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1 Objectives and operation challenges

This report presents the methodology used by SYSTRA for the Aalborg LRT preliminary operating plan, as well as the results of the study.

The quality of a public transport service depends on many criteria, such as:

- reliability
- frequency
- speed
- comfort
- service spread

In order to meet the required level of service for the LRT system, these criteria have to be considered during this preliminary operating study by taking into account the possible randomness in the daily operation and by sizing the appropriate rolling stock fleet. Therefore the aim of the study is to analyze all the operation characteristics of the proposed LRT line in terms of:

- Track layout requirements;
- Travel times and commercial speeds;
- Offer design;
- Rolling stock fleet requirements;
- Maintenance and operating costs.

2 Project characteristics

The following characteristics are considered as inputs for the preliminary operation plan:

2.1 Right-of-way classification

Aalborg LRT is not operated entirely on segregated right-of-way, and therefore speed limits differ along the route. The LRT right-of-way is classified into 4 categories:

- Grade-separated right-of-way: the trams are segregated from road traffic;
- Right-of-way shared with resident road traffic: the tram right-of-way is used by residents for local access. The trams operate in mixed traffic;
- Right-of-way shared with local residents, buses and pedestrians: in the Aalborg city center (on Østerågade/Boulevarden), the trams operate in a
pedestrian area shared with buses, and the right-of-way is also used by residents for local access.

- Right-of-way shared with buses on Jyllandsgade.

The following map presents the different sections of the tram route:

![Aalborg LRT map and right-of-way classification](image)

**Figure 1 : Aalborg LRT map and right-of-way classification**

### 2.2 Intersections and traffic lights

The proposed LRT route crosses 17 intersections controlled by traffic lights. 15 of them can be considered as major intersections where removing the traffic light and forbidding the crossing of the LRT right-of-way could cause significant disruption in traffic conditions in the city of Aalborg.

We advocate removing the traffic lights and forbidding the crossing of the LRT right-of-way by road vehicles at the 2 other intersections, which are the following:

- Algade/Østerågade/Boulevarden;
- Boulevarden/Brandstrupsgade/Vingårdsgade.

Additionally, we propose to add one traffic light on the University campus at the corner of Bertil Ohlins Vej and Fredrik Bajers Vej, in order to facilitate through traffic across the University.

At all the smaller intersections where there is currently no traffic light, we recommend to forbid the crossing of the LRT right-of-way by road vehicles.
The following map provides the location of the traffic lights and major intersections that are taken into account in the operation plan.

![Map of Aalborg LRT and right-of-way classification](image)

**Figure 2: Aalborg LRT map and right-of-way classification**

### 2.3 Bus routes sharing the LRT right-of-way

Some bus routes will share the LRT right-of-way on two sections of the line. These bus routes are taken into account in the simulation, as the buses might have an impact on LRT operations.

- Between Boulevarden and Ved Stranden, a bus runs every minute in each direction during peak hours;

- Between Karolinelundsvej and Jyllandsgade, a bus runs every 2 minutes in each direction during peak hours.

Buses and trams share the same platform at the following stations:

- Østerå
- Administrationsbygningen
- Aalborg St. / JF. Kennedys Plads
- Politigården
For these four stations, the platforms are extended from 40 to 60 meters, so that one LRT vehicle and one bus can stop at the same time.

For safety reasons, it is recommended that buses run behind trams as often as possible. Therefore, some space must be allocated for buses so that they can wait before entering the shared right-of-way. Priority must be given for trams and buses at traffic lights along the corridor. Finally, the platforms at the shared stations must be designed so that a bus can stop behind a tram.

Any future detailed alignment study should take this into consideration.

3 Track layout

An appropriate track layout is essential to maintaining a good level of service on the network and a reliable operation plan.

The track layout must allow for:

- Tramway operations under normal conditions with the minimum planned headway between two trains;
- Turn at the terminal stations;
- Entry and exit of vehicles on the line, to adjust the service capacity offered to the demand;
- Partial services between two stations in case of a disruption along the line.

3.1 Terminals

Terminal stations are key components of the track layout. The layout must allow for tram turnaround, and good regulation of the service. Space behind the station to park trains is also desirable for operations.

Marina

For the terminal station at Marina, tram turn-backs behind the station are proposed for maximal flexibility during peak hours and to provide the possibility to stock additional trams in case of damage. During off-peak hours, when headways are longer, trams can switch tracks before the station to reduce the cycle time.

