Adaptive Traffic Control System in a middle-size city

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Adaptive Traffic Control Systems in a medium-sized city – effects on traffic flows

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Abstract
Adaptive Traffic Control Systems (ATCS) are aimed at reducing congestion on road networks. ATCS adapt to approaching traffic to continuously optimise the traffic flows in the area. ATCS have been implemented in a range of locations, including the Nordic countries, with various effects. Due to congestion problems ATCS including 8 signalised intersections were installed on a 1.7 km part of the ring road in the medium-sized Danish city of Aalborg. To measure the effect of ATCS a with/without study was carried out. GPS data collected by a car following the traffic combined with measurements of transportation time for buses in service crossing the ring road formed the basis for the study. ATCS resulted in a 17% significant reduction in transportation time on the ring road in the most congested period, the afternoon peak. Less significant effects were found regarding the morning peak and midday off peak periods. The effect on buses was small, and the benefit on the ring road was partly gained at the cost of slightly increased transportation time regarding the crossing traffic. Also, it was found that thorough maintenance of the detectors connected to both traditional time-control signal management and in particular to ATCS is crucial.

KEYWORDS
Adaptive Traffic Control Systems, Intelligent Transport Systems; Congestion, Traffic Management, Evaluation Study

Introduction

Congestion and ITS

Congestion on the road network is a major and increasing challenge in most cities worldwide. In the USA, it is estimated that the annual costs due to congestions were $ 101 billion in 2010 (1) and similarly in the EU, it is estimated to cost well above 1% of the Gross Domestic Product or € 100 billion each year (2). These costs are mainly due to increased transportation time, fuel consumption, and emission costs (1).

So far the industrialised countries have found no way towards less transportation on a significant scale, and the EU has stated very clearly that reduced mobility is not an option (2). However, in most cases it is not possible or financially feasible to increase the road capacity with e.g. additional lanes and bigger intersections due to lack of space. Other solutions are therefore required to handle the increasing traffic flows. These solutions could be Smart Mobility Solutions or Intelligent Transport Systems (ITS) among others (2). ITS is a generic term for systems which make transportation smarter. The main challenges which the ITS are aimed at handling are congestion reduction, emission reduction and improved traffic safety (3,4). Adaptive Traffic Control Systems (ATCS) are one of the ITS aimed at reducing congestion and increasing the traffic flow possible on signalised road networks. ATCS are a

traffic management strategy, which makes traffic signals in a road network interact with other traffic signals in the system on the basis of the traffic flows in the various lanes of the road segments (5,6).
ATCS have been implemented in many cities worldwide in recent decades (5,7). Various effects of ATCS have been reported. In an American study, Hunter et al. found varying effects of ATCS. In one part of the studied road network ATCS reduced transportation time considerably, while in another part no clear effect was to be found. They also found in a literature review that some American ATCS decrease the time of transportation substantially, while other ATCS resulted in ambiguous effects (6). This is consistent with Fehon & Peters, who present a number of ATCS with positive effect on transportation time, number of stops, and mean speed. However, they also present ATCS, which failed to improve the traffic flow, but there was limited information about these (8). Samadi et al. found that ATCS in the Iranian city of Mashhad resulted in reduced transportation time. The effects were most clear in the peak periods, while a small positive effect at noon was registered (7). Another convincing result was found in the German city of Münster, where ATCS reduced transportation time considerably. Also, the difference compared to the time-control system shows the same pattern. Moreover, it was tested that buses in service also benefit from the system (9).
Less clear results are found regarding some ATCS implemented in Scandinavia. In Oslo an ATCS was implemented in parts of the city centre. Some positive results were found regarding car passability, while a clear negative effect was found on buses and trams in service. The latter despite the fact that careful simulations showed that cars and Public Transport (PT) were expected to gain from the ATCS. This study, however, found a number of effects outside the control of the ATCS, which might have affected the results (10). No evaluation results regarding Swedish and Danish ATCS are to be found, and an overview of most of the Scandinavian ATCS show no clear effects, but still a number of simulations indicated substantial reductions in transportation time for cars and particularly for PT (11). Finally, a number of references stated that the key challenge regardless of having ATCS or not, is to keep a sufficiently high level of maintenance of loop detectors, timetables for the time-control systems etc. Neither ATCS nor advanced time-of-day control can work properly if the system as a whole is not in operation. The effect of advanced traffic control systems decreases significantly the moment just a few loop detectors do not provide reliable data on the amount of traffic. (6,9,11).
Despite ambiguous evaluation results, ATCS are presently being implemented in many urban areas. Below is elaborated on the effects of implementing ATCS on a ring road in the Danish city of Aalborg.

