

1. Introduction

The planning procedures of public transport follow some standards everywhere. However, the different characteristics of each city and their customs and habits make that the transport planning system is particular in each region. This is the case of Copenhagen and Barcelona.

Both have a developed public transport network and they are working hard to improve it. However, the experience of each one in metro planning is pretty different.

On one hand, Barcelona has a large metro network for more than 80 years. On the other hand, the first metro of Denmark was opened four years ago in Copenhagen.

Both are also planning new lines, such as the new City Circle Line in Copenhagen and the future L9 in Barcelona.

This planning system is analyzed from the first phases. First of all, the viability of the new line from passengers' estimations, future prognosis, changes in the public transport shares and so on. The initial data is coming from surveys to the population to find out their behaviour in front of the future infrastructure. The procedure of these surveys is different depending on what planners want to get.

Moreover, the location of the stations determines the layout of the line. Hence, the good situation of them is essential to provide a good service to the population. Stations require fast and safe accesses to the trains. It means a good configuration to serve as many people as possible. The better is the service and the location of the station, the higher is the catchment's area. However, other parameters affects to this area, such as the configuration of the streets, the slopes, the age of the people, the transport mode used to get the station, etc.

Aside from the transport planning, the construction of a metro line has other consequences. These kinds of infrastructures have elevated costs that sometimes are impossible to pay off by the local governments. They need external help coming from political manoeuvres. Thus, the political decisions are essential to develop a metro line and sometimes there are collateral benefits.

Both Barcelona and Copenhagen have their political influences in the construction of new metro lines, but they are really different.

Hence, the aim of this thesis is to analyze the planning system of Copenhagen and Barcelona's metros, as well as the political decisions, and make a comparison between them.

Moreover, a theoretical frame of traffic and railway planning is explained according to some courses followed in the Center of Traffic and Transport in DTU, trying to apply these concepts for the planning system of the metro.

The thesis is divided in four main sections. First of all the explanation about these courses followed in DTU. Secondly, a thorough analysis of the Copenhagen's metro, both the actual and the future lines. The third section is about the Barcelona's metro, especially the planning process of the new L9.

Finally, the comparison between both cities, analyzing the transport planning tools used to develop these metro lines.

1.1. Courses followed in DTU

1.1.1. Traffic Models

The aim of this course is to obtain an overview of methods that are used in areas of transport modelling and infrastructure planning. These methods will be used to improve the transport systems, both for private and public transport. Basically, the methods are based using mathematical and statistical tools, as well as some computer programs, such as SAS, Arc GIS and Excel.

The planning system is organized within a structure called “The four step model”, originates during the 60’s in the USA. This structure is easy understandable and practical to work with it, but sometimes the model is too simple and the dependence of some steps between each other can distort the results.

The different steps are: trip generation, trip distribution, mode choice and assignment. Each step has a role and each level induces changes to the other ones. (Ref: Course 13130)

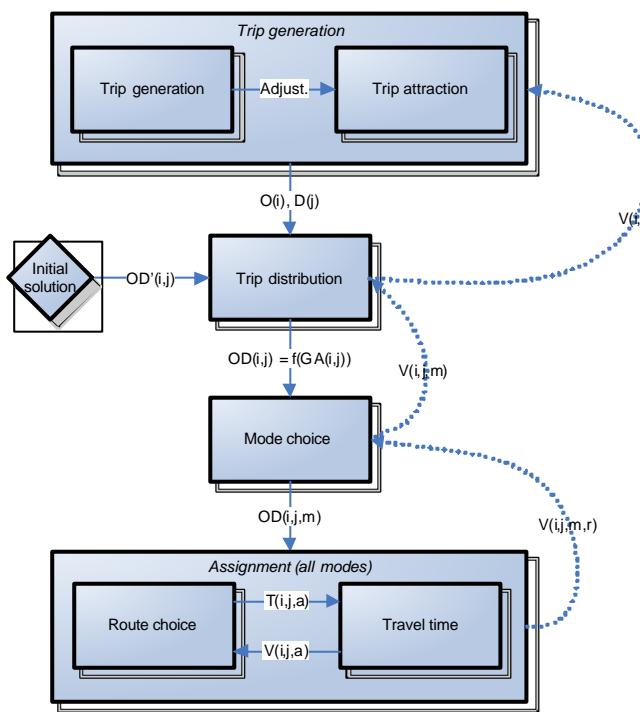


Fig. 1. Structure of the Four Step Model. (Ref: Course 13130, week 1)

1.1.1.1. Trip generation

The first step is the trip generation. Its role is to determine the number of trips generated and attracted in each zone. The difference between each other is that the generation is the number of trips from one zone while the attraction is the number of trips going to one zone. Normally, the generation is related to the demand side of the economy while the attractions are generated by the supply side of the economy. It is assumed that the trips include both home-based and non-home-based trips.

Although the trip generation and the trip attraction are separated processes, it is necessary to ensure that:

$$\sum O_i = \sum D_j$$

Ortuzar and Willumsen suggest 4 methods (Ref: Course 13130, week 3):

1. Hold Production Constant (all destinations are multiplied by a constant)
2. Hold attraction Constant
3. Sum approach so that ($\sum O_i = K = \sum D_j$)
4. WLS approach so that ($\sum O_i = a\sum O_i + b\sum D_j = \sum D_j$)

Usually the attracted trips are adjusted from the generated, using the Hold Production Constant. For that reason, information of generated trips is given from a survey and a trip generation model is built through different methods like regression analysis, cross-classification, growth factor, etc. The model is upscaled according to the information given by the population totals. Hence, the attracted trips are obtained.