Crossovers ahead of the station are not sufficient on their own, and a communication is provided between track 2 and track 1 at the back of the station so that the depot remains accessible if there is a tram stuck on track 1 at the arrival platform.
The depot is accessible directly from the Marina station, and tramways are injected onto the line at this station.

**Psykiatrien**

For the terminal station at Psykiatrien, tram turnaround behind the station is also proposed for maximal flexibility during peak hour, and easier use for passengers (as arrival and departure platforms are different). Some space behind the station can be reserved for tram storage.

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### 3.2 Partial services

Turn-back locations along the route must be chosen so that partial services can be operated in case of a disruption on some other point along the line. The positioning of the switches is strategic and is done according to insertion constrains, potential events and demonstrations, and the impact on travelers. Usually, the switches are located at stations with interchanges to other modes, or stations with high patronage. The switches should also be located in order to isolate sections of the line where events and/or demonstrations are most likely to occur.

*Figure 3: Use of crossovers in case of a disruption*

On the Aalborg LRT line, switches shall be implemented as follows.
- Around the pedestrian area on Østerågade/Boulevarden so that the rest of the line can be operated in case of an event or an incident in the historic city center. A switch between Aalborg St. / JF. Kennedys Plads and Politigården also allows operations between JF. Kennedys Plads (the train station) and Psykiatrien in case of a disruption on Østerågade/Boulevarden.

- Similarly, around the University campus to isolate it, so that the line can be operated between Marina and Pontoppidanstræde in case of a disruption on the University grounds.

- And between Petersborgvej / Humlebakken and Danalien.

The track map with the layout of the terminal stations and the position of the switches is presented below.
Figure 4: Track map with position of the switches for partial services
4 Simulation assumptions and tool

4.1 Simulation tool: BusRT

The simulation tool BusRT was developed internally by SYSTRA to model a BRT or LRT infrastructure (including parallel routes that share the right-of-way), calculate commercial speed along the route, and test the operational robustness.

BusRT is used in this feasibility study for running time and commercial speed calculations on the Aalborg LRT line.

The following characteristics are used as inputs to the simulation software:

- Track characteristics, including:
  - the length of each section;
  - the curve radius;
  - the slopes;
  - the speed limit on each section;
  - the stations (position, platform length, dwell time);
  - the traffic lights and priority type at each intersection.

- Rolling stock characteristics, including:
  - the technical characteristics (length, weight, maximum load, maximum acceleration, maximum speed, maximum lateral acceleration…);
  - the entry and exit point on the platform (including bus lines that use some sections of the tramway platform);
  - the headways and headway standard deviation.

The outputs provided by the simulation tool are of two types:

- Quantitative indicators, that are used mainly to determine the rolling stock fleet requirements:
  - Running time for each direction (average, minimum, maximum, variance);
  - Average commercial speed for each direction (average, minimum, maximum, variance).

- Graphical outputs:
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4.2 Rolling Stock characteristics
For the purposes of this study (for both development of the operating plan and design of the alignment) we have assumed that the Aalborg LRT rolling stock will be the same as that of Aarhus LRT; as such, the characteristics below are based on the RS tender specification for Aarhus LRT.¹ The following rolling stock characteristics are considered for the simulation:

- Length: 32 m²;
- Maximum load: 240 people per vehicle;
- Maximum operational speed: 80 km/h;
- Acceleration power: 1 m/s²;
- Maximum lateral acceleration: 1 m/s²;
- Nominal breaking: 1.2 m/s².

4.3 Speed limits
For the purpose of the simulation, the following speed limits are assumed:

- 50 km/h on grade-separated right-of-way;
- 30 km/h when the right-of-way is shared with resident road traffic and/or with pedestrians;
- 40 km/h at intersections with traffic lights.

4.4 Priority for trams at traffic lights
At each intersection with a traffic light, we have assumed that absolute priority is given to the light rail vehicle, thanks to green time insertion in the traffic light phasing. The vehicle is detected before the intersection in order to activate the priority system. However, a minimum green time is given to other traffic crossing

¹ Nonetheless, we point out that the ridership forecasts for Aalborg are such that smaller and thus less expensive rolling stock may be appropriate.
² The Aarhus LRT rolling stock will be between 36 and 44 meters long. For the purpose of this study, the minimum length of 36 meters is considered.
the intersection and the priority cannot be systematically guaranteed for every light rail vehicle. All of the intersection characteristics are integrated into the BusRT model, and the software takes into account the traffic lights and priority systems when simulating LRT operations on the line.

