

# Light rail project in Copenhagen – the Ring 2½ corridor

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## ***1. Abstract***

The need for high class public transport service of the increasing travel across the radial urban structure of the greater Copenhagen region was examined through planning of a light rail. The exact corridor (defined as the Ring 2½ corridor) and alignment of the light rail were documented and the locations of stops were examined through analyses of catchment areas. The timetable of the light rail was determined through travel time and correspondences with other high class public transport lines/corridors. The justification of the light rail was examined through factors like traffic impacts, operation economy, socioeconomics and strategic impacts. The light rail shows a good result on most factors. But it displays socioeconomic non-viability. However, this was expected when using the standard procedures. But the Ring 2½ light rail shows a better socioeconomic result than many other examined light rail projects.

*Keywords:* Light rail, public transport, traffic impacts, operation economy, socioeconomics

## ***2. Introduction***

As in many other cities in Europe traffic is increasing in Copenhagen. The radial arterial roads and highways leading to the Copenhagen city center are critical congested during peak hours. But also outside peak hours and on other roads in the region, the congestion has a heavy influence on free flow [1]. Also the greater Copenhagen area is getting denser in built-up area because of the lack of space in the city center resulting in new residential areas and work places in the outer but still urbanized areas of the city. This is leading to an increasing need for travel across the history-based radial urban structure of the city. Public transport users can only make such travel by bus, as rail lines in the Copenhagen area are radial lines leading from suburbs or satellite cities to the city center (except “Ringbanen” running fairly close to the city center). This means that public trips across the radial urban structure have to pass the city center when using rail; causing critical passenger loads on some rail sections – especially the joint tracks in the city center. Furthermore, public transport has a much lower percentage of the total trips across the radial urban structure than of the total radial trips indicating poor service of public transport [2].

### ***3. Objective***

The objective of the study has been to make an overall upgrade of the public transport system in the greater Copenhagen area; by examine a light rail for a high class public service of the increasing travel across the radial urban structure. Criteria for such a public transport line can be summarized:

- High existing customer base and potential for urban development
- Regional impact and relieving the existing S-train<sup>1</sup> lines with capacity problems
- General improvement of the public transportation with good connections to the radial lines and thereby obtaining synergies in the public transport system

### ***4. Defining the corridor***

Earlier studies of a high class public transport line running across the radial urban structure have suggested a layout following the existing ring road “Ring 3” [3] and [4]. This ring road has its alignment in the outskirts of the urbanized area of Copenhagen. It connects strategic important suburban city centers such as Ishøj/Broendby, Glostrup, Herlev Buddinge/Gladsaxe and Lyngby but it also runs through areas with no development at all. Furthermore, it has a long alignment and a light rail following this ring road will have a long line distance and is, therefore, expensive. Another solution for a high class public transport line across the radial urban structure could be in what is here defined as the Ring 2½ corridor.

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<sup>1</sup> Suburban railways (S-trains); the foundation of the greater Copenhagen public transport system

The Ring 2½ corridor is loosely placed between the two existing ring roads in the greater Copenhagen: “Ring 2” and “Ring 3”. This corridor would incorporate urban districts like: Avedoere, Hvidovre, Rødovre, Husum, Gladsaxe and Lyngby including areas that today only are serviced by busses. The corridor can be seen in figure 1. This corridor could provide a light railway closer to the Copenhagen city center in the south and merging with the Ring 3 in the north. This would not only mean a shorter length for a light railway in the Ring 2½ corridor compared to Ring 3; it would also mean that the light railway will run through more urbanized areas with higher passenger potential. Furthermore, it could give better connections to existing radial bus lines because of the placement closer to Copenhagen City. It could also provide better connections to future radial light rail systems.