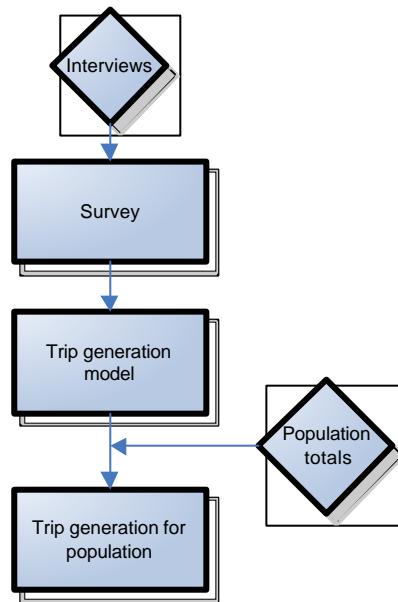


Fig. 2. General method of trip generation. (Ref: Course 13130, week 3)

1.1.1.2. Trip distribution

The next step is the trip distribution. Once the generated and attracted trips are known for each zone, it is time to estimate the number of trips between each pair of zones and obtain a trip distribution matrix. The method used to estimate the trip distribution is called Gravity Model and it has some differences with the Iterative proportional fitting (IPF) matrix estimation method. The IPF is an algorithm where the knowledge of structure for both the initial solution and the final totals is needed. The gravity model also needs the relationship between dimensions.

The boundaries for the IPF methods are the assumptions taken related to the retained information of the structure in the initial distribution, if it is necessary to estimate long-terms forecasts, a robustness is needed as the infrastructures in the network may change, for instance, the building of new links between two zones.

The Gravity Model is based on a major number of trips between two zones proportional to the population of both zones and invertible proportional to the distance between them. It is called gravity model due to its similarity to the physics theorem about the gravity attraction between solids.

$$T_{ij} = \frac{\alpha P_i P_j}{d_{ij}^2}$$

Where P_i and P_j are the total population for zones i and j correspondingly, d_{ij} is the distance between both zones, T_{ij} is the number of trips from zone i to zone j and alpha is an adjusting parameter. Remarkable is the fact that the variable distance does not have to be a truly distance in meters or kilometres, but also can be the driving costs to travel from i to j, the travel time, etc.

Actually it would be clearer and more reliable to talk about:

$$T_{ij} = \frac{\alpha G_i A_j}{C_{ij}^2}$$

Where G is the capacity of zone i to generate trips, A_j is the capacity of j to attract travellers, and C_{ij} is a cost function evaluated for the trips between this two zones. One of the most difficult steps in the gravity model is to estimate the cost function, which in general will be assumed to fulfil that $\partial T_{ij}/\partial c_{ij} < 0$, (the number of trips between two zones decreases with an increase of the cost between these zones). However the marginal decrease in T_{ij} with respect to c_{ij} might be different: (Ref: Course 13130, week 4)

- For different purposes
- For different areas
- For different countries

In order to ensure that row and column totals are met, an iterative calibration is needed. The double constrained gravity model, where both dimensions are constrained are given by:

$$T_{ij} = A_i O_i B_j D_j f(c_{ij})$$

$$A_i = \left(\sum_j B_j D_j f(c_{ij}) \right)^{-1}$$

$$B_j = \left(\sum_i A_i O_i f(c_{ij}) \right)^{-1}$$

(Ref: Course 13130, note 2)

Some usual models for the cost functions are the exponential function, the inverse power function and a combined (gamma) function between the first two. (Ref: Course 13130, week 4)

- The exponential function
 $f(c_{ij}) = \exp(-\gamma c_{ij})$
- The inverse power function
 $f(c_{ij}) = (c_{ij})^{-\phi}$
- The combined (gamma) function
 $f(c_{ij}) = \exp(-\gamma c_{ij})(c_{ij})^{-\phi}$

There are therefore two ways of estimating the parameters of the travel cost function, taking into account that generally Tij is a Poisson count process:

- Use a regression analysis
- Use an iterative approach

Once the parameters are found, the OD matrixes (trip distribution matrixes) are obtained using Arc GIS program and different tools within the next model:

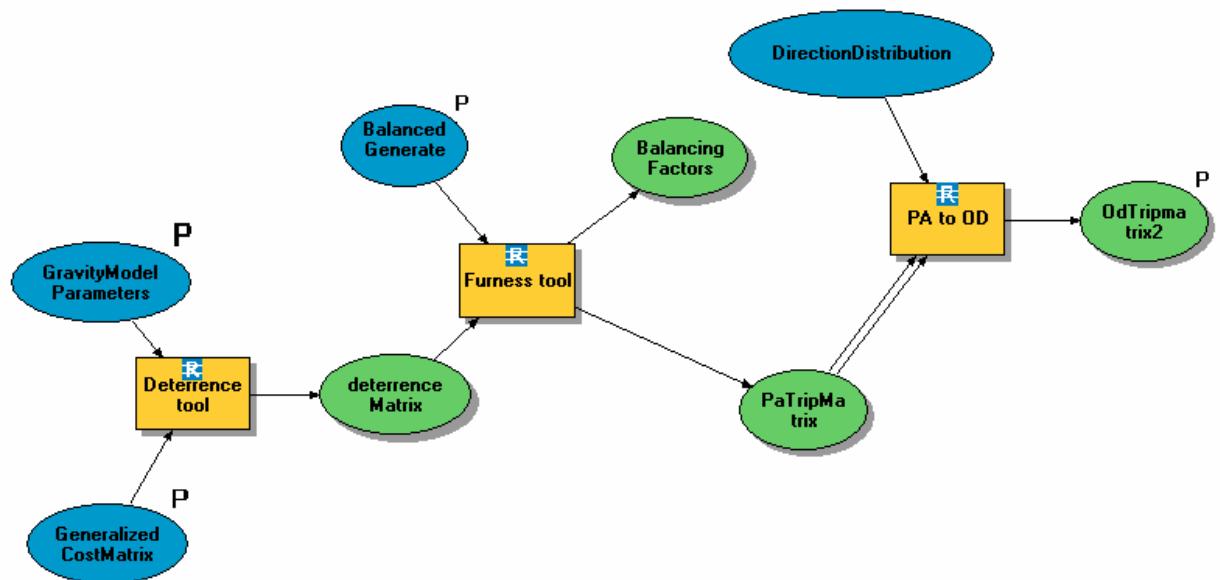


Fig. 3. Trip distribution model using Arc Map.

1.1.1.3. Mode choice

The third step is the mode choice and its purpose is to determine the market shares for the different transport modes, and how they vary when the prices changes, when a new mode is inserted, or for example when a taxation is implemented.

Usually the mode choice is based on a discrete choice model, and the most used are the multinomial logit model and the nested model.