Site and Project specification

The site

The fourth-largest city in Denmark, Aalborg, is facing the same challenges as most cities in industrialised countries. Despite the financial crisis the congestion level and the number of cars in the area have continued to increase (12,13). With its 126,000 inhabitants in its built-up area Aalborg is the main city in Region North Denmark (13). It is located on both sides of the Limfjord, an inlet, and the city is only connected across the inlet by two roads. To the east there is a tunnel with a motorway connection, and near the city centre there is a dual-lane distributor road crossing the inlet. Aalborg's position as the main city of the region and the fact that the main traffic connection from the northern part of the region to the rest of Denmark is via these two connections put Aalborg in a vulnerable traffic situation. The road segments closely linked with these two connections are highly congested and congestion situations on these links often cause congestion and traffic breakdowns on the adjacent central roads in the city centre. The overall road network and the inlet-crossing links appear in figure 1.

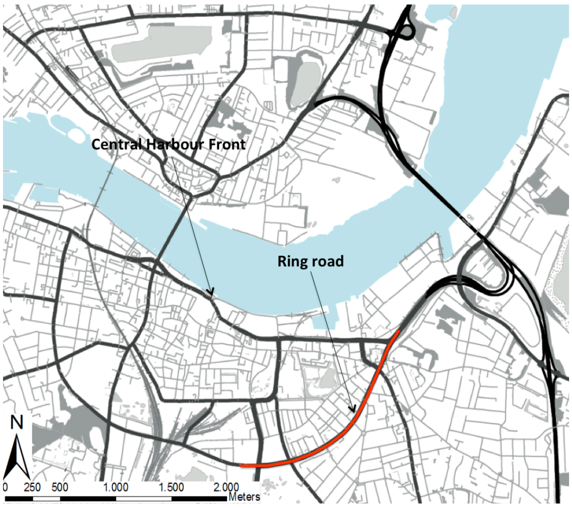

Figure 1. The overall road network and the two links across the inlet Limfjorden.

Also, until five years ago, running along the waterfront, a heavily congested dual carriageway separated the city centre from the now revitalised harbour areas. To open the city to the Limfjord, the harbour front was renewed and the carriageway was reduced to a one-lane carriageway. This modification reduced the traffic volume on the harbour front significantly. However, the traffic was reallocated to other distributor roads, in particular the main ring road around Aalborg Centre, Østre Alle. The ring road has to handle a significant part of the relocated traffic flow. See figure 2.

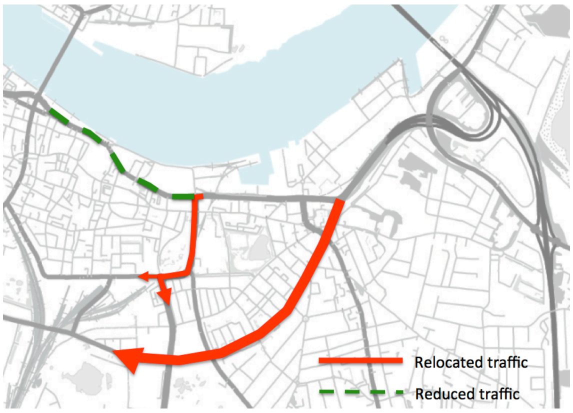

Figure 2. The effect on traffic flows due to the renewed harbour front. Principal sketch.

To handle increased traffic flows on the ring road, a more efficient road network was required. Østre Alle is a dual carriageway with bicycle paths on both sides and a number of crossing high-frequent bus routes. A significant amount of bicycling traffic is crossing the ring road. The cyclist volume on the road segment itself is limited, while the number of crossing cyclists is >1,000/day. The Annual Daily Traffic (ADT) is >20,000 on the most loaded segments, and the speed limit is 60km/h except on the easternmost part where it is 70km/h. The areas surrounding the ring road are a mix of medium and high-density housing.

The distance from the roadway to the nearest houses is low and additional lanes were desirable neither from a financial nor a city-planning perspective.
It was therefore decided to implement ATCS on the most congested part of the ring road, from the inlet-crossing motorway and beyond the central southern main entrance road.

