TRAFFIC FLOW MODELING AND OFFSET OPTIMIZATION IN URBAN ROAD NETWORKS WITH AN ENHANCED CELL TRANSMISSION MODEL AND GA

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ABSTRACT

The Cell Transmission Model (CTM) by Daganzo was enhanced in order to deal with signalized multi-lane junctions. In combination with an offset optimization algorithm based on genetic algorithms and a graphical user interface, the enhanced CTM was applied to a test area in Hannover, Germany. The thus optimized traffic control proved a significant improvement of traffic flow considering reduction of travel time and number of stops.

Keywords: Traffic Flow Modeling, Offset Optimization, Cell Transmission Model, Genetic Algorithm

INTRODUCTION

The Cell Transmission Model (CTM) [Daganzo, 1994, 1995] is a time and space discrete traffic flow model which was originally developed to estimate traffic flow on highways. In a first step, it was proven that the CTM is basically applicable on an urban road network and in combination with an optimizer based on genetic algorithms allows for quick offset optimization [Friedrich and Almasri, 2006]. The main objective of this paper was to establish a user-friendly software for offset optimization in urban road networks. The software was applied to a test area in the city of Hannover, Germany. The solutions were evaluated using microsimulations and empirical before-after studies.

The remainder of this paper is organized as follows: FORMULATION gives an overview about the enhanced CTM, the offset optimization and software establishment. FIELD STUDIES introduces the test area and discusses the results of the before-after studies. The paper ends with the drawn CONCLUSIONS.

FORMULATION

Enhanced CTM

The CTM provides an approximation to the LWR model [Lighthill and Whitham, 1955; Richards, 1956] and can be used to predict transient phenomena such as build-up, propagation and dissipation of queues. It employs a simplified version of the fundamental diagram based on a trapezium form, assuming that a free-flow speed, v_f, at low densities and a backward wave speed, w, for high densities are constant. Dividing the road sections into homogeneous cells i and time into homogeneous intervals of duration t such that the cell length is equal to the distance travelled by free-flowing traffic in one time interval, the LWR results are approximated by a set of recursive equations, (1) and (2). The subscript i refers to cell i; the cell upstream and downstream is (i-1) and (i+1), respectively (Figure 1).

$$n_i(t+1) = n_i(t) + q_i(t) - q_{i+1}(t) \tag{1}$$

$$q_i(t) = \min\left\{n_{i-1}, Q_i, (w/v_f)(N_i - n_i(t))\right\} \tag{2}$$

where:
n: number of vehicles
N: maximum number of vehicles
q: inflow
Q: inflow capacity