The Multinomial Logit model tries to estimate person-trips of the various alternative modes available, assuming that travellers, either individually or in groups, make rational choices between the available modes, based in part upon characteristics of those modes, and in part upon characteristics of the travellers. (Ref: Course 13130, Logit Derivation)

To go from one zone to another each individual may choose between different transport modes, e.g. car, plane, public transport (either bus, metro, etc.) or even by bike or on feet. In the discrete choice models it is dealt about which mode the individual will use depending on the different utilities that he or she can find for each mode.

The definition of these mode choices must satisfy three criteria (Ref: Course 13130, week 7):

1. Non-overlapping.
2. All alternatives should be represented (all the choices that individual can choose must be in the model).
3. Finite number of alternatives.

Once all the possible choices are set, a utility function is needed for all of them, which represents how utile is for the individual to choose this mode choice.

Usually the utility function will take on a linear-in-parameter form, some examples of the most common ones are:

$$\begin{aligned} \text{a.) } V_{ni} &= K_i + a_1 X_{1i} + a_2 X_{2i} + a_3 X_{3i} \\ \text{b.) } V_{ni} &= K_{1i} + a_1 X_{1i} + a_2 \log(X_{2i}) + a_3 \log(X_{3i}) \end{aligned}$$

Where K is a constant and X 's are variables that vary with the alternatives such as cost, travel time, sex, income, age, etc. N is the individual and i is the choice set.

Utility is a relative measure so the choice probability remains constant either if a constant is added to all the utility functions or if it is multiplied for all of them (the model is invariant to scaling). (Ref: Course 13130, week 7)

Then, once the utility function is defined, the choice probability is set by the following expression:

$$P_{1,2} = \frac{\exp(V_{1,2})}{\sum_i \exp(V_{1,i})}$$

1: individual

2: mode choice

P: probability for the individual 1 to choose mode 2

$V_{1,2}$: Utility function for the individual 1 to choose mode 2

The multinomial model is easy to understand and to estimate but at the same time it has several weaknesses caused by its simplistic representation of many situations.

The shortcomings of the logit model can be overcome by the use of a slightly more general approach called the nested logit model. In this kind of model the organization is done by the most similar alternatives within nests. This structuring will give a more flexible substitution pattern than the multinomial logit model, because alternatives within nests are allowed to be correlated.

In fact, the nested logit estimate a parameter for each nest in order to measure the degree of correlation within the nest. These parameters are often referred to as logsum parameters, which refer to the form of the conditional mean of the lowest nest given the upper level.

When dealing with a nested logit model it is particularly important to think very much how are you going to split the modes into the different nests in a hierarchical graph. (Ref: Course 13130, Note 4)

For example, one possible representation of the transport modes using nests could be the next:

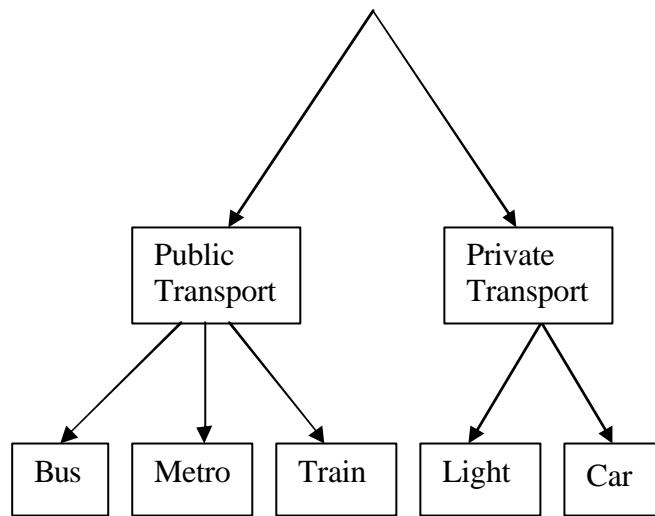


Fig. 4. Transport modes split into different nests.

1.1.1.4. Assignment model

Finally, the fourth and the last step is the assignment, also known as the route choice. Its role is to assign the traffic into the network.

When talking about assignments, basic concepts have to be taken in account:

- The supply-side of a transport system is made up of Road network $S(L,C)$, where L represent links and C costs.
- The demand-side, define the number of trips between O-D pairs.
- Speed-flow curves relate the use of the network to the level of service it offers.

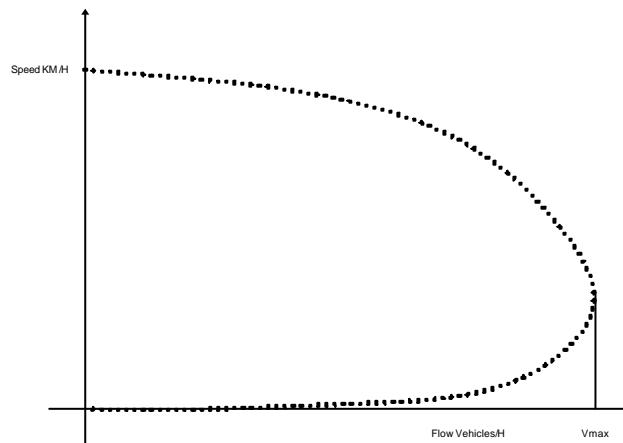


Fig.5 . Empirical speed flow curves for private transport. (Ref: Course 13130, week 9)

Four different models can be differentiated, depending on the stochastic effects and the capacity restraint.

Assignment models		Stochastic effects included?	
		NO	YES
Capacity restraint included?	NO	All-or-nothing(AOR)	Pure Stochastic (Dial Burrel)
	YES	Wardrop's equilibrium	Stochastic User Equilibrium (SUE)

Table 1. Assignment models

Different users' preferences are captured in each model:

In All-or-nothing assignment, each person minimizes his/her deterministic travel resistance and there are different assumptions: Traffic runs freely without delays (no congestion).

- Travellers have full knowledge on the transport network.
- All travellers are equal and have the same preferences.

Since congestion is not handled, any information on travel-time savings is got as a result of improved infrastructure.

In Wardrops' equilibrium, called user equilibrium models, the travel time depend on the traffic volume. Wardrop formulated two principles:

1. Under equilibrium conditions traffic arrange itself in congested networks in such a way that no individual trip maker can improve his/her path cost by switching routes
2. Under equilibrium conditions traffic should be arranged in congested networks in such a way that the average (or total) travel cost is minimized

The first is a user-optimum: Each individual minimize his/her own travel resistance (the more realistic principle of the two).