The implemented solution
An ATCS was implemented on the ring road covering the signalised intersection from the motorway and beyond the main southern entrance road. It includes 1.7 km of the road and 8 signalised intersections, one of which was a double intersection. The selected ATCS was the SPOT system, which has been implemented in a large number of locations in cities around the world (1,8). In Aalborg ATCS are adaptive in the sense that each signal is dynamically controlled as part of a model forecasting the traffic flow for all the intersections of the ATCS area. The aim is to minimise the accumulated waiting time for road users. Every third second each signal is therefore adjusted to the current traffic situation. On the basis of these adjustments a prognosis regarding the total traffic flow over the next two minutes is generated. Subsequently, the signals are adjusted optimally to handle the forecasted traffic pattern within pre-defined frames, maximum phases of red in the intersections for example. The frames are based on a traffic model established from traffic counts carried out in all intersections and approaching lanes of the section. Each traffic signal controller has a built-in unit, which communicates with the local signals, the surrounding intersections, and a central server. Various elements of cost are used in each subsection, the most important being the cost of full stop for a vehicle, the cost of idling, and the cost of tailbacks. One of the optimisation parameters being a prioritization of PT through a bus priority system, a higher weighting factor can be given to PT, while account is still taken of other means of transport. In case of ATCS downtime the traffic management is based on an updated time-control system. Further details about the general operation of ATCS are available in (5), and more specifically about SPOT ATCS in (14,15). The implementation and subsequent adjustment of the ATCS was carried out in the period from late 2010 to late 2011. The segment covered by ATCS and the location of the intersections and the bus routes appear in figure 3.

Figure 3. The studied section and the included intersections covered with ATCS (left) and the crossing bus routes (right) on the ring road.

Research question
ATCS have been implemented in many cities around the world and seem to have resulted in a significant reduction in congestion problems in many locations (6,8,9). However, ATCS results in the Nordic countries are mixed or unreported. In a number of cases, no measurable positive effect was to be found. See (10) for example. The research question was therefore this:

Does an ATCS on a congested two-lane carriageway reduce transportation time and congestion measurably in a medium-sized city in the Nordic countries?

Methods

Overall method

The study of the effect of ATCS is carried out as a *with/without* study. Basically transportation time and speed were measured after the ATCS was installed but deactivated and similar data were collected with ATCS activated. Results are presented as the effect on transportation time and the effect on the speed on the segment, shown by speed profiles.

FCD collected using the Chasing Car Method

Data for the study from moving vehicles, including GPS position, time, direction, and speed, were the basis for calculations. This type of data is termed *Floating Car Data* (FCD). Data consist of two sets of data: 1: FCD from a car following the general traffic pattern on the ring road, as also used in (6,9,10); 2: FCD from buses crossing the ring road as used in (9).
Two persons followed the traffic in their cars according to an adjusted version of the chasing car method. (16,17) suggest that one car is selected and then followed until it stops, turns away from the route of interest or becomes too risky to follow. In this study, the chasing car method was used: the participant driver would constantly be trying to overtake a number of cars similar to the one, which had overtaken her/him. This design was decided upon because the measurement road section is a dual-lane road. If the chasing driver followed a particular car it could be one, which was driving significant faster or slowlier than the general traffic. It was assessed that the adjusted method as described above would cause less variation from the actual driving pattern on ring road.

Methods of speed profiles

The speed profiles of a segment were made by dividing the studied part of the ring road into segments of 12.5m. The FCD were subsequently ordered in trips. If there was more than one waypoint/trip/segment only the first waypoint was kept. If no waypoint/trip/segment was available the speed from the previous segment was used. It is a procedure which results in small uncertainties, which however are not problematic because:

- at low speeds, when more than one waypoint is recorded, there might be differences, but they will be limited to the same segment because after a couple of seconds the waypoint is moved to the next segment if the speed becomes high (>20 km/h),
- many waypoints with a speed of 0 km/h are registered for the same segment for the same trip. However, despite the fact that focus is on speeds, the results are not affected because these waypoints are removed,
- the majority of the waypoints are distributed with one/segment/trip,
- during driving at high speed the number and sizes of changes in speed decrease within one second generally, and
- when several trips are carried out with generally identical driving patterns, any deviations due to fictitious or deleted waypoints will counterbalance each other, and the uncertainty caused by this simplification is minimal.

Subsequently the trips can be grouped according to time of driving and whether they were carried out with or without the ATCS activated.