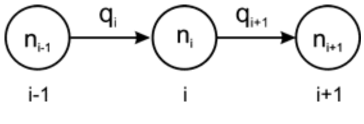


Figure 1 - Cell representation for CTM

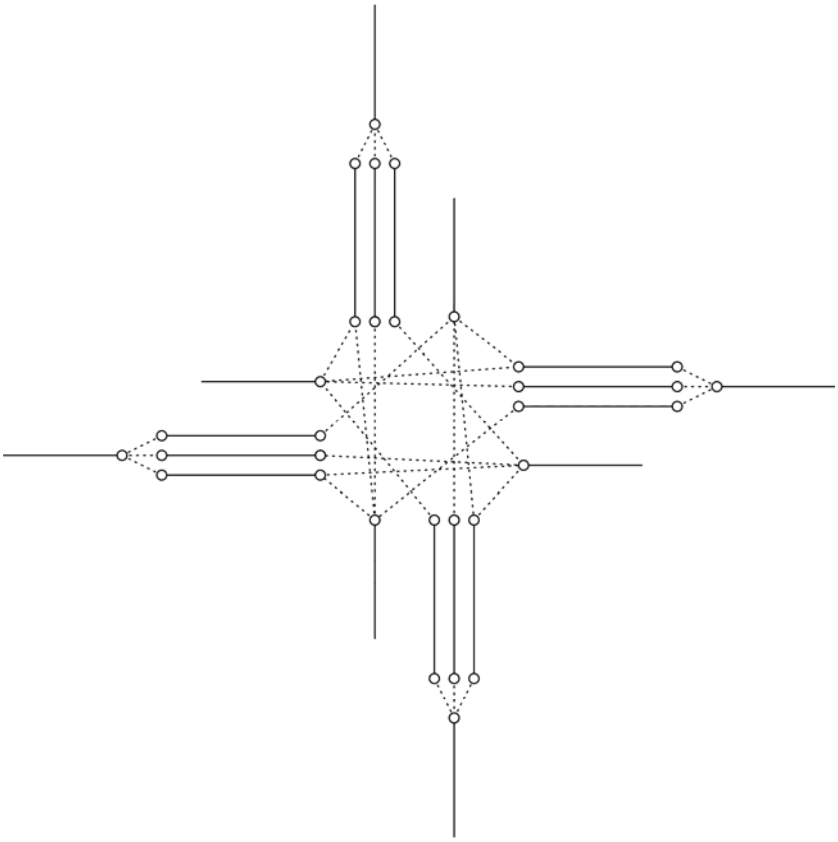
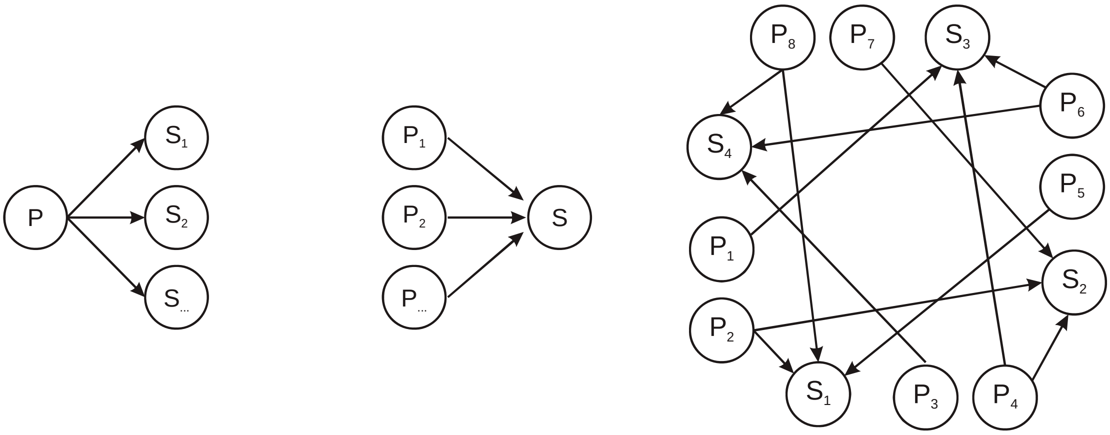


Figure 2 - Example of a junction in an urban road network with several lanes and turning movements (dashed)



a) b) c)

Figure 3 - Extended CTM: Examples for diverges (a), merges (b) and junctions (c) with unlimited number of predecessor cells or successor cells, respectively

Due to the fact that the CTM was developed for estimating traffic flow on highways, one crucial drawback occurs while applying it to an urban road network: The CTM only holds for diverge flows from 1 predecessor cell into 2 successor cells and merge flows from 2 predecessor cells into 1 successor cell, respectively [Daganzo, 1994 and 1995]. Thus, modeling traffic flows in a common multi-lane junction (see Figure 2) becomes intricate. For this reason, an algorithm called “general process of resource consumption” by Flötteröd and Nagel (2005) was implemented to the CTM to model diverges, merges and junctions. The thus enhanced CTM is now capable of modeling cell connections with an unlimited number of predecessor or successor cells, respectively, consistent with the LWR model (see Figure 3). Relevant output data of the CTM can be easily calculated with the following formulas:

