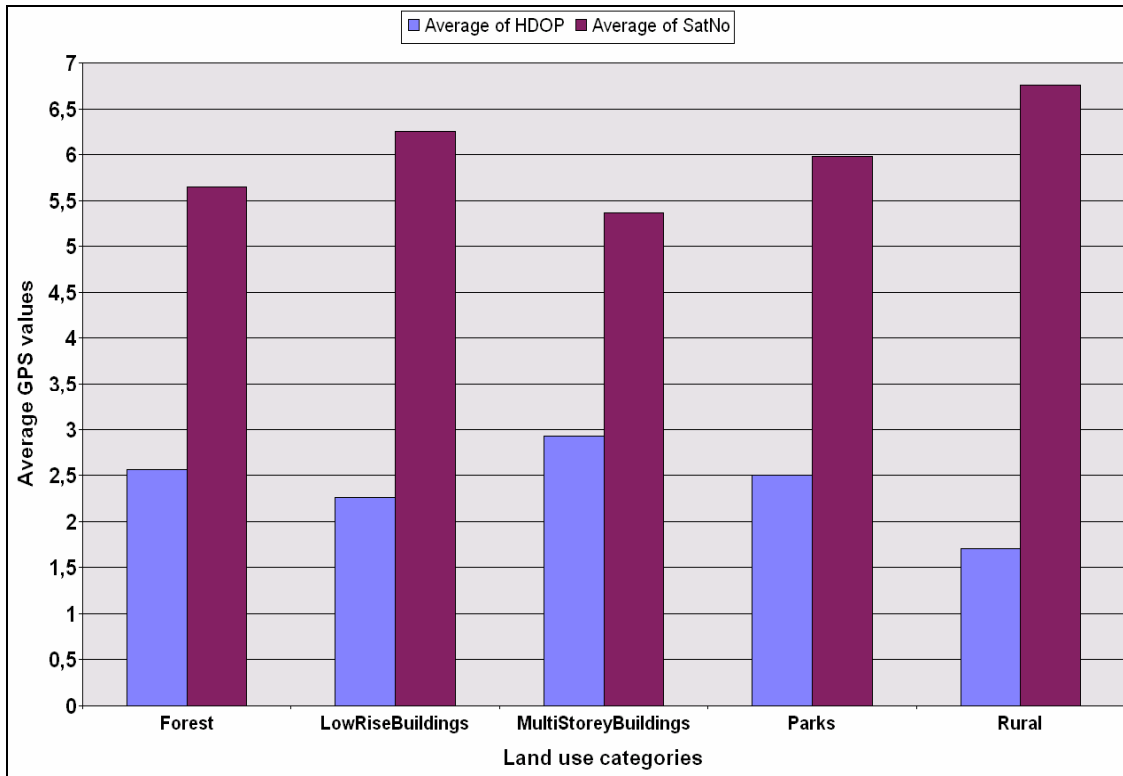
much better estimates, etc.). Since urban road pricing typically focuses on increased charges as the car approaches the city centre, it is naturally a problem that the accuracy is also biased with lower quality for the more dense built up areas. This is further illustrated on Figure 5, where the relationship between the satellite visibility and the charge level areas in the AKTA experiment is showed.



**Figure 5: Relationship between the satellite visibility and the charge level areas.**

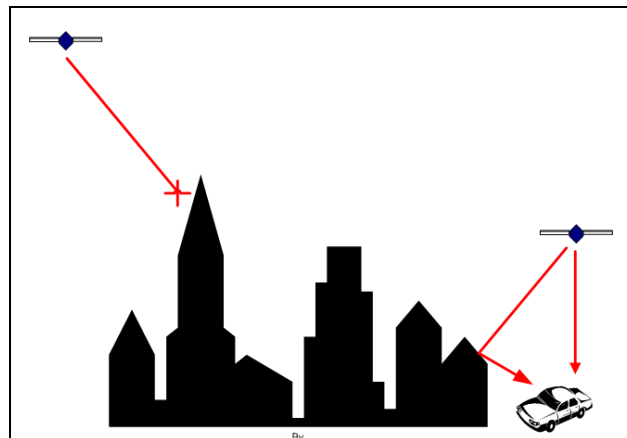
By calculating (by a spatial join) the satellite average for each zone with land use categories (land use layer), the relationship between the satellite visibility and the surroundings was found. Five characteristic land use categories were chosen in order to point out the most important differences. The average satellite number and HDOP for each of the 5 categories appear on Figure 6. The figure shows the satellite visibility in different types of areas. The average HDOP value was calculated similarly.