The second is a system-optimum: The total travel-time is minimised so that the average travel resistance is minimized. From the point of view of planners this is the most beneficial principle. (Ref: Course 13130, week 9)

In Stochastic models where the congestion is not included (Pure stochastic models), travellers have not full knowledge on the transport network. The logit model is the most used.

SUE is the preferable way of doing assignment, where both randomness and congestion have been implemented. This model can be based on probit-based route choice, but includes as well traffic dependent travel resistances.

When talking about real life, normally the users follow an AON model when the traffic in the network is really small. As there are not many cars everybody will choose the shortest and fastest way. Afterwards, and as the amount of cars in the road is increasing, the model turns into a SUE, assuming probabilities in the way that people choose different routes by the way they think they will get the best choice. And finally, when the network is heavily loaded and there become several congestions the model turns into a Wardrop's equilibrium. This is not general and usual but can be an approximation for some specific networks. (Ref: Francesc Robusté. UPC)

With the assignment, the real OD matrix is obtained and the new traffic is fitted into the network.

1.1.1.5. Application to the metro

Most of the theory shown above was applied for the implementation of a metro in Copenhagen.

Usually, in Copenhagen, the modes are divided between car, public transport, bike and walk, where the metro is within the framework of the public transport, as well as the bus and the train.

The traffic in Copenhagen area is divided in five periods per day, differentiating on the peak hours when people go to work in the mornings and when they come back to home in the afternoon, and the rest of the day:

- PM: Morning peak hour = 40 min
- MM: Around morning peak hour = 1h 20 min
- PE: Afternoon peak hour = 40 min
- EM: Around afternoon peak hour = 1h 20 min
- UM: Rest of the day = 20 h

Many years ago, the City of Copenhagen and the Danish Government agreed with the idea to construct a new urban railway. Anyway, the metro was not the only idea, and different studies were made between three alternatives:

- An automated driverless minimetro
- A driver operated tram
- A driver operated light rail

To see which alternative was the best, planners made a traffic forecast model, sequential and with a stochastic assignment. (Ref: Søndergaard M.)

They took different factors into account such as the extension of the infrastructure, the changes in bus and train after the new urban railway, some statistical forecasts of population and workplaces, developments in car ownership, travel cost and travel time, capacity restrictions in rush hours, etc.

After run the assignments for different scenarios the minimetro alternative was the best option for Copenhagen and after other studies the metro was developed.

In the following chapters it will put more emphasis in these studies and why the metro was the best option for the new transport mode.

Once the metro was chosen, further studies were carried out to figure out what the metro line could offer in a future in terms of traffic improvements into the network. That means market shares analysis between the different modes using the third step of the model and different assignments to see whether the traffic road inside Copenhagen would decrease or not.

Moreover, a traffic induced model was done to locate the stations, each one with its catchment area to provide the passengers with the best facilities.

1.1.2. Train simulation

The purpose of this course is to obtain an overview of the infrastructure elements of a railway network and apply the methods that are used for planning and operation of railways, in a theoretical way, but also in a practical.

The theory is based in basic concepts such as capacity, timetable, punctuality, simulation and infrastructure and safety elements.

The practical consequence of all the theoretical elements is shown under the software RailSys, which consists of three sub programs: Infrastructure Manager (STED) used to construct the infrastructure, Timetable and Simulation Manager (SIMU) which is used to create the timetable and finally Evaluation Manager (PE) used to analyse the possible operation troubles that are affecting the timetable.

When talking about the calculations of railway traffic, it has to take in account that these are different from the road traffic. First of all due to the travel time, where no congestions are occurred in railways, and secondly in terms of capacity conditions.

A second division can be done by train types, between passengers and freight trains. Due to the different characteristics, the discussion for each one will be different. An again, a third classification of train passengers could be given as: high speed trains, regional trains, peak hour trains and suburban lines, with a different deal for each one. (Ref: Course 13122, chapter 1)

1.1.2.1. Capacity

The word capacity can be defined as the number of passengers per train, but also in different ways as the capacity of a line (number of trains per hour in the line) or even the capacity of all the network and it can be analyzed from different points of view:

- Capacity demand required for the operators
- Technically possible capacity
- Capacity conditions

The capacity demand is done by three characteristics: requirement, sequence and train characteristics, and frequency. (Ref: Course 13122, chapter 3)

The possible capacity can be distinguished between the maximum (K_{\max}), the fundamental (K_{gr}) and the available capacity (K_{disp}).

Finally the capacity conditions analyses the correlation between the traffic intensity and the quality, both for operation and timetable quality, in terms of speed, punctuality and safety requirements.

Basically, the capacity can be described as:

$$K = q_{\max} \cdot n \quad (\text{trains/h})$$

Where q_{\max} is the maximum traffic intensity and n is the number of train paths.

But it is easier to analyze and compare with other modes of transport if this is done by the number of passengers transported: (Ref: Course 13122, chapter 2)

$$K_{\text{pass}} = N \cdot q_{\max} \cdot n \quad (\text{pass/h})$$

Where N is the passenger capacity of the transportation unit (pass/train).

It is also very important the technical limitations done by the infrastructure and the traffic regulations given by the safety procedures to calculate the capacity. A line is divided into block sections to ensure that there is enough space between consecutive trains. Each block section has its signals to provide the minimal safety conditions and to avoid possible accidents. Hence, the capacity is restricted to these block occupation times and it is related to the headway time, which is the time interval between the passing of the front ends of two consecutive trains moving along the same track in the same direction. (Ref: Course 13122, glossary)

The lower is the headway time reaching the minimum allowable one, which means no buffer time, the higher is the capacity.

1.1.2.2. Timetable

When talking about timetable it is indispensable to think about the level of service that the society needs. Although it is impossible to find the optimum timetable, the train operator tries to do the best, both for him and passengers. Sometimes is pretty difficult to find the equilibrium due to the different necessities. Train operator wants a good location and an important level of safety for the operations, among others. Customers want a good location as well, but also punctuality, good frequency, a timetable easy to remember, good correspondences, high speed, etc. Hence, the passengers are stricter and actually the timetable has to fulfil their expectations.