4.5 Dwell times

For the Aalborg LRT preliminary operating plan, the dwell times in stations were provided to SYSTRA by COWI. For the simulation, the dwell times are not considered constant, and a standard deviation of 4 seconds is added at each station.

<table>
<thead>
<tr>
<th>Stop</th>
<th>Dwell Time (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marina</td>
<td>20</td>
</tr>
<tr>
<td>Vesterkærer</td>
<td>20</td>
</tr>
<tr>
<td>Haraldslund</td>
<td>20</td>
</tr>
<tr>
<td>Vestbyen St.</td>
<td>20</td>
</tr>
<tr>
<td>Vesterå</td>
<td>20</td>
</tr>
<tr>
<td>Østerå</td>
<td>30</td>
</tr>
<tr>
<td>Administrationsbygningen</td>
<td>20</td>
</tr>
<tr>
<td>Aalborg St. / JF. Kennedys Plads</td>
<td>45</td>
</tr>
<tr>
<td>Politigården</td>
<td>20</td>
</tr>
<tr>
<td>Karolinelund / Bornholmsgade N</td>
<td>20</td>
</tr>
<tr>
<td>Bornholmsgade S</td>
<td>20</td>
</tr>
<tr>
<td>Petersborgvej / Humlebakken</td>
<td>20</td>
</tr>
<tr>
<td>Danalien</td>
<td>20</td>
</tr>
<tr>
<td>Grønlands Torv</td>
<td>20</td>
</tr>
<tr>
<td>Scoresbysundvej</td>
<td>20</td>
</tr>
<tr>
<td>Pendlerraplsden</td>
<td>20</td>
</tr>
<tr>
<td>Gigantium</td>
<td>20</td>
</tr>
<tr>
<td>Pontoppidanstræde</td>
<td>20</td>
</tr>
<tr>
<td>Universitetet</td>
<td>20</td>
</tr>
<tr>
<td>Biblioteksskolen</td>
<td>20</td>
</tr>
<tr>
<td>Selma Lagerlöfs Vej</td>
<td>20</td>
</tr>
<tr>
<td>Servicebyen</td>
<td>20</td>
</tr>
<tr>
<td>Universitetshospitalet</td>
<td>20</td>
</tr>
<tr>
<td>Psykiatrien</td>
<td>20</td>
</tr>
</tbody>
</table>

5 Offer design

5.1 Traffic forecasts

Ridership forecasts are based on the current demand for public transit in the tramway corridor. The offer is based on the ridership on the most loaded section and direction.
The general assumptions for the traffic forecasts are the following:

- Public transit ridership has an annual growth of 2% until the opening year of 2025 and only 1% beyond;

- Based on SYSTRA’s experience with French networks, the day-to-peak-hour coefficient is considered to be equal to 0.12.

The current most loaded section between JF Kennedys Pl and Karolinelund has an estimated ridership of 6,300 passengers per day per direction during peak hour. Therefore in 2055 (after 30 years of service), the most loaded section should see a ridership of about 1,300 passengers per hour per direction.

The current most loaded section between JF Kennedys Pl and Karolinelund has an estimated ridership of 6,300 passengers per day per direction during peak hour. Therefore in 2055 (after 30 years of service), the most loaded section should see a ridership of about 1,300 passengers per hour per direction.

5.2 Peak hour frequency

Based on the ridership forecasts, the minimum peak hour headway \( H \) (in seconds) required to handle peak-hour demand on the most loaded section and direction is calculated with the following formula:

\[
H = 3600 \times \frac{C_u}{D}
\]

where \( C_u \) is the capacity of one vehicle, and \( D \) is the peak-hour demand on the most loaded section and direction.

Here, the minimum peak-hour headway is \( H = 3600 \times \frac{240}{1300} = 665 \) seconds, or 11 minutes and 5 seconds. However, in order to maintain an attractive service on the
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line, a peak-hour headway of 6 minutes is considered in the simulation for the preliminary operating plan.

6 Journey Time & Cycle Time calculation

6.1 BusRT simulation results

The BusRT simulation results are obtained after simulating the Aalborg LRT operation during a 2-hour period under peak-hour headway.

