# MULTIMODAL TRANSPORTATION SYSTEMS: MODELLING CHALLENGES

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February, 2012

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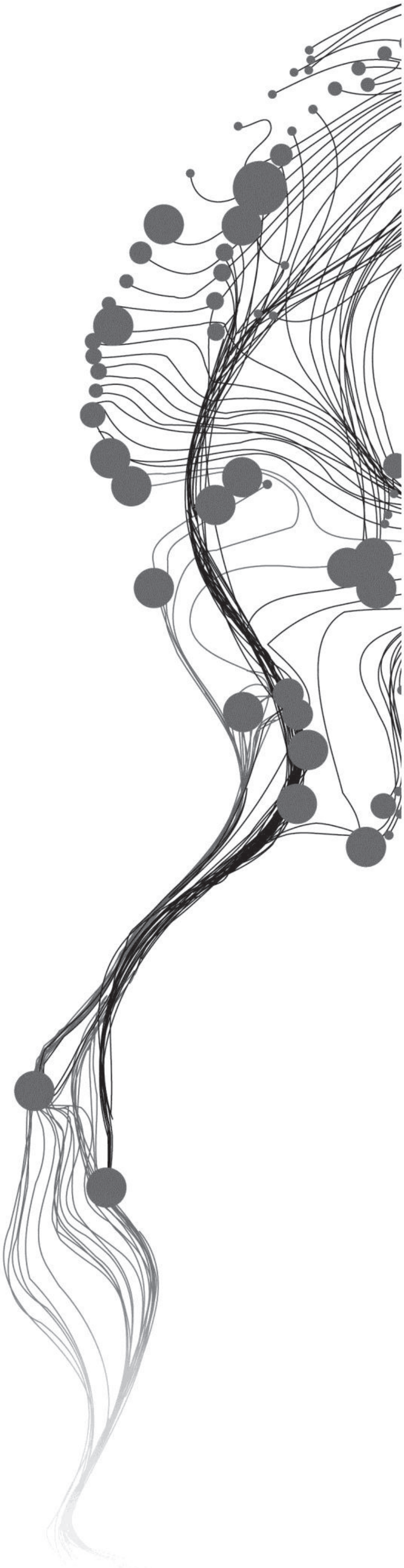

# MULTIMODAL TRANSPORTATION SYSTEMS: MODELLING CHALLENGES

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# ABSTRACT

Human mobility within an urban usually happens over a multimodal transportation network. For that reason, when studying, analyzing transportation systems we should not consider each mode of transport separately but we should look to it as multimodal transportation system with relations and dynamics between its components

In order to do any analysis related to transportation we need a model reflecting the multimodal nature of the system. The objective of the research is to develop a GIS data model for a multimodal transportation system combining different modes in one network that allows different modal combination in route planning.

The modelling concept adopted in this research is formulated by exploring the different GIS modelling techniques for multimodal transportation from literature, and experimenting with them. It consists mainly on having a separate entity (layer, feature class...) for each mode route representing this mode's network. Modes networks are physically separated from each other. The separation is vertical for different modes and horizontal for the different routes of the same mode. Connecting these separated entities is done through connectors entities representing the transfer action from one route to the other. The concept is applied at ArcGIS platform.

The effectiveness of the data model suggested is evaluated by developing a multimodal transportation network model for Enschede city incorporating bus, train, cycling and walking modes and performing path finding analysis with the developed network model.

The model developed has proved satisfaction in finding route over a multimodal network using the suitable modal combination that achieves the least cost path. The developed model is also able to simulate all the possible transfer scenarios between the integrated modes and to integrate the cost associated with the different elements, the cost of travelling and the transfer cost. The whole route details including the step by step directions and the detailed as well as the overall cost are also provided with the route.

Beside the path finding type of analysis, the data model presented in this research can be a platform for other transportation network based types of analysis.

# ACKNOWLEDGEMENTS

When thinking whom to acknowledge at the beginning of my Thesis, I came across a long list of people. I felt lucky having all those supporting and giving people around me throughout my life.

I would like to express my gratitude to all the teachers who ever tough me since my early age to this point of life, to my supervisors, to all the supporting friends I have, to my brother and sisters, to the greatest Mum and Dad and before all, my ultimate gratitude goes to Almighty Allah.