Delay in cell i in time step t [Friedrich and Almasri, 2006]:

$$d_i(t) = t \cdot \left(n_i(t) - q_{i+1}(t) \cdot t\right) \tag{3}$$

where:

n_i: number of vehicles
q_{i+1}: outflow at cell i (equal to inflow at downstream cell i+1, see Figure 1)

Stops in cell i over all time steps t [Lin and Wang, 2004]:

$$stops_i = \sum_t 0.5 \cdot \left(q_{i+1}(t) - q_i(t-1)\right) \tag{4}$$

where:

q_{i+1}: outflow at cell i (equal to inflow at downstream cell i+1, see Figure 1)
q_i: inflow in i in the previous time step

Offset optimization

The objective for the optimization process is the minimization of the optimization criteria, i.e. the output data of the CTM. The proposed objective functions are as follows.

Overall delay in the network (sum of delays in all cells throughout the planning horizon):

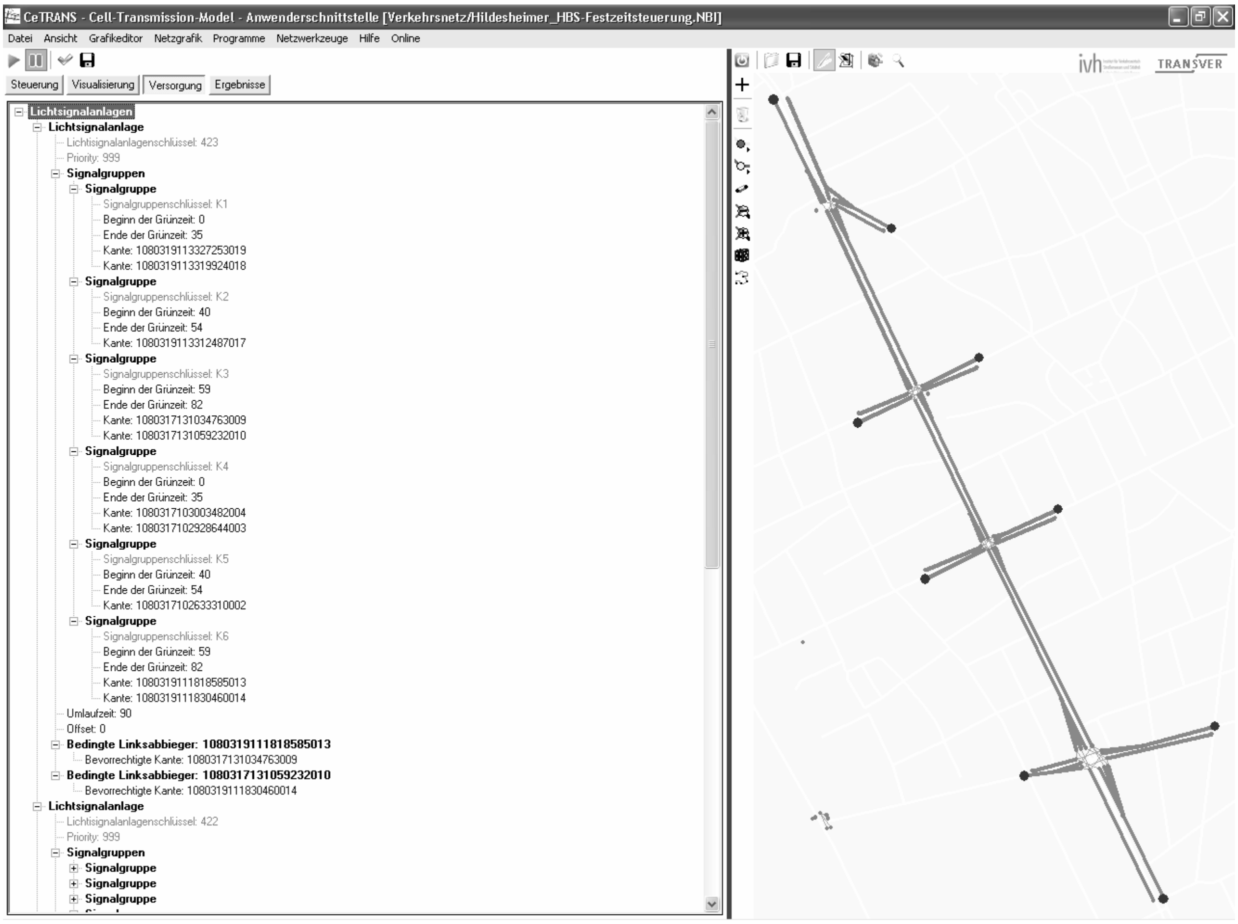
$$\min!\, f = \sum_t \sum_i d_i(t) \tag{5}$$