Methods for the calculation of transportation time
Transportation time between intersections is based on the time use between each passage of the intersections. To ensure that any delays caused by a particular intersection are ascribed to the right road segment, each road segment has been connected to its own intersection according to the direction of traffic. Hence the transportation time from immediately after the passage of an intersection to after the passage of the next intersection is used as transportation time on the section in question. Transportation times in each direction on the same section are not directly comparable, because the delays in two different intersections are connected to the same segment. See figure 4.

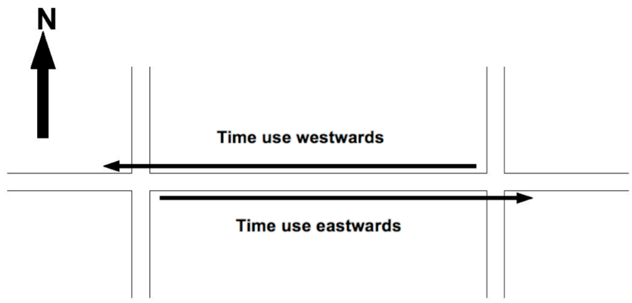

Figure 4 – The principle on which transportation time is calculated. Westwards it is the delay in the western intersection, which is included in the transportation time of the section and vice versa.

Methods for analysing FCD from buses in service
Transportation times for the 6 bus routes crossing Østre Alle in three intersections were calculated on the basis of FCD collected by the buses in question. FCD from the buses are only collected when the bus is within a distance of 35 m from the nearest bus stop. This data collection is standard for all buses in service and the FCD are extracted from a database. The analyses are therefore carried out similarly to the ones regarding transportation time on the road segment. However, the FCD analyses are much simpler as they just include data from each route between two bus stops on each side of the ring road.

Uncertainties
With the selected data collections the transportation time/speed of the most significant traffic flows were known. However, due to limited resources, the turning flows were not measured. In most of the included intersections it wasn't an issue, but in two of the most congested intersections there are significant turning traffic flows, and any effect on these can't be documented. Implementing an ATCS involves a number of decisions regarding the prioritization of traffic flow. A sufficiently calibrated ATCS will take into account the passability of high priority traffic flows. Assuming that suitable decisions and proper adjustment was carried out, there ought to be no significant deviation in the results.

Data
There was a triple collection of FCD on the ring road. The first, a *without* data collection, was in late 2010. Due to time constraints because of a little time span before the ATCS was activated, it had to be carried out within a period with bad weather, which affected the results significantly towards a highly increased transportation time. Data collection from one extra day in January 2011 with good weather conditions *without* ATCS activated was added to data. As it could be expected, the added data showed a markedly lower transportation time. In

March 2011 a *with* data collection was carried out, which showed small effects and significant variations in transportation time with ATCS activated. Subsequently, it was found that further development of the ATCS as well as maintenance on the existing loop detectors etc. was required. Additional *with* and *without* data collections were carried out in October 2011 when the traditional time-control system was updated. The *without* data were simply collected by closing down the ATCS during data collection. The *without* transportation time decreased slightly compared to the former study, while the transportation time *with* ATCS showed limited effect. After this it was found that the ATCS needed further calibration before it became fully operational. Calibration work was on-going until the end of 2011, and the final *with* data collection was carried out in the first part of 2012. The results used for the analyses are based on data collected in the latest *with* as well as the latest *without* period.

FCD were collected using 'The Chasing Car' method on the ring road on Tuesdays, Wednesdays, and Thursdays in the morning peak periods, midday off peak periods and afternoon peak periods, 7.00-8.30; 11.00-12.30; and 15.00-16.30, respectively. In total data were collected during 9 periods *without* ATCS and similarly during the *with* periods. FCD *without* ATCS were collected from 6-13 October 2011 and those *with* FCD from 28 February – 21 March 2012. The prolonged period was due to a period of snowy weather, which necessitated a postponement of the last periods of data collection *with* ATCS active. In total, the included FCD consisted of 249 trips on the ring road. 120 were collected *without* ATCS and 129 *with* ATCS active and were distributed equally in both directions. FCD consisted of 67,000 waypoints in total. Depending on the results in question, these FCD were simplified in various ways.