Reem Fawzy Abdelmoniem Mahrous
Enschede, February 2012

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# 1. INTRODUCTION

## 1.1. Background and Rational

People move continuously in space from origins for a purpose or to engage in an activity at destinations. Trips are made using different means of transport that can be motorized or non motorized modes of transport. Motorized like cars, trains, buses and non-motorized are basically walking and cycling. Trips are seldom made by only one mode of transport what is known as unimodal trips. On the contrary, according to Liu (2011) the human mobility within an urban area actually always happens in a multimodal transportation network. People use more than one mode of transport to reach their destination because of many reasons.

Each mode of transport has its weaknesses and strengths and using a combination of modes potentially cancels their negatives and maximizes their benefits. For example, cycling although its high spatial penetration range as you can reach almost everywhere with a bike, it is cheap and environmentally friendly and can be used throughout the day but distance travelled with a bike will remain limited because of the bike limited speed and the associated physical effort. On the other hand, public transport has almost unlimited travel distance range but it lacks flexibility because its dependency on a fixed schedule and no matter how large is the coverage of a public transport system it will never serve every commuter from door to door (Zuidgeest et al., 2009).

Furthermore, some unsolvable problems with only one mode if considered from the multimodal point of view can be solved. For example, finding a motor route to a location in a pedestrian only area is not possible. A pedestrian only route to this location would be too time-consuming. So following a double modal faster route provides a better solution. A route that uses a combination of a motor mode and walking like driving to the nearest parking lot to the location then walk to the location inside pedestrian area (Liu, 2011).

Therefore when studying, analyzing a transportation system we should not consider each mode of transport separately but we should look to it as multimodal transportation system with relations and dynamics between its components. But what is a multimodal transportation system?

### 1.1.1. Multimodal transportation systems

A multimodal transportation system as defined by Bielli, et al.(2006) is “the combination of all traveller modes and kinds of transportation systems operated through various systems”. From this definition we can distinguish the main elements of a multimodal transportation system as:

- Travellers
- Different modes of transports
- Different operators.

Dewitt and Clinger defined it from the perspective of the movement or the trip. According to them, a multimodal urban transportation system can be defined as “the use of two or more modes involved in the movement of people or goods from origin to destination”(Dewitt & Clinger, 2000). However, the focus of this research is only travellers’ movement.

Components of the multimodal transportation system can be distinguished as: modes of transport routes and lines and the infrastructure network they operate on from one side, and on the other side the movement of the travellers. The intersections of these components bring the concepts of transfer and transit.

Transfer points are the points that connect the modes' networks together in one larger network and where travellers can change mode. Transfer is the core concept of multimodality and what makes the multimodal system different than considering each mode separately.

From that we can say that a multimodal transportation system is **a set of choices of modes of transport which travellers can use with different combinations according to their needs and preferences to reach their destination.**

### 1.1.2. The need for modelling movements in a multi modal transportation system

The focus of this research is the modelling of these sets of choices (modes of transport networks), their interactions, and intersection in order to provide travellers with a tool to plan their trips and preset their choices. Commuters need improved means to solve the problems affecting their journey in a multimodal context aiming to find the optimal route between the source and the target of the trip using different modes of transportation (Wang, Zhang, Hong, Guo, & Yu, 2009). Providing commuters with path finding options or the optimal route with the least cost as well as the overall travel cost is expected to help in trip planning and route choice. Such information can only be obtained by a model encompassing all modes in one network. Incorporating all the modes in one model with all possible change between modes and with different travel costs (distance, time, money, effort) can help people take travel decisions, whether to the travel using a single mode or multiple modes, to follow a shortest distance route to the destination or take a route that minimizes the total travel time, or to take the route with the least effort. According to Mandloi & Thill (2010), A GIS data model supporting route planning in an urban area is effective if it is able to model these scenarios.

The same concept is also applicable for other types of flow that use transportation networks like goods and information, only the preferences are different. But the focus of this research is on people.