6.1.1 Quantitative results

BusRT provides running time results for all the LRT trips operated in the two directions during the 2-hour simulation period.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Average Running Time (min)</th>
<th>Min Running Time (min)</th>
<th>Max Running Time (min)</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marina - Psykiatrien</td>
<td>34.7</td>
<td>33.8</td>
<td>36.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Psykiatrien - Marina</td>
<td>34.0</td>
<td>33.3(^{3})</td>
<td>35.0</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Similarly, the average speed along the route is calculated for each trip. BusRT provides the following aggregated results:

<table>
<thead>
<tr>
<th>Direction</th>
<th>Average Speed (km/h)</th>
<th>Min Average Speed (km/h)</th>
<th>Max Average Speed (km/h)</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marina - Psykiatrien</td>
<td>19.9</td>
<td>19.1</td>
<td>20.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Psykiatrien - Marina</td>
<td>20.3</td>
<td>19.7</td>
<td>20.4</td>
<td>0.1</td>
</tr>
</tbody>
</table>

6.1.2 Time-space diagrams

The time-space diagram shows the position of the vehicles along the route at a given time. The stations are also shown, as well as the traffic lights and the red times for each of them.

Additionally, the time-space diagram shows the position of the buses that use the LRT right-of-way of two specific segments\(^{3}\).

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\(^{3}\) The difference in running times between the two directions can be explained by the 6.5% slope on Sohngårdsholmsvej. Trams go uphill towards Psykiatrien, hence a slightly longer running time, and a slower speed.

\(^{4}\) The diagram shows the impact of the buses on LRT operations. Reliability of the LRT line might be affected by the high frequency of the bus lines that use the LRT corridors.
Figure 6 - Time space diagram with 6-minute headways.
Red lines represent traffic lights, grey lines represent stops.
Yellow lines represent the buses that operate on the tramway right-of-way.
6.1.3 Speed profiles

The speed profiles along the route are obtained from BusRT for the two directions. The graphs give the average speed at each point of the route.

![Speed Profile](image-url)

*Figure 7: Speed profile [Marina - Psykiatrien] direction*
Figure 8: Speed profile [Psykiatrien - Marina] direction
6.2 Peak-hour cycle time calculation

The peak-hour cycle time (or round-trip journey time) is calculated as the sum of:

- the average end-to-end journey time in each direction;
- a 5% margin to allow for reliability in case of slight delays
- the turning time behind each terminal station;
- a layover time that corresponds to 10% of the average running time.

The turning time during peak hours is calculated at the two terminals:

- At Marina:
  - time to go from the arrival platform to the track end: 65 seconds since the crossover is relatively far away from the terminal station (the tram first needs to cross the intersection);
  - time for the conductor to walk from one cabin to the other: 45 seconds with the tram empty;
  - time to go from the end of the track to the departure platform: 75 seconds;

- At Psykiatrien:
  - time to go from the arrival platform to the track end: 40 seconds;
  - time for the conductor to walk from one cabin to the other: 45 seconds with the tram empty;
  - time to go from the end of the track to the departure platform: 30 seconds.

The minimum turning time is therefore **115 seconds at Psykiatrien**, and **185 seconds at Marina**.

The total cycle time is:

<table>
<thead>
<tr>
<th>Direction</th>
<th>Average running time (seconds)</th>
<th>Margin 5% (seconds)</th>
<th>Layover time (seconds)</th>
<th>Turning time (seconds)</th>
<th>Total (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marina - Psykiatrien</td>
<td>2,079</td>
<td>104</td>
<td>218</td>
<td>115</td>
<td>2,516</td>
</tr>
<tr>
<td>Psykiatrien - Marina</td>
<td>2,042</td>
<td>102</td>
<td>214</td>
<td>185</td>
<td>2,544</td>
</tr>
<tr>
<td><strong>Total Cycle Time (seconds)</strong></td>
<td><strong>5,060</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Cycle Time (hours)</strong></td>
<td><strong>01:24:20</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7  Rolling stock fleet and depot size

7.1  Rolling stock requirements
The necessary rolling stock fleet includes the following:

- The number of trams necessary at peak period to meet the transport demand, in function of the round-trip cycle time;

- One additional tram for operation management;

- Additional trams for maintenance in the depot

The total rolling stock fleet necessary is **18 trams**.