Overall stops in the network (sum of stops in all cells throughout the planning horizon):

$$\min!\, f = \sum_t \sum_i stops_i(t) \tag{6}$$

The two objective functions have an irregular shape within the solution space. For solving them, a heuristic approaches based on genetic algorithms (GA) was developed already [Almasri, 2006]. This serial genetic algorithm (SGA) considers the relative offsets of a group of junctions one at a time. These junctions are located on traffic direction of vehicles moving from an origin to a destination. Instead of performing GA operations on the entire chromosome, only the part related to this group of junctions is considered. The remaining junctions are fixed by the optimal values found in the last iteration. However, the fitness of new chromosomes is determined by evaluating all of the network junctions and not only the group of junctions under analysis. By disconnecting the simultaneous search into a sequence of searches, the length of the chromosome in the SGA is considerably short. By shortening the chromosome, and thus the solution space, a small population of chromosomes is sufficient to find quasi-optimal offsets quickly. In the next step, the offsets of the next group of junctions are optimized. In a serial search such as this, the order in which the junctions and offsets are respectively treated and searched greatly influences the optimization results. The SGA procedure consists of the following steps:

1. Determine groups of relative offsets and their order of search
2. Initialize each relative offset in each group with a value equal to the time needed to travel freely from the first junction to the second one and binary encode this value
3. Start the GA process with the first group determined in step 1 and randomly generate a population of chromosomes encoding each solution, which represents all relative offsets in this group of junctions in the tested network
4. While termination condition is not met (e.g. a chosen number of generations):
    a. decode chromosomes into sets of relative offsets and then evaluate the fitness of all the individuals using the CTM;
    b. put fittest chromosome into a mating pool;
    c. produce a number of offsprings by crossover and mutation;
    d. replace weakest chromosomes with superior offspring.
5. Fix the best relative offsets of this group and repeat steps 3 and 4 with the order determined in step 1 until all groups are finished.



- **Lichtsignalanlagen**
  - **Lichtsignalanlage**
    - Lichtisignalanlagenschlüssel: 423
    - Priority: 999
    - **Signalgruppen**
      - **Signalgruppe**
        - Signalgruppenschlüssel: K1
        - Beginn der Grünzeit: 0
        - Ende der Grünzeit: 35
        - Kante: 1080319113327253019
        - Kante: 1080319113319924018
      - **Signalgruppe**
        - Signalgruppenschlüssel: K2
        - Beginn der Grünzeit: 40
        - Ende der Grünzeit: 54
        - Kante: 1080319113312487017
      - **Signalgruppe**
        - Signalgruppenschlüssel: K3
        - Beginn der Grünzeit: 59
        - Ende der Grünzeit: 82
        - Kante: 1080317131034763009
        - Kante: 1080317131059232010
      - **Signalgruppe**
        - Signalgruppenschlüssel: K4
        - Beginn der Grünzeit: 0
        - Ende der Grünzeit: 35
        - Kante: 1080317103003482004
        - Kante: 1080317102928644003
      - **Signalgruppe**
        - Signalgruppenschlüssel: K5
        - Beginn der Grünzeit: 40
        - Ende der Grünzeit: 54
        - Kante: 1080317102633310002
      - **Signalgruppe**
        - Signalgruppenschlüssel: K6
        - Beginn der Grünzeit: 59
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        - Kante: 1080319111818585013
        - Kante: 1080319111830460014
    - Umlaufzeit: 90
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    - **Bedingte Linksabbieger: 1080317131059232010**
      - Bevorrechtigte Kante: 1080319111830460014
  - **Lichtsignalanlage**
    - Lichtisignalanlagenschlüssel: 422
    - Priority: 999
    - **Signalgruppen**
      - **Signalgruppe**
      - **Signalgruppe**
      - **Signalgruppe**