However, as each customer has different requirements and necessities, it is impossible to satisfy all of them for equal and the operator must do an average within a plan of operation, getting a candidate timetable that will be the basis of the final timetable. Next figure shows the limitations influence for each pattern.

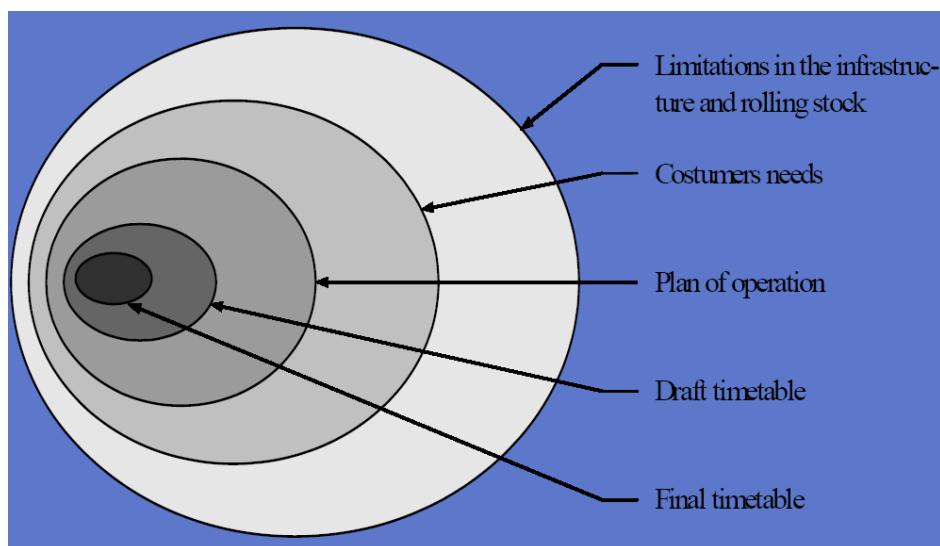


Fig. 6. The planning process in case of timetabling.

In a timetable evaluation there are different quality parameters that have to take in account: (Ref: Course 13122, chapter 7)

- High regularity
- Direct connections
- Good transfer conditions
- Regular departure schedule
- Short travel time
- High departure frequency

All of them are important and some points are conflicting between others. For that reason equilibrium is found to make the timetable.

Once the timetable is established and the trains are running in a normal operation with a certain capacity, the improvement of the line is always in discussion. Everyday users are more demanding in terms of quality and quantity, and this railway capacity is one of the points to be improved. That means universal and transparent capacity consumption calculation method.

1.1.2.3. UIC code 406

One of these calculation methods was defined by the International Union of Railways (UIC). This Union adopted a code called 406, in June, 2004, dubbed UIC CODE 406. The purpose of this code is to calculate the capacity consumption by using a pre-constructed timetable on a given infrastructure, as this a basic necessary condition for the capacity examination. The timetable must be real operation or it could be a case study one. For a given infrastructure, headways between the trains can be calculated by providing layout and signalling of a line.

The code also aims at providing a more basis to schedule more trains at high quality standard levels as well as providing a common view on different types of the lines with aid of simulation. As specified in the code, capacity consumption is analyzed within a line section by compressing timetable train paths in a pre-defined time window, as this varies according to time of day, weekday and season.

The basis for compression is one representation day over a peak period of at least two hours and this shall be fixed by reference to the purpose of analysis. Furthermore, effects on neighbouring line sections as result of this compression are not accounted for. This is because, compression is carried out on a limited line section as specified in the code.

However, during compression, all train paths are pushed together up to attain the minimum theoretical headway with respect to the order of the timetable without recommending any buffer time and this is achieved by either constructing graphical analysis or analytical situation. The rules for this compression described in UIC code 406 will be that, neither the running times nor the overtaking crossings or stopping times is changed. (Ref: Leaflet of UIC code 406)

1.1.2.4. RailSys

The practical part of the course is to know the applications of a train simulation program, in this case RailSys program, and try to apply the theoretical concepts in it.

RailSys was developed by Rail Management Consultants in Germany and even though it is a quite new train simulation program, it has been already used in several countries to develop their railways networks, include Denmark, where for example Banedanmark and Atkins use it.

RailSys is a software system for analysis, planning and optimization of operational procedures, and their applications are really wide: (Ref: www.rmcon.de)

- Timetable construction and modelling
- Running time calculation
- Planning of capacities
- Infrastructure planning
- Scheduling possessions and planning of special traffic
- Planning of logistic concepts for large scale projects
- Design, investigation and registration of timetables
- Validation of nationwide basic interval timetables
- Investigation of operational quality, punctuality and guaranteed connections
- Completion of disposition strategies in cases of delays and operational disturbances
- Cost-benefit analysis

As explained above, RailSys is divided in STED, SIMU and PE sub programs. Each one has its own purpose and procedure.

STED is used to construct the infrastructure. That means all the elements that take part into the physical infrastructure such as nodes, links, signal system and block sections, overlaps, speed boards, stations and stopping locations, platforms, standard routes and so on.

SIMU is useful to create the timetable. First, train characteristics, number of them, dwell times and other information are given, and secondly the timetable is created. Railsys program deals the railways analysis as real as possible. Hence, delays and other important contraindications for the good operation are created. Once the simulations are made, the analysis of them is done within the PE, which tries to give graphical results for a better interpretation.