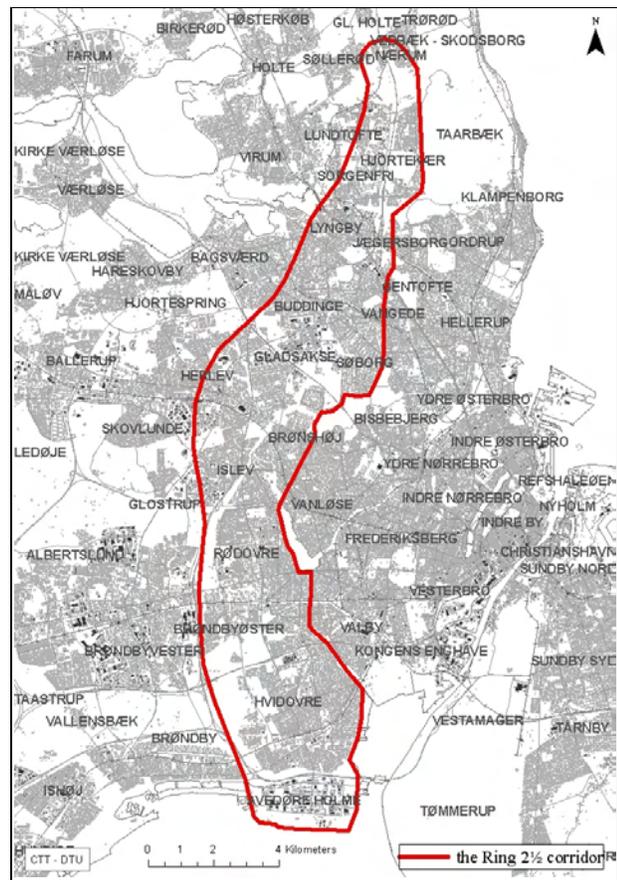


Figure 1 – the Ring 2½ corridor

## 5. Rail solution

The existing high class public transport modes in the Copenhagen region are (aside from the regional trains) S-trains and Metro and in the more rural areas also minor branch lines. The existing rail modes are not perfectly suited for the corridor. S-train alignments are wide and stringent and there is little room for such an alignment. A driverless Metro (or S-train) demands a segregated alignment to avoid any obstacles on the tracks. Therefore, it is often placed under ground-level, in tunnels or elevated above ground. This means that such solutions are often very expensive in construction. A more suitable mode for servicing the corridor is a light rail. Light rails are more flexible than traditional rail systems. For example they have a low turning radius that enables them to follow a curving course much like busses. Another great advantage is their ability to drive in mixed traffic like a tram when a segregated alignment can not be obtained. Such flexibility is very well suited for the corridor where there is no obvious alignment or major road to follow.

## 6. Analyses

With a fixed corridor the framework for the light rail solution could be found. First the alignment of the light rail was determined.

### 6.1. Alignment

The corridor is long and wide and since there is no obvious ring road to follow there are various options for alignment placing as seen in figure 2. The corridor was therefore split up in four sections and in each section several alignments were examined. By examining one section at a time the combinations of alignment alternatives narrowed down. When the best alternative in each section was determined the alignment was implicit defined as a sequence of the best alternative in each section.

Initially the alignment alternatives were chosen from various criteria including assumed passenger potential, locations with large passenger generation or attraction, existing bus routes, connection with existing S-train lines, availability of space on roads and placement of tracks. For each alternative the line potential was examined for decision support in the selection of the final alignment. Line potential means the potential in population and workplaces in a buffer around the full distance of an alignment alternative. The method was performed by overlay analyses in GIS making buffers around the alignment alternatives and intersecting them with a modified HSK zone layer containing information about population and workplaces on a much disaggregated level<sup>2</sup>. The line potential for alignment alternatives in each section was then compared taking their different distances into account.