Figure 4 - Screenshot Software (Traffic Signal-Editor and Net-Editor)

Software establishment

The software allows an easy, quick and elaborate offset optimization in urban road networks. It includes four main components:

1. Net-Editor
2. Traffic Signal-Editor
3. CTM-Control and Offset Optimizer
4. Output Visualization

Within the Net-Editor, the user can easily create the urban road network in a common node-link-style; all relevant traffic signal parameters such as cycle time, phases, green times etc. can be edited using the Traffic Signal-Editor (see Figure 4). The CTM-Control and Offset Optimizer component is an interface between the Editors and the CTM (which runs as an independent application within the software). The user chooses the simulation and optimization parameters (time interval, optimization criteria, termination condition) and starts the optimization. The results of the optimization criteria and the new offsets are visualized in the Net-Editor.

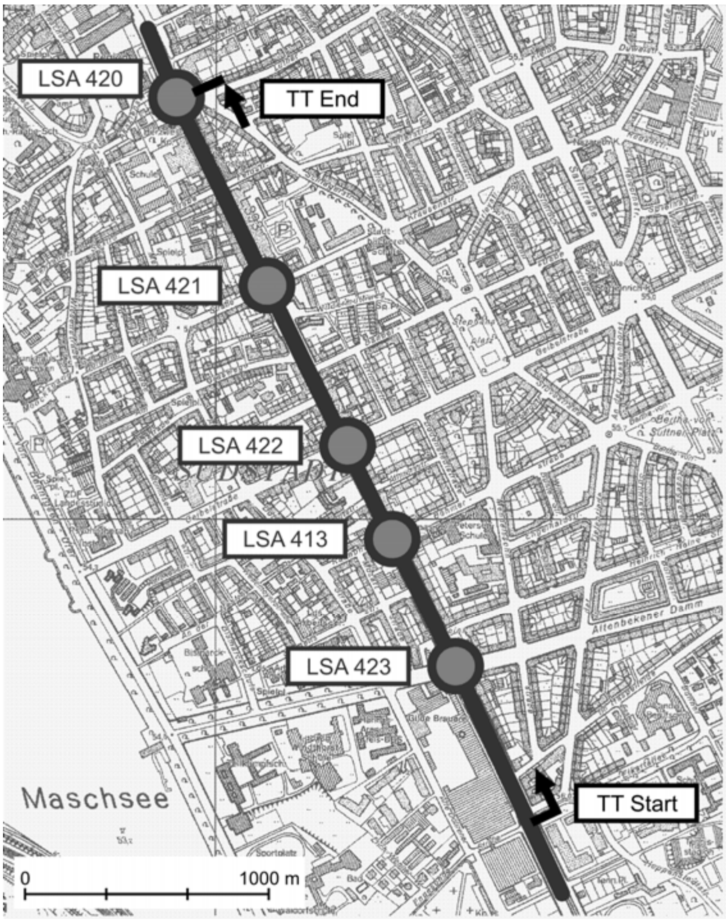


Figure 5 – Test Area. Dots represent Traffic Signals, TT = Travel Time Measurement