Outside Copenhagen, the results of a spatial join between the GPS logs and a zone layer showed how the wooded areas also affect the GPS quality as expected (Figure 8). The forests have about 5-6 satellites in sight, while the surrounding areas have 6-7. As the minimum of required satellites are 4, this difference provides a far better quality of the signal.



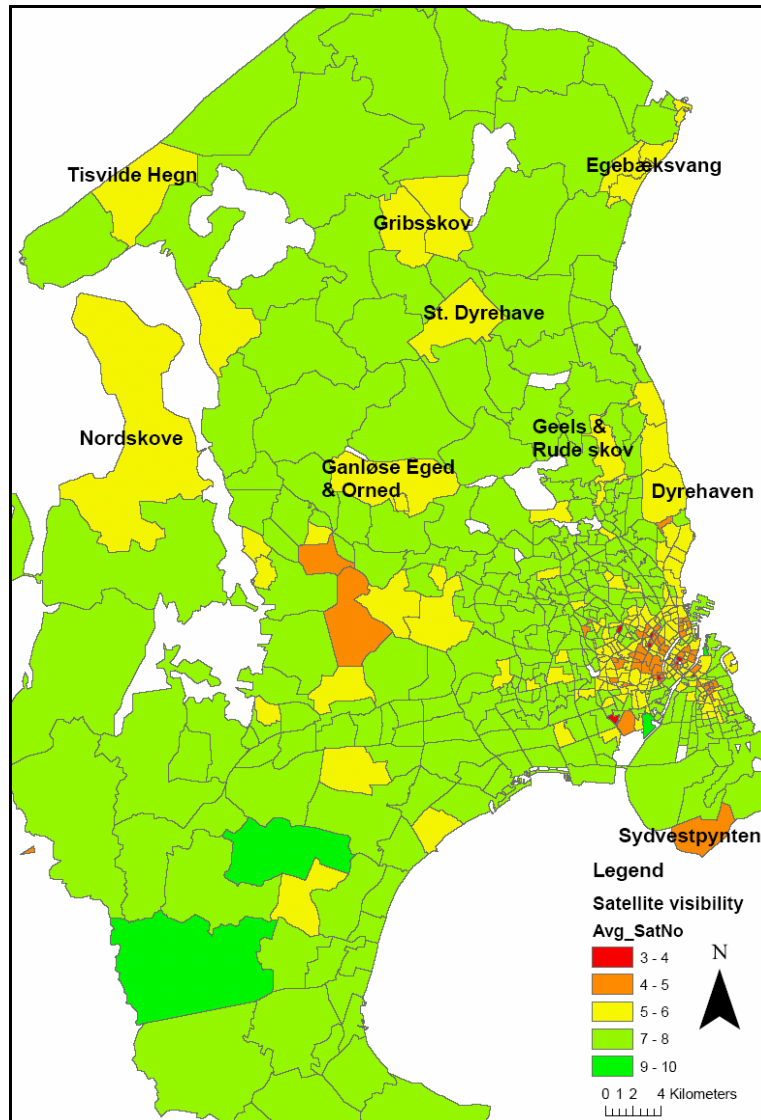
**Figure 6: Satellite visibility and HDOP for different area types.**

In the forest areas, the GPS conditions are worse than in the park areas, which is due to the closer planting and higher trees in the forest, where also the satellite signals are subjected to uncertainty caused by multipath. Multipath occurs, when the satellite signals are not received directly, but are partly reflected on surrounding surfaces. When the GPS signal is reflected on large objects like buildings and trees, the signals from the satellites are delayed which causes output errors (See Figure 7).



**Figure 7: Multipath and signal blocking.**





**Figure 8: Illustration of lower signal quality in forests (marked by name) in the outer area of the region compared to the rural areas (Zonal polygons based on OTM zonal map layer).**

## Part 2 - Analyses of the streets' suitability

The streets' suitability for road pricing was examined based on average values calculated for every road in downtown Copenhagen and visualization in ArcMap. In connection with road pricing it was interesting to examine which roads were suitable with regard to the satellite conditions. A road may have good satellite conditions in one end, while the conditions worsen in the opposite end, due to transverse streets or other changes in the surroundings. The satellite conditions were examined for the road network in Copenhagen by establishing a buffer (of 30 m) around every street in the network. Afterwards, the average GPS values (e.g. the average satellite number and the average HDOP) were calculated by a spatial join for every road section based on the data within the buffer. The results were then compared to the building density.