FCD from the buses in service crossing the ring road consisted of FCD from 625 crossings of the ring road *without* ATCS and 631 *with* ATCS. The PT authority only has access to bus data younger than 1 year. Hence it was not possible to get the *without* data. ACTS was therefore deactivated for one week in late February 2013 to collect the *without* data. The following week the *with* data were collected, so that any effect due to extra optimisation of ACTS during 2012 could be avoided in the comparison. The bus data included data for all crossing buses in the periods studied. They include the time of departure from the last bus stop before crossing the ring road and the transportation time up to the arrival at the next bus stop.

Results

Speed profiles

In the morning peak period a certain effect of the ATCS can be recognised. ATCS resulted in a slightly changed speed profile. In the middle of the section the lowest speeds were increased. A similar pattern was found between Intersection B and D, where the lowest speeds were significantly increased. From Intersection B westwards speeds were reduced. It should be noted that the westernmost intersection, Intersection A, was not part of the ATCS, but it is reasonable to assume that the tailbacks from Intersection B, the most congested intersection of the ring road, occasionally affect the traffic flows passing Intersection A. The general effect is unclear, but ATCS results in slightly higher minimum speeds, hence it contributes to a smoother driving pattern. See figure 5.

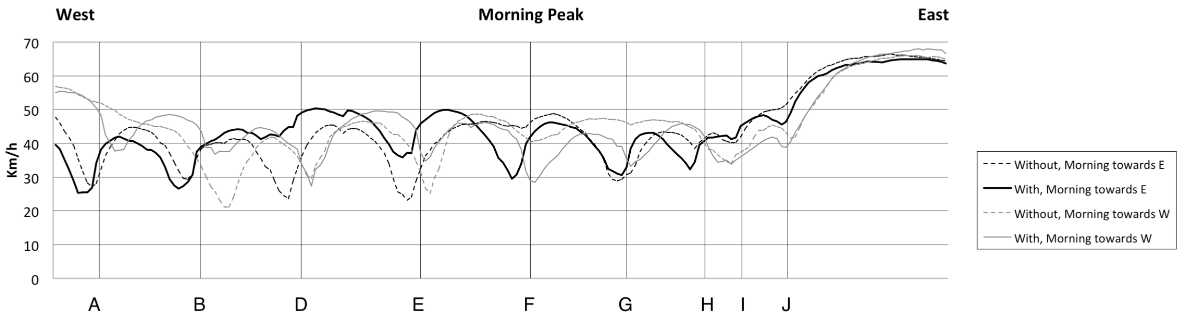

Figure 5. Speed profiles for the morning peak period *with* and *without* ATCS.

In the midday off peak towards the east speed was reduced across the Intersection A and H. Despite this, the ATCS resulted in higher speeds across the remaining intersections. Hence, similarly to the morning result, a significantly smoother driving is found with the ATCS implemented. Towards the west speed in general was reduced except around the Intersection B – the most congested intersection of the section. This indicates that traditional time-control systems can give the same results or better when the congestion level is low. See figure 6.

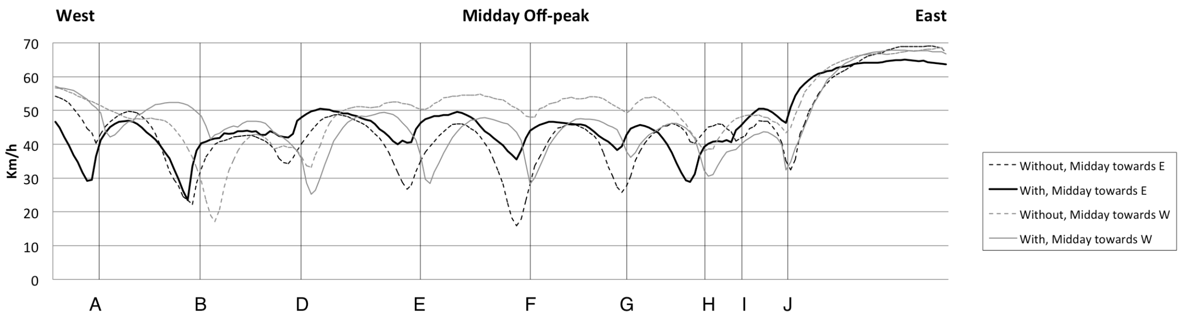

Figure 6. Speed profiles for the midday off peak period *with* and *without* ATCS.