7.2  Depot size
The depot would be located at the western end of the LRT line, about 800 meters away from the Marina terminal station.

The depot shall be large enough to accommodate all the rolling-stock fleet required for peak-hour operations.

The workshop adjacent to the depot shall have sufficient capacity for the planned operation, including repairs and heavy maintenance.

8  Operating and maintenance costs
Annual operating and maintenance costs are calculated based on the vehicle-km operated each year for commercial services and deadheading trips. In France, the cost of the depot and the depreciation of rolling stock are not considered as operation costs. The same approach is applied here and therefore these costs are not included in the following calculation.

8.1  Calculation of the vehicle-km operated each year
Each day is divided into three periods: peak hours, day hours and evening. For the preliminary operation plan, the estimated frequencies for the three periods are respectively 10, 8 and 4 tramways per hour and per direction.

It is assumed that the LRT is in operation 19 hours on all days of the week. On weekdays, the LRT operate on peak-hour headway for 6 hours, on day-hour headway for 6 hours, and on evening headway for the remaining 7 hours. On weekends, the LRT operates on day-hour headway for 12 hours and on evening headway for the remaining 7 hours.

The annual production of vehicle-kilometers is based on 261 week days and 104 weekend days per year.
The vehicle-km traveled in deadheading trips must be added to the vehicle-km traveled for commercial service. The deadheading trips consist of the 800 meters between the depot entrance and Marina station, as well as the 300 meters traveled each time a tram turns around at Marina. It is considered that there is no deadheading trip between Marina and Psykiatrien, i.e. all vehicles traveling between the two terminal stations are in service.

<table>
<thead>
<tr>
<th></th>
<th>Weekdays</th>
<th>Weekends</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trips/day/direction</td>
<td>136</td>
<td>124</td>
</tr>
<tr>
<td>Vehicle.km/day</td>
<td>3,210</td>
<td>2,926</td>
</tr>
<tr>
<td>Vehicle.km/year</td>
<td>837,706</td>
<td>304,346</td>
</tr>
<tr>
<td>Total vehicle.km/year</td>
<td>1,142,051</td>
<td></td>
</tr>
<tr>
<td>Vehicle.km/day (deadhead)</td>
<td>59</td>
<td>49</td>
</tr>
<tr>
<td>Vehicle.km/year (deadhead)</td>
<td>15,347</td>
<td>5,117</td>
</tr>
<tr>
<td>Total vehicle.km/year (deadhead)</td>
<td>20,464</td>
<td></td>
</tr>
<tr>
<td><strong>Total vehicle.km/year</strong></td>
<td><strong>1,162,515</strong></td>
<td></td>
</tr>
</tbody>
</table>

8.2 Operating and maintenance costs

Based on SYSTRA’s experience, the average operating and maintenance cost for an LRT network in France is **7 €/vehicle.km**.

To compensate for the difference in economic conditions between France and Denmark, this average costs is multiplied by the ratio of the gross domestic product (GDP) per capita in Purchasing Power Standard (PPS) in 2011 for the two countries.

<table>
<thead>
<tr>
<th>Country</th>
<th>GDP per capita in PPS (2011)</th>
<th>Average operating and maintenance cost (€/veh.km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>108</td>
<td>7.00</td>
</tr>
<tr>
<td>Danemark</td>
<td>125</td>
<td>8.10</td>
</tr>
</tbody>
</table>

The exchange rate from euros to Danish kroner was **EUR 1 = DKK 7.4602** on February 1<sup>st</sup>, 2013.<sup>6</sup>

The annual operating and maintenance costs for the Aalborg LRT are: **70.3 million DKK**

9 Analysis of climate-related particularities

Aalborg is located in North Jutland, and the weather is quite typical of Denmark.

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<sup>5</sup> Data from 1st of December 2012, source: Eurostat.
<sup>6</sup> Source: European Central Bank.
The rolling stock used in Aalborg will be designed to operate regardless of the environmental conditions. The trams will also be designed for outdoor parking; however, covered stabling will reduce the impact of snow, ice and frost. Maintenance costs will be reduced, and the equipment mounted on the roof will function more effectively and more reliably.

Additionally, the vehicle ends should include snow deflectors, aimed at cleaning the tracks during heavy snow fall, so that operations can be continued during snow episodes.

When the weather is extremely cold, running trams overnight at a certain interval to keep tracks, switches and catenaries heated and to prevent ice from forming might also be required.