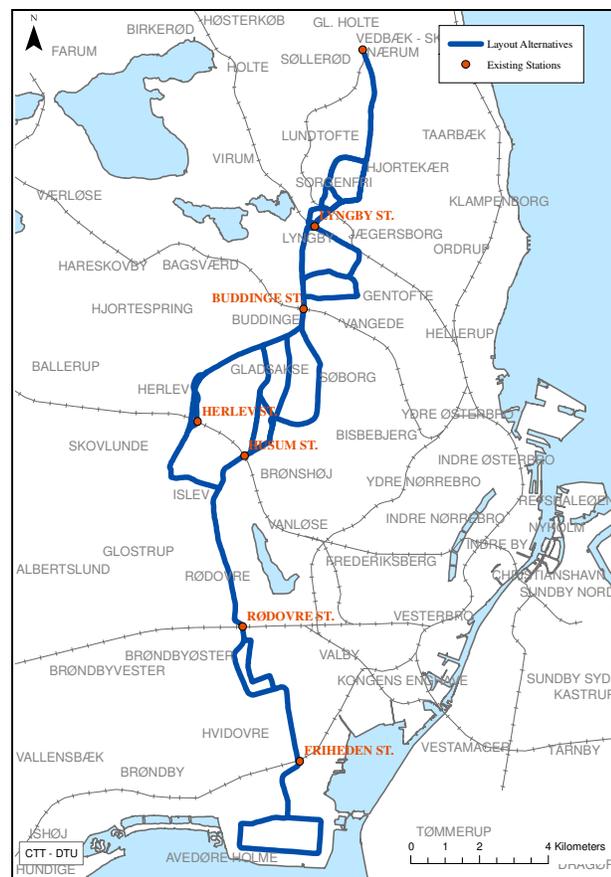


Figure 2 – Alignment alternatives for the Ring 2 1/2 light rail

<sup>2</sup> This layer is based on the HSK land use zonal layer and OTM (Traffic model of the Oerestad – originally used to model the existing Metro system in Copenhagen) model zonal layer containing information about population and workplaces. The two layers were modified so that the information on population and workplaces was disaggregated to the more fine-graded HSK zone layer (modified on CTT) [5]. Other data such as CVR, BBR or CPR could also have been used.

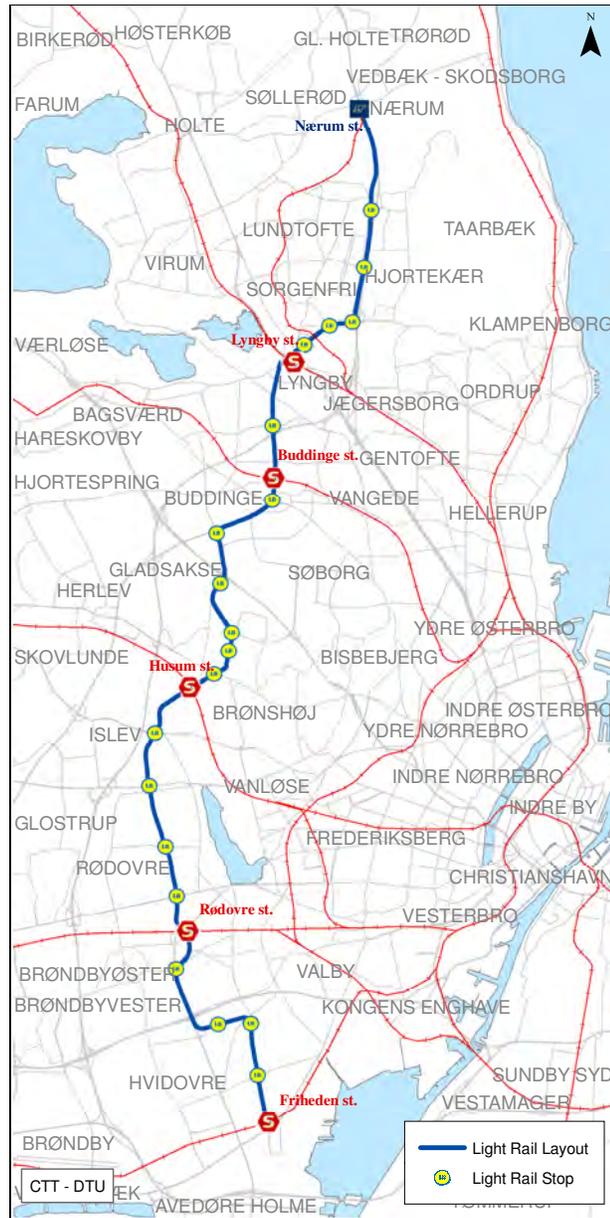
Through that method it was possible to opt out of some of the alternatives leading to only one or two different alignment alternatives in each section. The line potential method was only used for decision support hence it is not quite realistic because it is only possible to access a public transport line at stops or stations. To choose the final alignment of the light rail it was, therefore, necessary to include stops in the analyses. All the alignment alternatives are shown in figure 2.

## **6.2. Locations of stops**

The initial placement of stops along the alignment alternatives was done through an empirical procedure. Stops at existing S-train stations were considered to be fixed in order to secure good connection between the two high class transport systems. This meant fixed stops where the light rail crosses S-train lines at the following S-train stations: Friheden, Roedovre, Husum/Herlev, Buddinge and Lyngby plus the branch line stop at Naerum. Stops between the fixed stops were chosen from criteria such as assumed passenger potential, locations with large passenger generation or attraction, stops of the corridors most important bus line (200S) and average stop distance. The initial placement of stops gave up to four alternatives between each fixed stop because the alignment also varied.