FIELD STUDIES

Test area

A main arterial of the urban road network of Hannover, Germany (Figure 5) was chosen as test area for field studies. The test area includes 5 junctions, mainly with actuated traffic control. The objective was to improve northbound traffic flow towards the city centre in the morning peak hour from 7:30 to 8:30 a.m. Extensive traffic measurements (link and turning flows, travel times northbound via ANPR and GPS-tracked floating car data) were taken in March 2009. Those data were used to build up and calibrate the test area in the microscopic traffic simulator AIMSUN NG 5.1. It served as a virtual reality of the test area, allowing for analyzing the impact of the offset optimization solutions under laboratory conditions before testing them in the real world. The junction 423 was declared as reference point for the relative offsets of the downstream junctions. Due to public transport priority rules at junction 423, it’s actuated traffic control remained unchanged. Simple fixed time control programs according to HBS (2001) were designed for all other junctions. The test area’s network was edited in the Net-Editor; the fixed time control programs in the Traffic Signal-Editor, respectively. (423´s actuated traffic control was transferred into a pseudo fixed time program according to the average green time split.) Then, the relative offsets for the northbound traffic were determined with the CTM and Offset Optimizer and tested in the virtual reality. They proved significant reductions of both travel times and number of stops, and thus the most promising solution was implemented in the traffic controllers of junction 413 to 420. Again, travel times northbound and GPS-tracked floating car data were taken in April 2010. The results of the concluding before-after-studies are discussed in the following.

Before-after studies

Figure 6 depicts before-after studies of travel times taken by ANPR measurements. Overall, a significant reduction in the average travel times in the morning peak hour can be stated, i.e. 3:30 minutes before optimization in March 2009 and 2:51 minutes after optimization in April 2010. The corresponding traffic demands were found to be nearly the same, thus the effects on travel times are mainly due to the change in traffic control. A closer look on the average travel times within every 5-minute interval reveals that this holds for every interval, except from 7:45 to 7:50 (police operation which caused a temporal bottle neck). Obviously, this reduction could only be possible due to the fact that every driver experiences smaller delay times and number of stops, and thus is able to travel the arterial more smoothly. Regarding the before-after studies of the GPS-tracked floating car data in Figure 7, this assumption is proved to be right. Before the optimization (March 2009), every FCD trajectory shows at least one stop at a traffic signal en route. After optimization (April 2010), the number of stops is reduces drastically; thus, the trajectories correspond to a smaller travel time. The few stops and delays are mainly because of the fact that junction 423 had to keep its actuated traffic control. Inevitably, the varying green time splits in real world contradict with the offsets solutions estimated with the model.