The results reveal a connection between the GPS quality and the density of the built-up areas in Copenhagen. The GPS values are worse in Copenhagen especially in the inner neighbourhoods and in the city centre, where the critical values were found (refer to Figure 9). Better signals appeared within the parks in Copenhagen given that the critical values decrease in these areas.

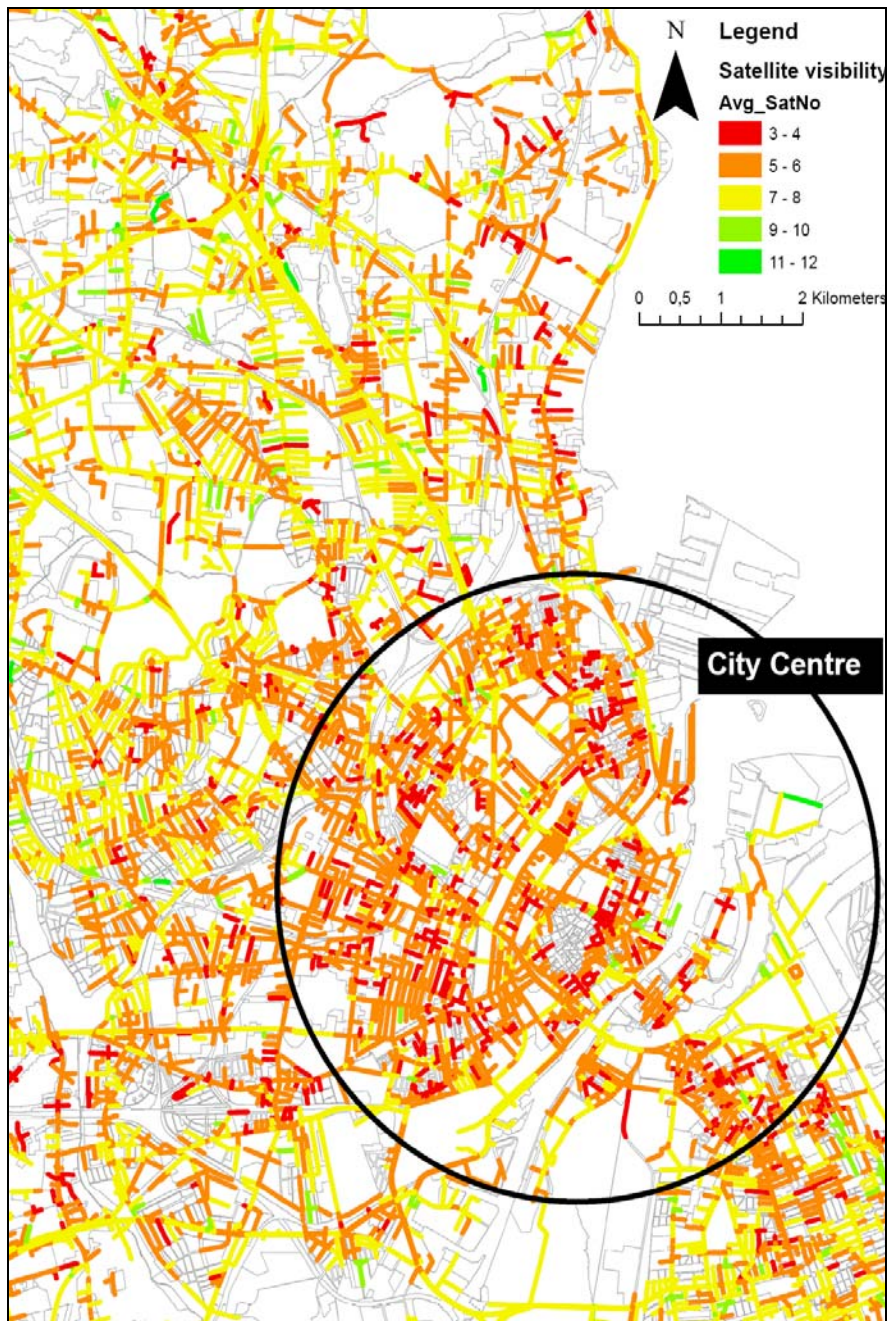


Figure 9: Average satellite visibility per road in Copenhagen (road map based on KRAKS kdv geodatabase, [www.krak.dk](http://www.krak.dk)).