To determine the best alignment and stop alternatives the catchment area of stops were examined using both an inner and an outer catchment area. The stops on each alternative were selected and the the catchment areas were then calculated as circular buffers in GIS<sup>3</sup>. As in the line potential method, the potential of each stop alternative was calculated through overlay analyses using the modified HSK zone layer that contains information about population and workplaces. The parameters assigned to inner and outer catchment areas were based on market shares observations for existing S-train stations [6]. The potential of stop alternatives between the fixed stops were compared to each other taking number of stops, line distance, presumed cost and presumed travel time into account. The best alternative in each section determined the final alignment and locations of stops of the Ring 2½ light rail; shown in figure 3.

The light rail will have a total length of 25.4 kilometers from Friheden station in the south to Naerum station in the north. A total of 26 stops give an average stop distance of one kilometer. The light rail will have an alignment more or less segregated from other traffic on most of the line distance leaving only four percent definite tram driving. Recommendations are less than 10 percent of mixed traffic driving in order to secure fast travel time and safety [7].



**Figure 3 – Final alignment and locations of stops of the Ring 2½ light rail**

<sup>3</sup> Buffers could also be calculated as walking distance to/from stops instead of a distinct buffer radius and circular catchment areas [8] and [9]. However, the process is a little more complicated and demands a detailed street network.

### 6.3. Timetable

With the physical framework for the Ring 2½ light rail given, the planning of a timetable started. First the running time was determined. From the alignment placement and the allowed speed on the roads, that the light rail was set to follow, the average running speed between each stop was determined and thereby also the travel time. Some of the line sections were well suited for a high running speed e.g. along the Elsinore motorway in Lundtofte where the alignment is fully segregated from other traffic. Therefore, light rail equipment with a high maximum speed was required. Also good Acceleration and deceleration was required for tram and urban driving. The stopping time at stops was determined from calculated passenger potential at each stop and assumed change loads with other public transport services. This is because higher passenger loads means longer stopping time. Various running time supplements were incorporated in the total travel time; a general supplement to ensure a time buffer to catch up delays and a specific time supplement when the light rail crosses large radial roads where it is not possible to obtain green light priorities.

All together the light rail will have a total travel time of 43 minutes from Friheden station to Naerum station. This means an average travel speed at 35 km/h. Running mostly in urbanized environments it is a fairly high average travel speed and 8 km/h faster than the average travel speed of the fastest bus in the corridor. Generally the average travel speed of busses in the greater Copenhagen region is 23 km/h [10].

The operation plan for the light rail is a base line running the full line distance and a fast line variant running only between Friheden and Lyngby station. This was chosen because a fast line variant ensures a lower travel time for the longer trips across the radial urban structure. The fast line variant only stops at the most important stops based on transfer possibilities and expected passenger loads. The fast line variant has a travel time at 26 minutes between Friheden station and Lyngby station giving an average travel speed of 45 km/h. Both the base line and the fast line variant are running with 20 minute intervals in daytime operation. This means an approximately 10 minute frequency between Friheden and Lyngby station.

In order to determine minutes of departure to the final timetable the transfer possibilities with other public lines primarily S-trains were examined. By minimizing waiting times in transfers with other lines the impact of the light rail in the public network will be better in terms of time savings. Minutes of departure were determined from operation in evening hours where waiting times are most critical. All transfers between the light rail and the crossing radial S-train lines were included in the examination and they were weighed after their importance and expected change loads. A worksheet model including timetables for the radial S-train lines calculated the optimum minutes of departure for both directions by minimizing the total waiting time at transfers<sup>4</sup>. For the best results temporary running schedules were prepared. The best fitted schedule in terms of turn around times and rolling stock rostering for the base line and the line variant combined was then chosen as the final timetable for the Ring 2½ light rail. The proposed timetable can be seen in figure 4.