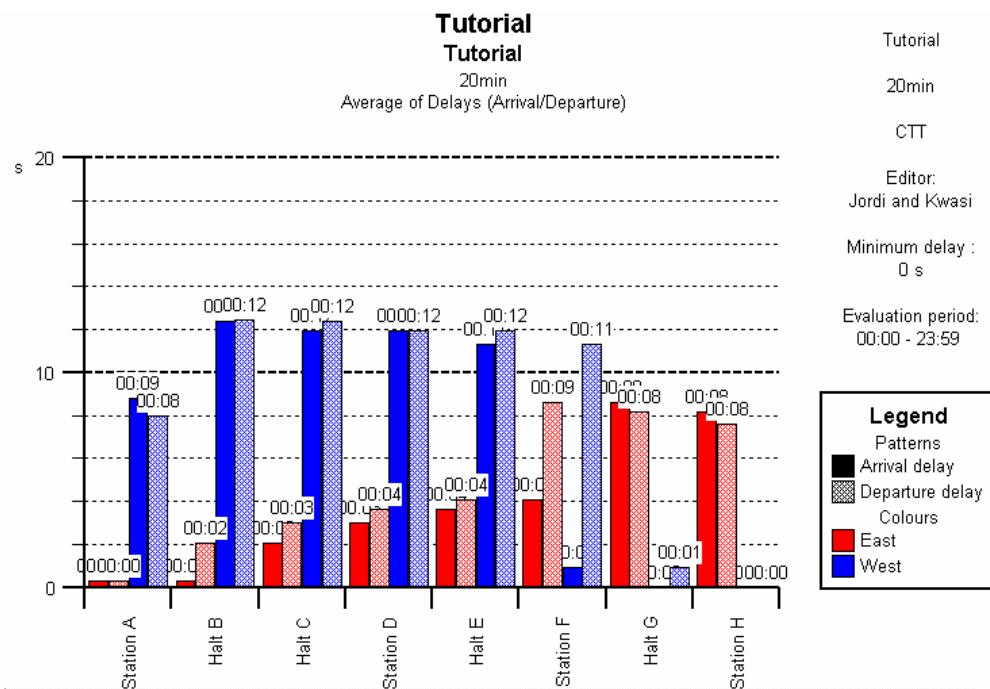


Fig. 7. Example of a graphical interpretation using Evaluation Manager (PE).

1.1.2.5. Application to the metro

Although the planning process in a railway system is more complicated than the metro due to the more complexity of the network and its elements, most of the methods and tools are also used when developing a metro system.

In a regular railway line where the safety system can not determine the position and speed of the trains more clearly than the specific block section, and where different train classes are fitted into the network, the practical headway time obtained is about 3-4 min/train. (Ref: Course 13122, chapter 2)

In metro lines, this headway time can be reduced, as there is only one type of train and the technical and safety system is normally more advanced. Thus, the operation system of the Copenhagen metro reaches a headway time of 90 seconds/train.

Using the capacity formulas explained above, the capacity of the metro line can be calculated. Taking a headway time of 1.5 minutes/train, it means 40 trains/hour, and knowing that the passenger capacity of the transportation unit (N) is approximately 300 passengers:

$$K_{\text{pass}} = N \cdot q_{\text{max}} \cdot n \quad (\text{pass/h})$$

$$K_{\text{pass}} = 300 \text{ pass/train} \cdot 40 \text{ trains/h} \cdot 1 = 12.000 \text{ pass/h}$$

Comparing this result with the capacity of the suburban trains, where they can transport 800 passengers/train and the minimum headway is approximately 2 minutes, obtaining a capacity of 24.000 passengers/h, it can be observed that is the double of the metro's capacity, even having a higher headway time.

However, the passenger capacity of the metro is much smaller than the suburban trains, because of their length. Metros are only 40 meters long, while suburban trains are double.

The Copenhagen metro is the first driverless operated train system in Denmark. With this fully automatic control system there are many advantages: trains can be split up into many shorter trains with more frequency and consequently, there will be shorter waiting times for the passengers in the stations. The automatic operation also reduces the risk of human error.

All the safety system of this automatic train operation will be discussed later on, explaining how it is working and the advantages of the driverless operation.

The good point of the Copenhagen metro in the planning process is that, with such a high frequency (headway times of even 90 sec/train), metro's users do not need a timetable. People know that the waiting time in the station will be so short that they will catch the metro whenever they want, without any delay in their organization. Hence, the metro operator has to care only about the time periods that metro will run during the day, the frequencies during rush hours and non peak hours and the stopping times in the stations.

Although no timetable is needed, simulations and further capacity analysis must carry on to ensure a good operation during its implementation. HASTUS, a simulation and transit scheduling program was used in the Copenhagen's metro. This Canadian program was created in 1979 and the good point is that the data can be mixed with some Geographical Information System (GIS), which makes easier the interpretation of the results. Aside from transit scheduling, customer information and daily operations are taken into account.

1.1.3. Arc GIS for Master Students

The aim of this course is to obtain an overview of the functionality of the Arc GIS program and analyze the different applications of this program within transport planning. Theoretical concepts are taught to develop them later on through this software. Also general information on how to deal with databases is given, especially in Access program.

So far, how to use the assignment model with special attention to Car Assignment, mobility, accessibility, induced traffic and Cost-Benefit analysis are most of the theoretical part of the course.

GIS is the abbreviation for Geographic Information System, which means that you will have as much information as possible from a region in your computer. And what is really interesting about using GIS tools is that you can mix information from databases with digital maps so then is much easier to understand and have a better idea of what you are working with or what you are looking for. For example, if you are talking about population densities is much understandable a digital map with different colours depending on the amount of density instead of a database with different numbers for different zones with a different ID for each zone. It is very useful also when talking about things like noise calculations or influenced areas, which are very difficult to be seen in a database but very easy understandable in a drawing.

GIS is being applied in many ways. Some of the applications could be agriculture, defence and intelligence, emergency management and public safety, environmental management, forestry, health care, oceanography, coastal zone and marine resources, telecommunications, water resources, transportation, etc.

Transportation, of course, is the application of this course and there are a lot of analysis that could make with ArcGIS, specially studies of road traffic. For example, how the traffic influence over the network with the construction of a new freeway, how to detect bottlenecks in the road network during the peak hours, etc.

Arc GIS program can be divided in three sub programs: ArcMap, ArcCatalog and ArcToolbox. With ArcMap it is possible to visualize the infrastructure, make queries with data and make the analysis of this geographical data. ArcCatalog is more a data organization to manage it in a easier way and it generates data if it is necessary. Finally, ArcToolbox permits the conversion of data and the geoprocessing. Here, Car Assignment is located. (Ref: Course 13165, Introduction to GIS)

As it was explained before in traffic models course, Car Assignment is a Stochastic User Equilibrium model. First of all, a model for each period of the car assignment has to be constructed. Different inputs like links, link types, traffic types, Car Assignment parameters, OD matrix, centroids, connectors and finally the number of iterations to run the model. The Car Assignment tool is within the TrafficAnalystToolbox and as a result, four outputs are obtained. Hence, it is possible to represent graphically some information such as the traffic load in the roads using lines with different thickness, the traffic on the connectors, etc. However is not possible to have a graphical representation of different values, like value of time (VoT), the traffic's costs, etc.