In the afternoon peak towards the east the ATCS generally resulted in a higher speed through the western and through the eastern part of the section in particular. Also, the lowest speeds increased substantially. Towards the west, the ATCS generally resulted in increased speeds except around the Intersections D, E, and J. Just as towards the east the ATCS resulted in significantly higher minimum speeds and thus a smoother and faster traffic flow towards the west. See figure 7.

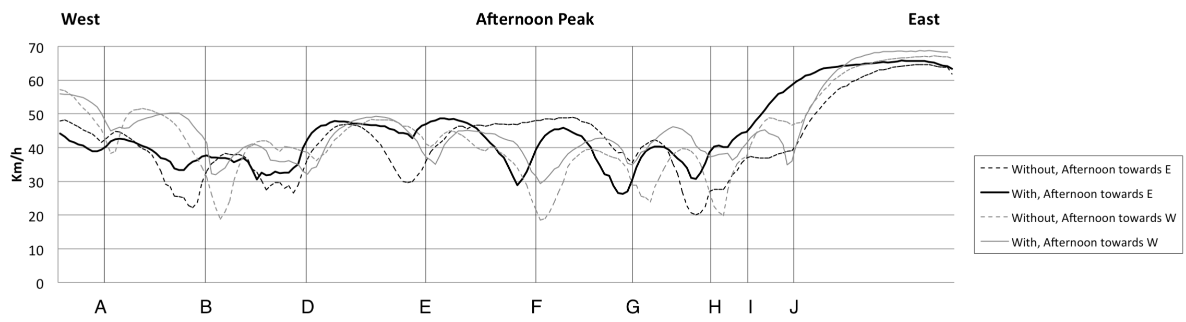

Figure 7. Speed profiles for the afternoon peak period *with* and *without* ATCS.

ATCS had an uncertain effect on speed in the morning peak and resulted in marginally reduced speed at midday, whereas, during the afternoon peak hours, there was a clear increase in speed. Also, in all three periods, the lowest speeds were replaced with higher and the overall speed variation decreased in the majority of trips due to less low speed.

Transportation time on the ring road

In the morning peak, transportation time decreased slightly *with* ATCS. *Without* ATCS the transportation time towards the east was 4.18 min. decreasing to 4.12 min *with* ATCS. A similar increase due to ATCS was found towards the west, where transportation time increased from 4.02 min. to 4.09 min. Overall, there is no clear effect of ATCS in the morning peak period. The limited effect reflects that the mean speed only differs from 30.7 to 32.8 km/h.

During the midday off peak period transportation time in general was lower compared to the morning peak, as expected. Towards the east *with* ATCS, transportation time was reduced from 4.03 min. to 3.52 min. The opposite effect is found towards the west, where transportation time increased from 3.32 min. to 4.00 min. *with* ATCS. It should be noted that both results are lower than all other registered transportation times. Overall in the midday off peak period transportation time increased by 8 sec. from 3.48 to 3.56 min. *with* ATCS. The mean speed *without* ATCS differed from 32.5 to 37.4 km/h, while it differed from 33.1 to 34.1 km/h *with* ATCS activated.

Significantly positive effects on transportation time appear in the afternoon peak. *With* ATCS transportation time towards the east was reduced by 59 sec. from 5.12 to 4.13 min. A similar although slightly lower effect is found towards the west where transportation time went from 4.58 to 4.11 *with* ATCS. The total effect *with* ATCS was a reduction in transportation time of 53 sec., equivalent to a 17% reduction in transportation time. The mean speed *without* ATCS was 25.5 to 26.6 km/h. increasing to 31.3 to 31.5 km/h *with* ATCS. See table 1.

Table 1 - The mean transportation time on the ring road *with* and *without* ATCS (minutes)

	Morning peak		Midday off peak		Afternoon peak	
	Transpor-tation time	Mean speed (km/h)	Transpor-tation time	Mean speed (km/h)	Transpor-tation time	Mean speed (km/h)
ATCS towards east	4:12	31.4	3:52	34.1	4:13	31.3
Time-control towards east	4:18	30.7	4:03	32.5	5:12	25.4
ATCS towards west	4:09	31.8	4:00	33.1	4:11	31.5
Time-control towards west	4:02	32.8	3:32	37.4	4:58	26.6
ATCS total	4:11	31.6	3:56	33.6	4:12	31.4
Time-control total	4:10	31.7	3:48	34.8	5:05	26.0

Overall it should be noted that the best effect *with* ATCS appeared in the afternoon peak – the time with the highest transportation time before ATCS was activated. So the implemented ATCS has the best effect when the congestion level is highest.