Further, the analysis showed that the HDOP value improved significantly, when the number of visible satellites was more than 5. This is so because there hence are 5 equations to determine 4 unknown quantities, so that the redundant observation improves the positioning accuracy.

The analysis showed that the critical values in Copenhagen primarily were found in the streets in downtown Copenhagen and the nearest neighbourhoods. In the cities outside Copenhagen, where the city centre is to be found on a main street, the analysis showed a tendency of several critical values in the main street and the transverse side roads. This tendency was in accordance with the building density in those particular cities.

Along the highways and the motorways, the satellite coverage was good as expected with the exception of road stretches under bridges and through tunnels, where several signal fallouts occurred.

### Analyses of signal fallouts on map-matched data

Subsequently, the signal fallouts for every road were examined based on a map match dataset. Since the original GPS data did not contain information about the actual occurred signal fallouts, due to the receiver being unable to determine the position with less than 3 visible satellites, it was found interesting to examine the map matched data, where these signal fallouts were registered and the position estimated.

In the map matched database, all signal fallouts were registered for every street section. Based on that, a ratio between the number of actual signal fallouts and the total number of loggings in the street section were calculated for each road in Copenhagen. Hence the ratio value for the road section was 1, if all the loggings were signal fallouts and 0 if there were no signal fallouts in that road section. The ratios were plotted on a map in ArcGIS, in order to show the scale of the signal fall-out problems.



**Figure 10: Signal fallouts scale per road in Copenhagen (road map based on KRAKS kdv geodatabase, [www.krak.dk](http://www.krak.dk))**

The results for one specific area in downtown Copenhagen were compared to the results from the smaller field experiment, in order to certify the results.

Figure 10 illustrates those roads in Copenhagen, where signal fallouts in the signal reception occurred in over 80 % of all GPS positions. Furthermore, the results showed that the smaller side roads had more signal fallouts than the wider ones. The difference is quite systematic, since all the major (and therefore wider) roads have none or few signal fallouts.

## **5. Conclusions and perspectives**

The dense built-up areas make the GPS quality degrade in Copenhagen. With road pricing in mind, the results of the analysis are less than satisfactory. If the road pricing system becomes operational, the system requires reliability which allows traffic adjustment by use of variable road pricing charges depending on the travel. By such a charging system, a complete fair pricing is only possible if the positioning is sufficiently accurate. In order to make a road pricing system function satisfactorily, the GPS quality related to the roads has to be improved. As it appears from the ArcGIS analysis, the GPS quality depends on the density of the built-up areas, which is why the problem areas are found in the most closely built-up neighbourhoods [3]. With road pricing in mind, the stand-alone GPS quality is not sufficient. This is especially the case for road type dependent systems and cordon based systems, while kilometre-based systems may be combined with algorithms that estimate the cost after the cheapest charging principle for trip-segments with signal loss.

The positioning accuracy is improvable by integration of future GNSS (Global Navigation Satellite Systems) and augmentation systems, which at present are being developed. The advantages of upgrading old systems and developing new ones relate to the co-operation between the systems. Receivers which are integrated with the different systems have a variety of advantages. Due to the increased number of satellites, the receiver is more reliable and robust against jamming. Integrated augmentation systems have showed an improvable impact in other countries. Examinations of simulation have showed how the integrated augmentation systems improve the satellite coverage in major cities. This, however, only reduces the problems, but it does not completely eliminate them [4].

Using ArcGIS for the GPS analyses made the quality control less complicated, since the inaccurate positions easily could be pointed out and analysed in relation to the surroundings. Due to the systematic analyses completed by the use of the ArcGIS's tools, it was simple to locate areas with poor signal reception and make further analyses for these areas. The layout maps made with ArcMap were excellent for illustrating the GPS quality problems, showing both the GPS logs and the land-use categories underneath.

The overall evaluation of the stand-alone GPS quality is that the satellite coverage in Copenhagen at present is inadequate for GPS based road pricing. By introduction of a GPS based road pricing system, several complications in connection with kilometre charging may possibly occur due to the several signal fallouts and the estimated critical areas in Copenhagen.

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