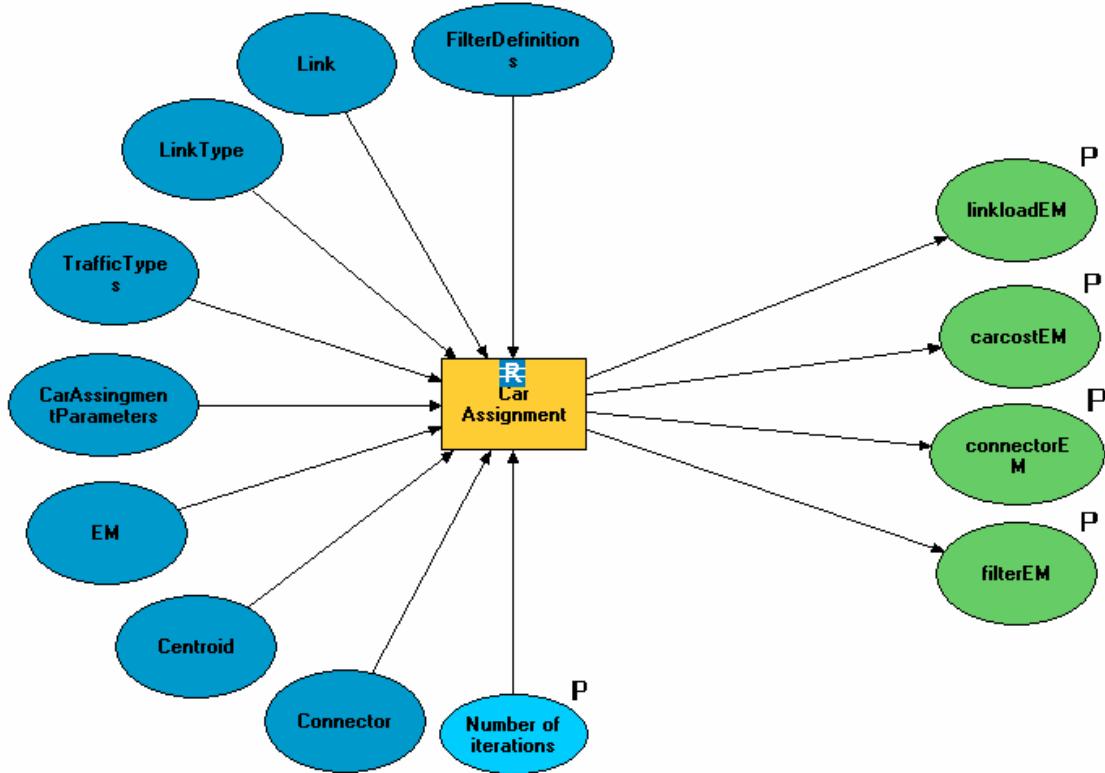


Fig. 8. Car Assignment model

Aside from the 5 time periods, 5 different categories are studied, depending on the type of trips:

- Category 1: Home/Work
- Category 2: Business
- Category 3: Education and spare time trips
- Category 4: Vans
- Category 5: Trucks

The reason to separate the traffic in five categories is because each one has its own preferences and characteristics. Hence, commuters and freight may have better knowledge on the road network than other travellers, business travellers have usually a higher value of time than other travellers, truck accelerate, decelerate and turn slower than passenger cars, demand models have typically multi class structure and finally traveller influences each other across trip purposes, due to capacity. (Ref: Course 13130, week 9)

Traffic and congestion analysis using maps are really useful to find troubles in the network. Hence, a road can have a lot of traffic but a good capacity, which makes a non congested road. On the other hand, a small capacity with less number of cars can be a bottleneck in the network.

There are different ways to calculate the congestion using the capacity, the speed or the travel time.

For example, capacity congestion is calculated by the next formula:

$$Con = \frac{\text{TrafficLoad}}{LHCapacity \cdot Time \cdot N^o Lanes}$$

Where:

TrafficLoad: number of cars in each road.

LHCapacity: Is the capacity for each lane per hour.

When talking about mobility and accessibility, the first difference to understand is that mobility refers to individual beings while accessibility is something to do with a region, area town, etc.

There are many definitions for both concepts but the most used ones might be:

- Accessibility: How many people can reach a specific location in a specific quantity of time?
- Mobility: how far can a person travel from one point within a given time frame? And extending the definition, not even how far but how many households or workplaces can be reached? (ref: Course 13165, Accessibility and mobility)

They are both related to the quality of the network, thus a properly connected network will assure the possibility to travel fast to your destination which turns into an increase of both issues.

Hence, the accessibility of one zone is interesting as it reflects how attractive it is to locate businesses with respect to employees and customers as suggest how many people can reach that zone in a particular.

It is important to notice the accessibility and mobility must not be taken in absolute values but they need to be in comparison with some external factor.

There must be a factor that correlates them that can be the size of the area that is being studied, the population of this area, the workplaces, the total traffic going away, etc.

For instance, an increase of 100 trips to a zone with 10.000 people can not be treated in the same way of an increase of the same number of trips to a zone of 1.000 people, or an increase of 100 trips to a zone with an area of 100km² is not equal to an increase of 100 trips to a zone with an area of 1.000km².

Furthermore, they should be studied not only during the peak hours but also for the rest of the day.

When a new infrastructure is implemented further studies are taken in account, within the Cost-Benefit analysis (CBA): construction cost, maintenance cost of the infrastructure every year, time gains in the network by the users, driving costs, accidents, some environmental aspects like noise and pollution known as social costs, expropriations, etc.

CBA is a widely applied method for evaluating the “goodness” of public investments as well as for ranking alternative investments. In short, the basic feature of CBA is the comparison of costs and benefits, which are all measured on the same scale: that of monetary units. (Ref: Course 13165, Trafiksystemanalyse, F2002, Cost-benefit analysis) CBA is based on welfare theory, which assumed that each consumer makes choices to maximize his/her own welfare. A utility function is used to represent this welfare and the sum of all utility functions for each user gives the “utilitarian welfare function”, which represents the welfare of the society as a whole.