| Friheden - Nærum/Lyngby        |                 |  |          | Nærum/Lyngby - Friheden        |              |  |         |
|--------------------------------|-----------------|--|----------|--------------------------------|--------------|--|---------|
| L                              |                 |  |          | L+                             |              |  |         |
|                                |                 |  |          | mon-sat                        |              |  | mon-sat |
|                                |                 |  |          | daytime                        |              |  | daytime |
| <b>Friheden st.</b>            | <b>10 30 50</b> |  |          | <b>04 24 44</b>                |              |  |         |
| Brostykkevej                   | 12 32 52        |  |          |                                |              |  |         |
| Arnold Nielsens Boulevard      | 14 34 54        |  |          |                                |              |  |         |
| Hvidovre Hospital              | 16 36 56        |  | 08 28 48 |                                |              |  |         |
| Park Allé                      | 18 38 58        |  |          |                                |              |  |         |
| <b>Rødovre st.</b>             | <b>20 40 00</b> |  |          | <b>11 31 51</b>                |              |  |         |
| Roskildevej                    | 22 42 02        |  |          |                                |              |  |         |
| Rødovre Centrum                | 24 44 04        |  | 14 34 54 |                                |              |  |         |
| Jyllingevej                    | 26 46 06        |  |          |                                |              |  |         |
| Slotsherrensvej                | 28 48 08        |  |          |                                |              |  |         |
| <b>Husum st.</b>               | <b>30 50 10</b> |  |          | <b>19 39 59</b>                |              |  |         |
| Husum Torv                     | 32 52 12        |  | 21 41 01 |                                |              |  |         |
| Kobbelvænget                   | 33 53 13        |  |          |                                |              |  |         |
| Tingbjerg                      | 34 54 14        |  |          |                                |              |  |         |
| TV-Byen                        | 35 55 15        |  |          |                                |              |  |         |
| Gladsaxe Trafikplads           | 37 57 17        |  | 25 45 05 |                                |              |  |         |
| Buddinge Rundkørsel            | 39 59 19        |  |          |                                |              |  |         |
| <b>Buddinge st.</b>            | <b>40 00 20</b> |  |          | <b>27 47 07</b>                |              |  |         |
| Gammellosevej                  | 42 02 22        |  |          |                                |              |  |         |
| <b>Lyngby st.</b>              | <b>44 04 24</b> |  |          | <b>30 50 10</b>                |              |  |         |
| Lyngby Storcenter              | 45 05 25        |  |          |                                |              |  |         |
| Sorgenfrigårdsvej              | 46 06 26        |  |          |                                |              |  |         |
| Lundtoftegårdsvej              | 47 07 27        |  |          |                                |              |  |         |
| Anker Engeltunds Vej           | 49 09 29        |  |          |                                |              |  |         |
| Lundtofteparken                | 51 11 31        |  |          |                                |              |  |         |
| <b>Nærum st.</b>               | <b>53 13 33</b> |  |          |                                |              |  |         |
| <b>From Friheden to Nærum</b>  |                 |  |          | <b>From Nærum to Friheden</b>  |              |  |         |
| mon-fri                        | 5:10 - 0:30     |  |          | mon-fri                        | 4:56 - 0:36  |  |         |
| sat                            | 5:10 - 0:30     |  |          | sat                            | 4:56 - 0:36  |  |         |
| sun                            | 6:10 - 0:30     |  |          | sun                            | 5:56 - 0:36  |  |         |
| <b>From Friheden to Lyngby</b> |                 |  |          | <b>From Lyngby to Friheden</b> |              |  |         |
| mon-fri                        | 6:04 - 18:44    |  |          | mon-fri                        | 5:59 - 18:59 |  |         |
| sat                            | 7:04 - 15:44    |  |          | sat                            | 6:59 - 15:59 |  |         |

Figure 4 – Timetable for the Ring 2½ light rail

When a brand new high class public transport service is introduced in the network some existing lower class lines will be more or less redundant. Therefore, it is possible to close down competing lines – cut down their frequency or shorten their line distance. This means saved operation cost for closed down lines. It is a balance though; closing of too many lines can result in an overall poorer service. A rearrangement of the bus system would probably be needed to fit the existing bus lines perfectly to the new higher class line. However, this is a very complicated procedure because of the complexity of the bus system. Therefore, only a rough adaptation of the bus system was made, meaning only closing of obvious competitive bus lines or bus vehicle hours. Bus line 200S was considered to be a directly competitor to the light rail because they share a very similar alignment between Friheden and Lyngby. Bus line 200S was, therefore, closed all though it has a shorter distance between stops than the light

<sup>4</sup> It is a planning method and, therefore, it does not take changes in route choice into account even though such changes have an influence e.g. [11]

rail. From Lyngby to Nærum bus line 300S would be somewhat competing to the light rail. But the bus has a long line distance and many other functions. It also drives a different route in the Lyngby area and the light rail has a lower frequency on this stretch. Therefore, bus line 300S was not closed but instead cut in those departures only running between Gladsaxe Trafikplads and Lyngby station and between Lyngby station and Naerum station.

