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GPS-based Road Pricing

Copenhagen in Denmark has conducted an experiment in alternative driving and congestion charging using car tracking based on GPS. A main limitation of GPS is that quality depends on satellite visibility, which is best when building height and density are low. Road pricing is an area in which this limitation shows. Although GPS quality alone is insufficient, GPS car tracking may become feasible when integrating (future) Global Navigation Satellite Systems and augmentation systems. A fair pricing system charges the most when a car drives through the busiest parts of an urban area and least when driving outside such areas. A prerequisite for a fair pricing system is that car positioning be sufficiently accurate every time everywhere. The accuracy of car tracking based on GPS depends on the number of satellites in view, the quality of each signal (HDOP) and the location of the satellites with respect to the vehicle and its direction of movement. At least four satellites should be visible for estimation of the three location coordinates and the time component. However, four satellites represent a minimum and provide quite unreliable results; visibility of five or six satellites provides much better estimates. A HDOP value of less than four indicates good signal quality and hence a good measurement.

Signal Receipt

Reliable, uninterrupted positioning can usually only be achieved under open skies or when obstructions are few. Forest areas are particularly sensitive to signal interruption because trees cut off signals, and the same is true for built-up areas where high or densely placed buildings may interrupt signals. Signal problems also occur while driving through tunnels and under bridges. For road pricing it is essential that GPS is sufficiently available and enables reliable services, and for this permanent signal receipt is a prerequisite. Since charges are usually highest in city centres accuracy requirements are highest in those areas characterised by high density of high buildings whilst reliability of GPS signal receipt is precisely lowest in such built-up areas.

Observations

To test the feasibility of GPS as a positioning component in a road-pricing system in an urban area, five hundred cars collected GPS data over a two-year period. The onboard GPS receivers calculated and stored the carâ€™s position every second and registered time and date, number of visible satellites, HDOP (Horizontal Dilution of Precision), distance and speed. The resulting database, which included about 250,000 trips and 120 million GPS observations, was imported into GIS. Since the data on each car was stored in a separate file, a united database was created to enable overview analyses on the data. The log-files were imported into the database, consisting of 42,000,000 observations. Limitations on the part of Windows to handle such a large database led to subsets being created using SQL. The collected GPS data was analysed in relation to different land-use types and building density.

Land Use

Land-use types were derived from the land-use map, which contains about 12,000 polygons and covers the greater Copenhagen area. It is very detailed, having 44 categories (Figure 1). Building density provides an approximation of the height and closeness of buildings. The density map of Copenhagen contains information on the density of people and workspaces per square kilometre and consists of 32,000 polygons attributed with land-use category and building density, the latter estimated from both population and workplace density (Figure 2). Building density enables analysis of the relationship between satellite availability and density. For this a buffer of 30 metres was created on all GPS logs, followed by a spatial join between the buffers and the density map. This resulted in an average density for each GPS position. A clear relationship was found between density and the number of visible satellites (Figure 3). For example, in areas with a density of 22,000 only three satellites are visible, and where the density is 5,000 twelve satellites are visible. Spatially joining the satellite average for each zone with land-use categories gives the relationship between satellite visibility and land use. To indicate the most important differences, the 44 land-use categories were aggregated to five. The average satellite number and average HDOP for each of the five categories are shown in Figure 4.

Road Network

To establish which roads allowed cars to be reliably tracked the average number of satellites visible and average HDOP values for every road in central Copenhagen were computed and the result visualised in ArcMap. The results were examined by creating a buffer area of 30m around every street. These averages were then calculated by spatial join for every road section, using the data within the buffer. The values appear to be worse in the city of Copenhagen where building density is high, especially in the inner quarters and in the city centre, while better values appear in parks (Figure 5). The analysis showed that the HDOP value improved significantly when the number of visible satellites exceeded five. This is because redundant observations improve positioning accuracy. Critical HDOP values were found primarily in the streets of central Copenhagen and neighbourhood. In urban areas outside Copenhagen where high building density is found along the main street, critical values appear in the main street and its side roads. There was reliable tracking of cars on major roads and motorways, except under bridges and in tunnels.

Concluding Remarks

This long-term experiment demonstrates that car tracking based on GPS is not yet feasible for dense urban areas such as Copenhagen. It is possible that an increase in the number of satellites will mean improvement in the future. But 100% reliability every time everywhere is probably unachievable. The use of GIS in the analyses enabled straightforward quality control since GPS positions could be easily analysed within their spatial context.

Further Reading

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â€¢ Nielsen, O. A., 2004, Behavioural Responses to Pricing Schemes: Description of the Danish AKTA Experiment. Journal of Intelligent Transportation Systems, Vol. 8(4), pp 233-251. Taylor & Francis.
â€¢ Nielsen, O. A. and JÃ¸rgensen, R. M., 2004, Map-matching Algorithms for GPS Data â€“ Methodology and Test on Data from the AKTA Road Pricing Experiment in Copenhagen. World Conference on Transport Research Society (WCTRS), Proceedings, Paper 1435, D05 July 7th, Istanbul, July 4-8, 2004.
â€¢ Zabic, M., and Nielsen, O.A.. A Geographic Information Analysis of Global Positioning System Quality for Road Pricing. (Submitted to Transportation Research Part C).
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