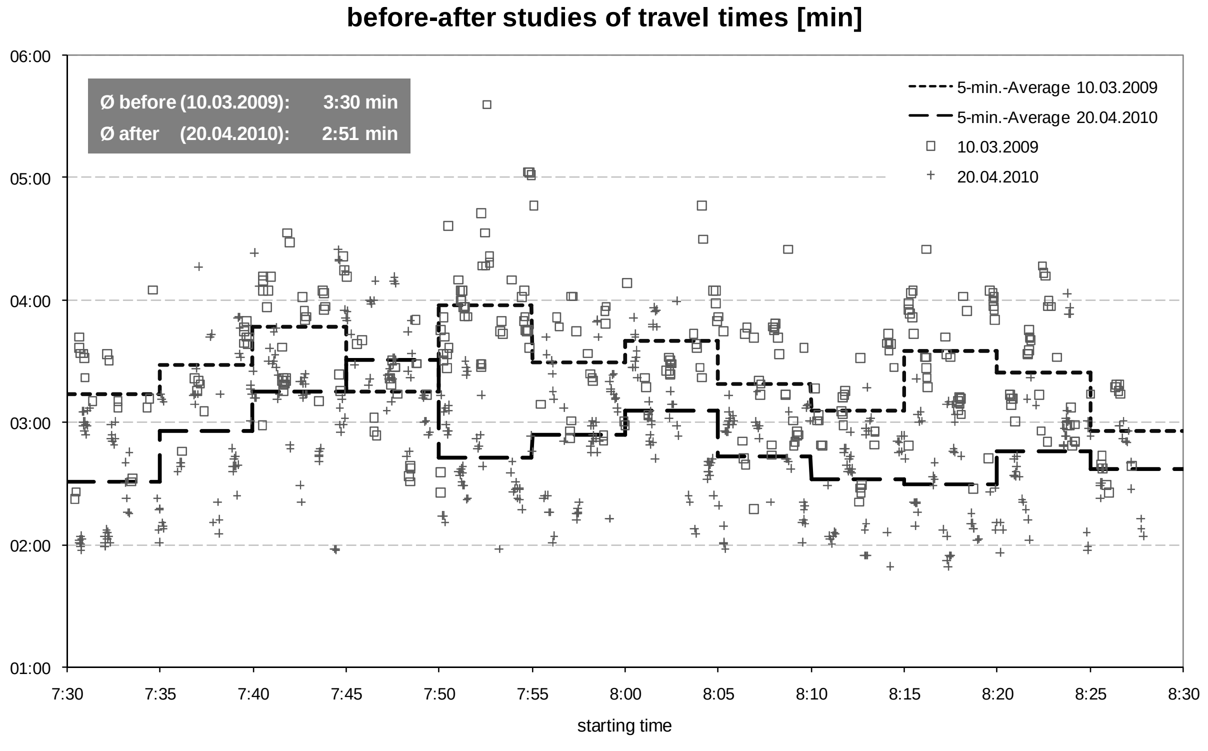
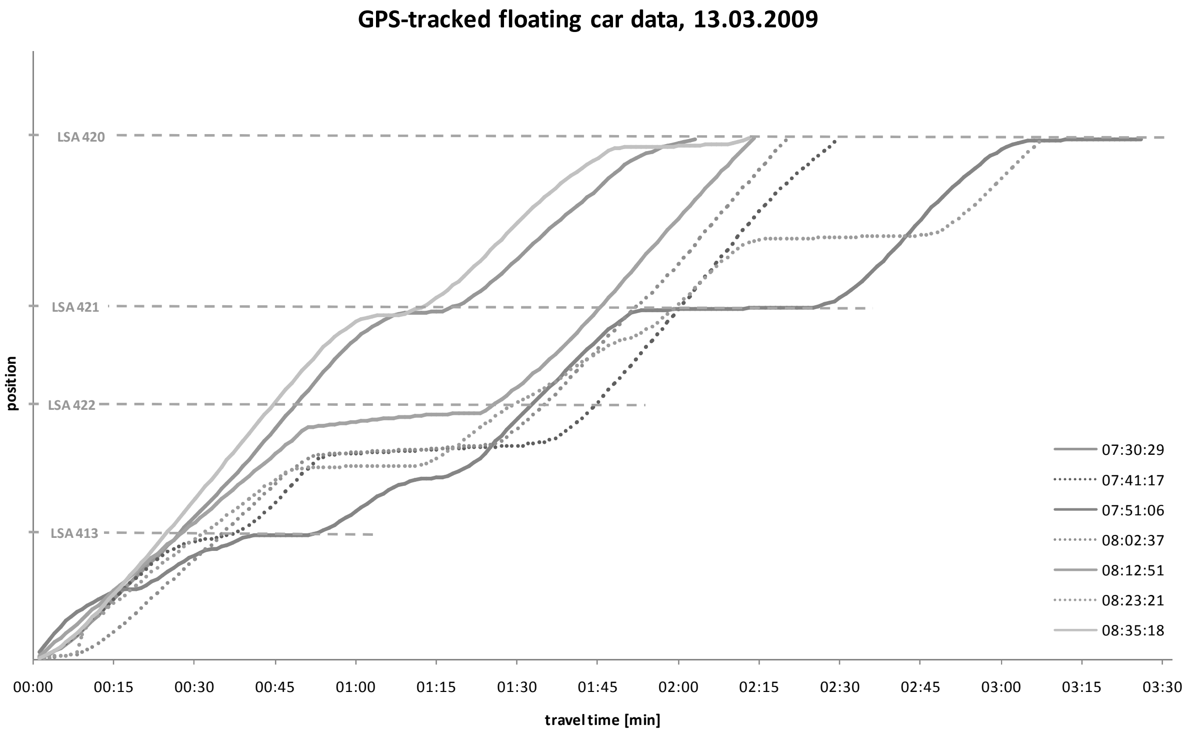


Figure 6 – Before-after studies of travel times.