## 7. Traffic impacts

The traffic impacts of the light rail in the public transport system were examined. This was done by traffic modeling of the public transport network in the greater Copenhagen region; without and with the light rail. For traffic modeling was used a timetable-based public route choice assignment-model developed at CTT (as in [12]). Zonal structure and trip matrixes were based on OTM. In order to simulate new trips caused by time savings induced traffic in the public transport network was also modeled (as in [13]).

The results of the traffic modeling indicated some positive impacts in the network because of the light rail. E.g. the light rail will increase the number of travellers in the corridor considerable. Furthermore, the light rail will relieve some of the S-train lines with capacity problems; especially in the city center. This tendency can be seen in figure 5.

The highest load on the light rail will be between Gladsaxe Trafikplads and Lyngby station where more than 2,000 passengers will use the light rail during the morning peak hours. The annual average daily number of travellers will be 28,400 solely based on a translocation of public users. Compared to the existing bus line in the corridor (200S) the increase in travellers will be approximately 160 %.

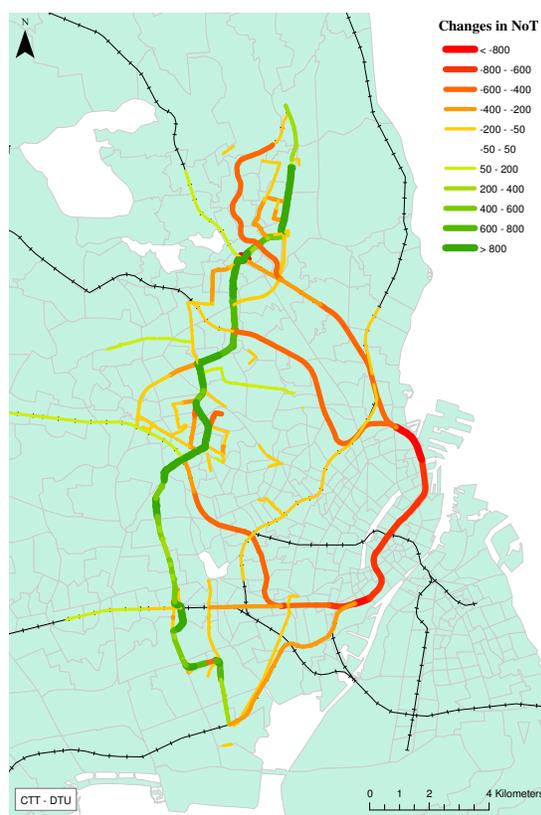
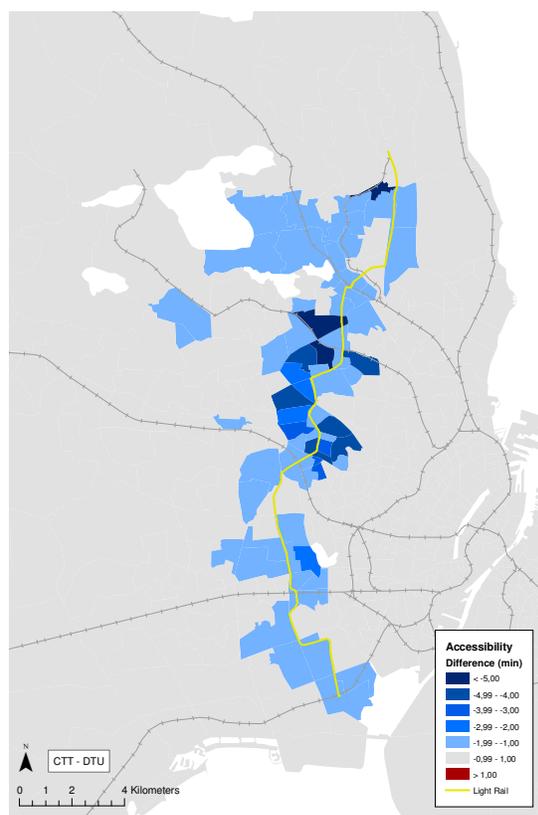


Figure 5 – Changes in number of travellers as a result of the light rail (Morning peak hours)

Experience shows that up to 10 percent of a new light rail's users have transferred from cars [14]. If the same percentage is appointed to the Ring 2½ light rail the annual average daily number of travellers will increase to 31,600.

Calculations of time savings in the public transport system because of the light rail showed some useful tendencies. Regional accessibility and mobility based on average travel times from zone to zone weighed by number of travellers shows a positive effect preferably in the zones around the light rail. As indicated from the regional accessibility viewed in figure 6. Some zones will gain up to five minutes in saved travel time in both trips to and from zones.