Actually, the utilitarian welfare function does not care about individual utility functions. For example, a society with two consumers A and B, where A has a positive worth of his welfare of 1000 DKK and B has a negative of 800 DKK, the social welfare function

will have a 200 DKK positive worth. Even though B loses welfare, the society has a positive value.

Once all benefit and cost elements have their own monetary values, there are different ways to calculate the social profitability of a project:

- First Year Rate of Return
- Net Present Value
- Benefit Cost Rate

Next figure shows an example of a mobility map created with ArcMAP application in the Greater Copenhagen area.

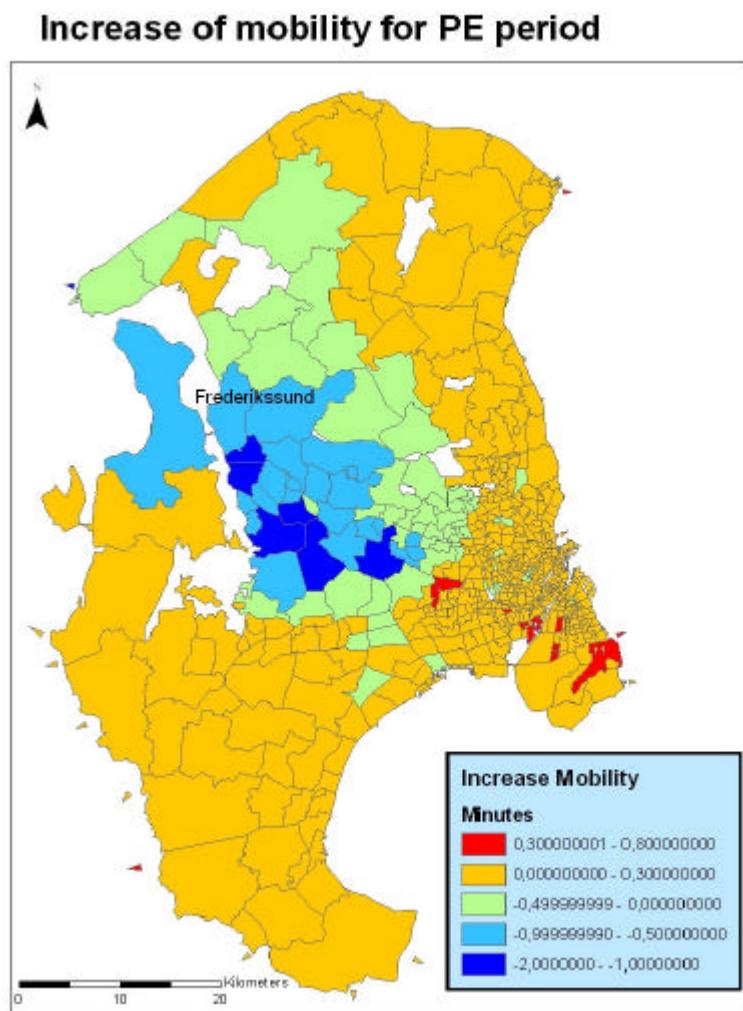


Fig. 9. Example of a digital map

1.1.3.1. Application to the metro

Although the applications of ArcGIS for this course have been aimed at road traffic, they can be also applied for the planning system of a metro line.

The Copenhagen metro connects the west of the city with the east part to the future Ørestad city and the airport. This is a new link connecting these two points and unique for its exclusive right-of-way.

For that reason, analysis of mobility and accessibility could do before and after the implementation of the metro, but also analysis for the road traffic involved in the influential area of the metro, both for private transport and bus traffic. Intuitively, the construction of the metro line should decrease the traffic inside Copenhagen and should improve some of the congestion problems. That is not so easy to see without assignment models and graphical interpretation of the results. Hence, ArcGIS is a good tool to make deeper analysis.

Maps of density population can be useful when planning the layout of the line, always thinking in future developments. Thus, it would not have sense to build a metro line in Ørestad region without the future urban planning development that Copenhagen wants to do in this area.

On the other hand, Cost-Benefit analysis is done for the metro planning at all levels. First of all when the idea to construct a new urban railway came up, three types of rail transport were analyzed, as explained before, doing a CBA for all of them. Accidents, inconvenience during construction, environment and general economy were some of the studied points.

These studies, together with traffic analysis, were used to choose the metro as the best new urban railway. After that, deeper analyses were made to evaluate the profitability of the infrastructure, both for short and long term periods.

The connection between the metro line and the future Ørestad city, as well as the social analysis of the infrastructure, will be developed later on within the next chapters. Although it would need a complete Cost-Benefit analysis to draw conclusions, due to the language, as most of the information is in Danish, the social economic effects of the construction of the metro line will be explained only in a qualitative way.

Thanks to geographical information systems, it is possible to combine photomaps with the layout of the metro, etc.

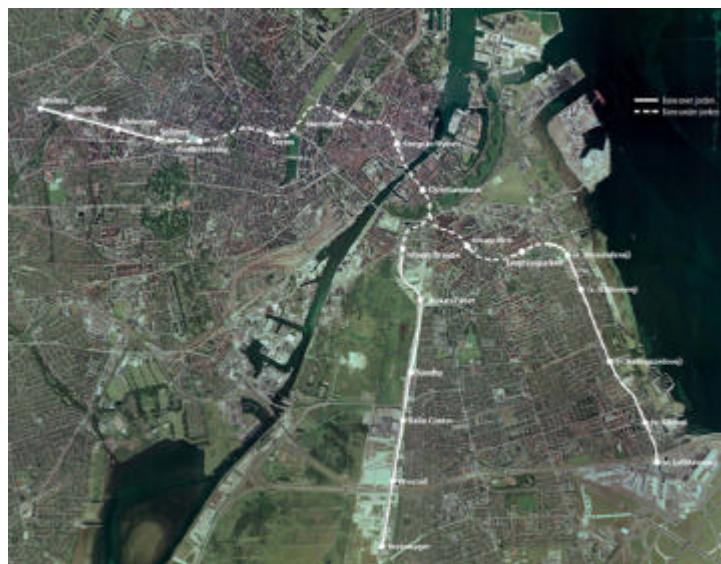


Fig. 10. Copenhagen city map with the metro's layout. (Ref: www.orestadsselskabet.dk)