Transportation time for crossing buses
With ATCS active 631 bus crossings are included in the analyses. *Without* ATCS the number is 625. ATCS resulted in various effects on bus transportation times. In the morning peak, there was an 8-sec. increase in transportation time, mainly due to increased transportation time in Intersection D and turning buses in Intersection H. During midday off peak the transportation time was virtually unchanged. In the afternoon peak the transportation increased by 4 sec. This was due to increased transportation time in Intersections D and F, while in H transportation time decreased. Overall, ATCS has a slightly negative effect on the buses' passability. See table 2.

Table 2 - The mean transportation time for buses in service and number of trips included in data across the ring road *with* ATCS and *without* (minutes)

		Without ATSC			With ATSC		
		Morning peak	Midday off peak	Afternoon peak	Morning peak	Midday off peak	Afternoon peak
Intersection D	Time	1.40	1.26	1.36	1.49	1.34	1.53
	Count	118	98	108	120	100	116
Intersection F	Time	1.38	1.24	1.25	1.34	1.32	1.36
	Count	38	35	36	35	35	36
Intersection H	Time	1.41	1.43	1.49	1.38	1.27	1.41
	Count	51	27	60	52	26	59
Intersection H, Turning	Time	0.42	0.29	0.53	1.12	0.30	0.49
	Count	19	11	24	20	9	23
Total (unweighted)	Time	1.25	1.16	1.26	1.33	1.15	1.30
	Count	226	171	228	227	170	234

Statistical tests on FCD
Statistical tests were carried out regarding transportation time on the ring road. The overall effect of ATCS was an average reduction in transportation time of 13 sec. (95% confidence interval (CI) from 3 to 22 sec.; p=0.009). This estimate was adjusted according to the time of day (morning, midday, and afternoon) and driving direction (eastwards and westwards). Further analysis showed that the effect on transportation time was modified by both the time of day and driving direction. Only in the afternoon peak period a statistically significant benefit of ATCS was seen, that is, an average reduction of transportation time of 53 sec. (95% CI from 37 to 69 sec. In both directions p was <0.001). In the morning no effect was found (p=0.26 and p=0.20 towards the east and the west, respectively). In the midday off peak period towards the east no effect of ATCS was found (p=0.78), while towards the west the transportation time *without* ATCS was statistically significantly lower (p=0.026). Data were analysed in 3-way ANOVA. Assumptions of normality and variance homogeneity were fully met.

Discussion, conclusion, and recommendations
The number of trips included in the analyses is 249 – which is lower than, for example, for the study in Münster, where 1,598 trips were driven. However, they were distributed on 5 routes and also, there were one *before* and two *after* periods. A similar sample size was used by

Hunter et al. who reported 1,663 trips distributed on 8 routes. Also, these trips were divided into 6 different time periods, so the number of trips per result was not high. Compared with these studies the number of trips per time period/route of the Aalborg study is not significantly different. Comparison between mean transportation times during the two *without* data collections in Aalborg showed small deviation – an indication that any significant uncertainty in transportation time due to the number of trips included is low. Another uncertainty regarding the effects of ATCS is that the turning flows were not measured. It can't be neglected, but it should be remembered that in setting up a framework for an ATCS some overall priority decision has to be taken and implemented. Also, a sufficiently calibrated ATCS will take into account the passability of high priority traffic flows. Assuming that adjustment was carried out, there ought to be no significant deviation in the results. Thus it seems reasonable to assume that the data collection methods used have no substantive weaknesses. However, should there be any methodological weaknesses, they are not likely to seriously affect the reliability of analysis results.

The main results show that in the morning peak and the midday off peak period no clear effect on transportation time on the ring road can be found when ATCS is compared to *without* ATCS. The effect *with* ATCS in the afternoon peak was a reduction in transportation time of 53 sec., equivalent to a 17% reduction. These results are reflected in the speed profiles for the ring road, where the clearest effects during the afternoon peak are increases in the lowest speeds and hence reduced speed variation. Despite the fluctuating effects regarding the other time periods, a substitution of the lowest speeds with higher speeds also shows reduced speed variation in this case. As for the crossing buses, no similar positive effect can be found, although, in spite of significant variations, ATCS did seem to increase transportation time slightly. Overall ATCS reduces transportation time, and the effect is most clear when the transportation time is highest – there being an increased effect with an increased congestion level. Thus a better effect can be expected with the congestion level increasing in the years to come. However, an improved effect will be partly at the expense of the crossing buses, whose transportation time was slightly increased. Despite this, the tentative conclusion is that the prospective increase in traffic volume will be handled better *with* ATCS than *without*.