GPS-tracked floating car data, 13.03.2009

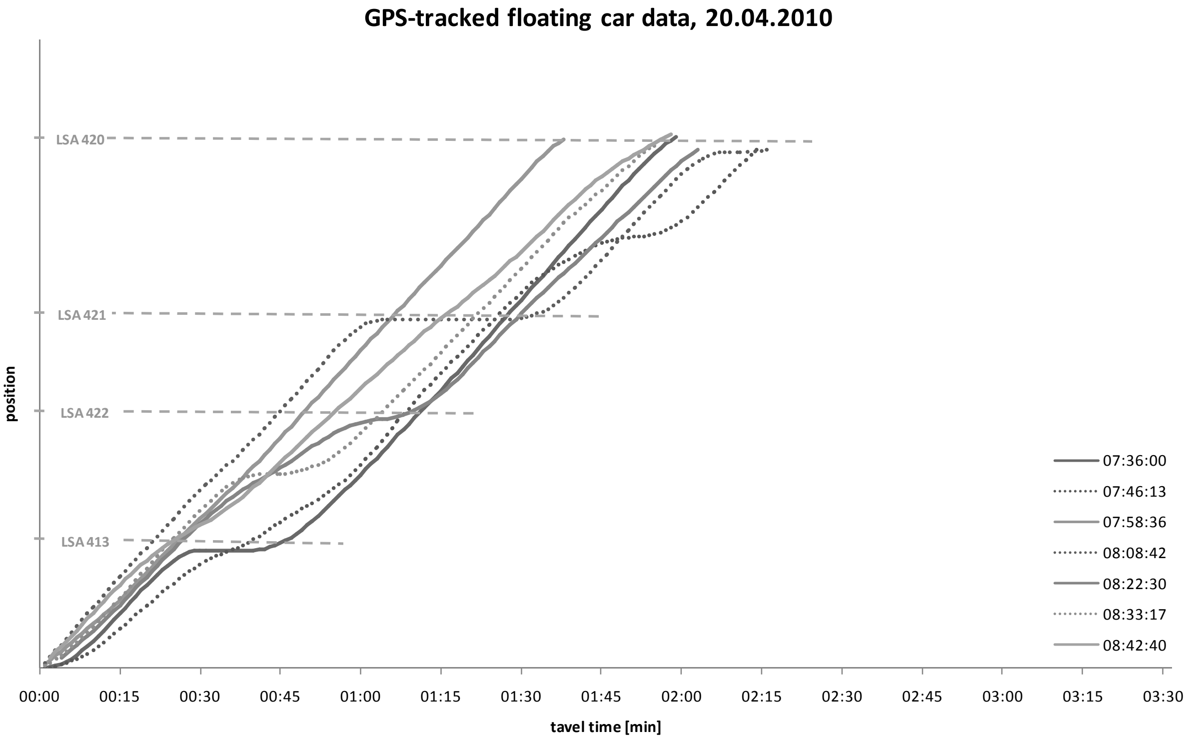

GPS-tracked floating car data, 20.04.2010

Figure 7 – Before-after studies of GPS-tracked floating car data.

CONCLUSIONS

The enhanced CTM is able to calculate the optimization criteria needed for the offset optimization functions. Thus, the established software which combines the enhanced CTM with an offset optimizer based on a serial genetic algorithm performs well. The optimized offsets and fixed time control programs proved a reduction of travel times and number of stops in the test area. Although, optimizing offsets between fixed time and actuated traffic controlled junctions suffers some difficulties. Further investigations are needed in order to model traffic actuated control with the CTM.

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