**Figure 6 – Regional accessibility – weighed time savings in trips to zones**

## 8. Economics

The economics of the Ring 2½ light rail is probably the most important indicator of its justification. The actual cost of the light rail is crucial for decision makers and the socioeconomics is often used as a measurement for infrastructure projects viability.

### 8.1. Initial cost estimate

The initial cost was calculated from different parts of the construction and purchases such as track equipment, price for stops, repository and control center, rearrangements, and purchase of the rolling stock. The total initial cost of the Ring 2½ light rail was calculated to 2.2 billion Danish kroner; approximately 88 million Danish kroner a kilometer track line. With only half of the cable price included due to scrap value of cable cost [15] the total cost will be 1.6 billion Danish kroner. It seems like a high cost but it is a fairly low cost compared to e.g. a Metro system.

### 8.2. Operation economy

The operation economy is the running cost and revenue of the light rail. The running cost is primarily the cost of operating the rolling stock. But the running cost is also maintenance of tracks and stops plus reinvestments. The annual cost of the Ring 2½ light rail operation was estimated to 75 million Danish kroner. The revenue of the light rail is ticket sales. A low

estimate is that the light rail will have the same share of the public transport system revenue as a bus line. Though the trips might be of a longer distance the light rail was given the same income per traveller as the existing bus line 200S. This income is 6.28 Danish kroner per traveller [10] and with 28,400 daily passengers the running revenue for the light rail will be 65 million Danish kroner per year. This means that the light rail will have a negative operation result at about 10 million Danish kroner annually. However, this is not a critical result and the level of self-financing at 87 % is better than most busses [10]. A higher estimate of the income share or including car users' transfer to the light rail could bring the operation economy close to balancing.

### 8.3. Socioeconomics

There is a standard procedure for evaluating socioeconomic viability of transport infrastructure projects and the guidelines are defined by the Ministry of Transportation [16]. This procedure was partly used for the evaluation of the Ring 2½ light rail. More specific was used a cost-benefit analysis (CBA) based on factor prices (as outlined in [15]) where the socioeconomic benefits and disbenefits are compared to the cost to see whether the project has an overall positive influence on the society. The operation cost and externalities such as accidents, noise- and particle pollution of the light rail are disbenefits. While benefits are saved operation cost and reduction in accidents, noise- and particle pollution from the cut down of bus lines or bus vehicle hours. The biggest benefit, however, is usually the savings in time cost in the system from the improved public infrastructure. Time savings were calculated from differentiated values of time using specific values for the different use of time in a public journey (access/egress time, wait time etc.) [16]. Furthermore, specific values for in-vehicle time based on each public transport mode were estimated and used in the time saving calculations [2]. The total time saving in the public transport system as result of the light rail was calculated with Rule of the half and gave a total of 84 million Danish kroner. Annual benefits and disbenefits are shown in table 1.

| Socioeconomic impacts                        | million DKK |
|--|-------------|
| <b>Annual cost of the light rail</b>         |             |
| Operation                                    | -74.9       |
| Externalities                                | -1.9        |
| <b>Annual savings of reduced bus service</b> |             |
| Operation + Externalities                    | 26.8        |
| <b>Annual time savings</b>                   | 84.1        |
| <b>Total</b>                                 | <b>34.1</b> |

**Table 1 – Benefits and disbenefits of the Ring 2½ light rail**

The sum of the annual benefits exceeds the sum of the annual disbenefits meaning the light rail has a positive influence on the society. The annual result of benefits and disbenefits is 34 million Danish kroner giving a first year rate of return (FYRR) at 2.1 %.

The primary result of the socioeconomics analysis is measured by net present value (NPV) and benefit cost ratio (B/C). The net present value was calculated to -997 million Danish kroner and the benefit cost ratio was calculated to 0.39 using a rate of interest for costing purposes at 6 % and a depreciation period at 50 years (as recommended by the Ministry of Transportation [16]). This means that the Ring 2½ light rail project is not socioeconomic viable. However, it is rare that new public transport infrastructure shows socioeconomic viability using the standard procedures. E.g. also the thorough examination of the Ring 3 light rail displays socioeconomic non-viability [3]. Even though the calculations showed no viability it is still a fairly good result compared to other examinations of light rails [15].