The evaluation procedure has been instructive, and three recommendations can be extracted from the experiences: 1: sufficient time and resources must be allocated to ensure that the physical equipment (loop detectors, wires etc.) are fully operational, before a positive effect of ATCS can be achieved. 2: there must be sufficient time and resources to optimise the ATCS after it has been implemented, and 3: in order to enhance ATCS optimisation there is an advantage to be gained by making evaluation part of the optimisation procedure, as an iterative process will allow erroneous optimisations to be detected.

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References

1. Schrank, D., Lomax, T., Eisele, B. (2011). *Urban Mobility Report*. Texas Transportation Institute, The Texas A&M University System. USA.
2. Directorate General for Mobility and Transport. (2011). *Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system*. European Commission, Brussels.

3. Stough, R. (2001). *Intelligent Transport Systems: Cases and Policies*. 1st ed. Cheltenham. USA: Edward Elgar Publishing Ltd.

4. Segui Pons, J. M. (2003). *The Territorial effects of Intelligent Transport Systems*. Networks and Communication Studies. vol. 17, no. 1-2, pp. 39-52.

5. Stavanovic, A. (2010). *Adaptive Traffic Control Systems: Domestic and Foreign State of Practice - A Synthesis of Highway Practice*. Transportation Research Board, Washington, D.C.

6. Hunter, M. P., Wu, S. K., Kim, H. K., Suh, W. (2012). *A Probe-Vehicle-Based Evaluation of Adaptive Traffic Signal Control*. IEEE Transactions on Intelligent Transportation Systems. vol. 13, no. 2, pp. 704-713.

7. Samadi, S., Rad, A. P., Farhad, F. M., Jafarian, H. (2012). *Performance Evaluation of Intelligent Adaptive Traffic Control Systems: A Case Study*. Journal of Transportation Technologies, vol. 2, pp. 248-259.

8. Fehon, K., Peters, J. (2010). *Adaptive Traffic Signals, Comparison and Case Studies*. ITE 2010 Western District Annual Meeting. 27-30 June. San Francisco. USA.

9. Krøyer, B. (2009). *Et "Münster"-eksempel på Adaptiv Signalstyring (A prime example of Adaptive Traffic Control System)*. Trafik & Veje - Dansk Vejtidsskrift. vol. 86. no. 11, pp. 36-38.

10. Oslo Kommune. (2003). *SPOT i Kvadraturen - Før/etterundersøkelse. (Adaptive Traffic Control System in the 'Quadrature' – before/after study)*. PROSAM-rapport no. 107.

11. Tveit, Ø. (2007). *SPOT in the Nordic countries: How successful has it been? How successful could it have been? How successful can it be?*. Presentation. SINTEF – Teknologi & Samfund.

12. Mogensen, J. (2012). *Floating Car Data for information and planning*. CIVITAS ARCHIMEDES Seminars: Cycling, ITS and Alternative Fuels. 14/11. Aalborg Municipality. Aalborg. Denmark.

13. Statistics Denmark. (2012). *StatBank Denmark*. Available at: http://www.statbank.dk/statbank5a/default.asp?w=1280. Accessed 29/11, 2012.

14. Hansen, P. B., Frederiksen, L. B., Christensen, P. (2004). *Signalregulering på Centrumforbindelsen med UTOPIA/SPOT (Signal management on the Centre Connection with UTOPIA/SPOT)*. Dansk Vejtidskrift. vol. 81. no. 9, pp. 16-20.

15. Christensen, P. (2005). *SPOT - en styringsfilosofi i udvikling (SPOT – a management philosophy under development)*. Dansk Vejtidskrift. vol. 82. no. 11, pp. 68-70.

16. Dixit, V. V., Pande, A., Abdel-Aty, M., Das, A., Radwan, E. (2011). *Quality of traffic flow on urban arterial streets and its relationship with safety*. Accident Analysis and Prevention. vol. 43. no. 5, pp. 1610-1616.

17. Park, Y., Abdel-Aty, M. (2012). *Development of a Proactive Hotspot Identification Method for Urban Arterials Using a Stochastic Catastrophe Model*. Traffic Research Board. vol. 90.