One should keep in mind that sketch planning of an infrastructure project will not likely result in socioeconomic optimization regarding the load of the infrastructure. Such an optimization demands an iterative process with recalculations of the operation plan and

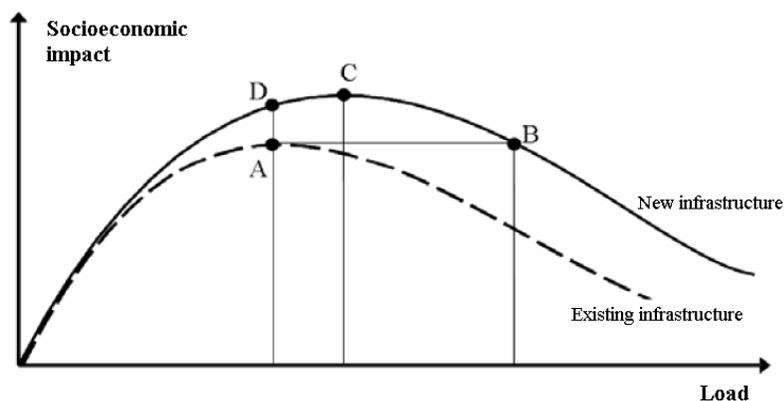


Figure 7 – Socioeconomic impact as function of infrastructure load [15]

timetable or long term practical optimization by experience. As shown in figure 7 it is feasible not to improve the socioeconomic impact by a new infrastructure if the load of the infrastructure is too heavy (point B in figure 7) [15]. When sketch planning a project it is not possible to tell to what degree the load of the infrastructure is optimized hence to what degree it obtains socioeconomic utility. As a matter of fact, chances are small of reaching the optimization point (point C in figure 7) even through qualified sketch planning and the socioeconomic result of the Ring 2½ light rail will thereby be more or less underestimated.

#### 8.4. Strategic impacts

The cost-benefit analysis is based on fixed monetary calculations and can therefore only include impacts which can be valued and have a regular measurable impact. But a large infrastructure project also has some long term impacts which are not included in the cost-benefit analysis. One of those is development areas, meaning areas with expected development because of the new light rail. Along the proposed alignment of the Ring 2½ light rail there are three relative large potential areas whose development in a long term can contribute to the success of the light rail in a self-perpetuating process. Furthermore, a new light rail can contribute to urban condensation in its catchment areas. How a high class public transport line can start urban development and condensations is last seen by the Copenhagen

Metro line 1 in the Oerestad. Studies from the catchment areas of the Copenhagen Metro also imply that the property value increases because of the new public transport service [17]. If a light rail can generate 2/3 of a Metro increase an estimate of the Ring 2½ corridor showed a total increase in property value at 1.2 billion Danish kroner. This was showing that there can be significant impacts from other effects than those included in the cost-benefit analysis. Strategic impacts can be estimated through multi criteria analyses (MCA) and incorporated with cost benefit analyses (CBA) for a systemic estimate of infrastructure projects [18].

## ***9. Conclusions and perspectives***

From an exclusively socioeconomic approach, the sketch planning of this project shows that the construction of the Ring 2½ light rail can not be justified. However, the standard benefit-cost procedures rarely show socioeconomic viability for new public transport infrastructure. Furthermore, the net present value (NPV) and the benefit-cost ratio (B/C) for the Ring 2½ light rail are better than seen in many other light rail projects [15].

The light rail shows some useful traffic tendencies. It relieves S-train lines with existing capacity problems and it increases the number of public travellers in the corridor significantly. Furthermore, the time savings for public transport users because of the light rail will be relatively high. Those tendencies along with the fairly acceptable operation economy indicate that the Ring 2½ light rail will have a positive daily impact. This is also backed up by the positive annual socioeconomic benefits. For the giving objective of improving public transport travel across the radial urban structure the light rail seems able to carry out the service.

As a light rail solution along Ring 3 is well examined, this study suggests that a Ring 2½ light rail could be qualified for further examinations of a high class public transport service of the increasing travel across the radial urban structure. Even though light rail systems on Ring 3 and Ring 2½ seem to be more or less competitive, they might show an even better result coexisting. This is because they service different districts in the south of their course and in the northern part of their course they can share the same alignment saving construction cost and maintenance of tracks.

There is yet no existing light rail system in Copenhagen or Denmark but experiences from neighbouring countries are very good and light rail systems are successful in many cities around the world e.g. [19] and [20]. It is, therefore, fair to believe that a light rail system also will have a positive impact in Copenhagen and the Ring 2½ corridor is one of the qualified alternatives.

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