On the other hand, such model can act as a decisions support tool for transportation policies such as introducing new routes or line for a specific mode of transport in the overall performance of the transportation system of an area. A range of other functionalities can also be done with a model for multimodal transportation system like assessing accessibility of an area or the service area of different facilities (health, educational) over a multimodal network. However, the focus of this research is the route finding functionality.

### 1.1.3. GIS and transportation modelling

Among all the supporting technologies of transportation and navigation, Geographic Information Systems (GIS) always plays an important role (Liu, 2011). GIS as a powerful tool for geospatial data management; visualization, presentation and analysis are widely used to model transportation networks (Mandloi & Thill, 2010). The literature chapter (chapter2) reviews other capabilities of GIS making it a suitable platform for such a modelling task.

Most of commercial GIS software contains packages which solve the conventional route planning problem, but without taking into account the integration of multiple transport modes. Also, some of route planning systems are making efforts to integrate more transportation modes, e.g. Google Maps added "Walking", "By public transit", and "Bicycling" options besides "By car" in its Get Directions function for some areas but still the route planning is performed separately for each mode, i.e. one mode at time (Liu, 2011).

For that a mode that integrates all the modes of the transport system of an urban area in one network is believed to be capable to define routes between origins and destination, over the network, making use of different modes in order to find the route with the least cost.

## 1.2. Research problem

How to develop a model for the multimodal transportation system of an urban area using GIS? A model capable of supporting route planning over a multimodal network by finding the route between a pair of origin and destination on the network; making use of all the available modes and allowing all possible transfer between modes to find the route with the least cost.

## 1.3. Research objectives

### 1.3.1. Aim

To develop a GIS data model for a multimodal transportation system that combines different modes of transport in one network and mode all the possible transfers between the modes such that it can assist in route planning.

### 1.3.2. Sub objectives

1. Understanding the components and relations of a multimodal transportation system
2. Reviewing existing techniques used in modelling multimodal transportation and evaluate them
3. Determining the appropriate key modelling concept(s) to be used in developing the model
4. Building the model
5. Operationalize and test the model

## 1.4. Research questions

1- **Understanding the dynamics of a multimodal transportation system**
   - What are the key components/elements of a multi modal transportation system?
   - What are the key relation/interactions between the system elements?

2- **Reviewing and evaluating existing techniques used in modelling multimodal transportation**
   - What are the main existing approaches used in modelling multimodal transportation in a GIS environment?
   - What are the shortcomings/benefits for each approach?
   - What are the suggested improvements (if any) proposed?

3- **Determining appropriate key modelling concept for a multimodal transportation system**
   - What is the approach (or combination of techniques) to be adopted in building this model?
   - What is the suitable technique to model transfer between different modes and within the same mode?
   - How to integrate different impedance associated to different transfer types?
   - How to incorporate different attributes associated to modes and transfer points in the system (travel impedance, transfer impedance, passenger preference for a mode…)?

4- **Building the model**
   - How to implement the techniques determined in previous stage to build the model?
   - What are the functional requirements for the model?

5- **Operationalize and test the model**
   - What are the modes of transport in Twente region?
   - Is the model able to find route using different combination of modes?

- Is the model capable to perform the different transfer possibilities between the modes?
- Is the model able to determine travel cost for the provided route?
- Are all the provided modal combinations logic?

## 1.5. Conceptual framework

From definitions reviewed in section 1.1.1, multimodal transportation system main components can be identified as: modes operating on infrastructure network and travellers moving from origin to destination using these modes. So, logically speaking, three conceptual layers can be defined in a multimodal transportation system.

- Physical level: encompassing infrastructure network (streets network, train railway network, metro railway network).
- Transportation level: in which elements of modes of transport are defined. Transportation modes operate on infrastructure network. Modes routes are delineated based on existing infrastructure. Train railway is the train route instead of just its physical existence. Roads are detailed to its modal functionalities. Roads represent: bikes lanes, car paths, bus lines and pedestrian sidewalks. Also different stations, stops, terminals and parking are present in this layer.
- Movement or trip layer: in which people use the previous two layers to move from origin to destination with different combinations according to their preferences and characteristics.

combining all these components in a GIS model representing multimodal transportation system is the objective of this research (Figure 1-1).

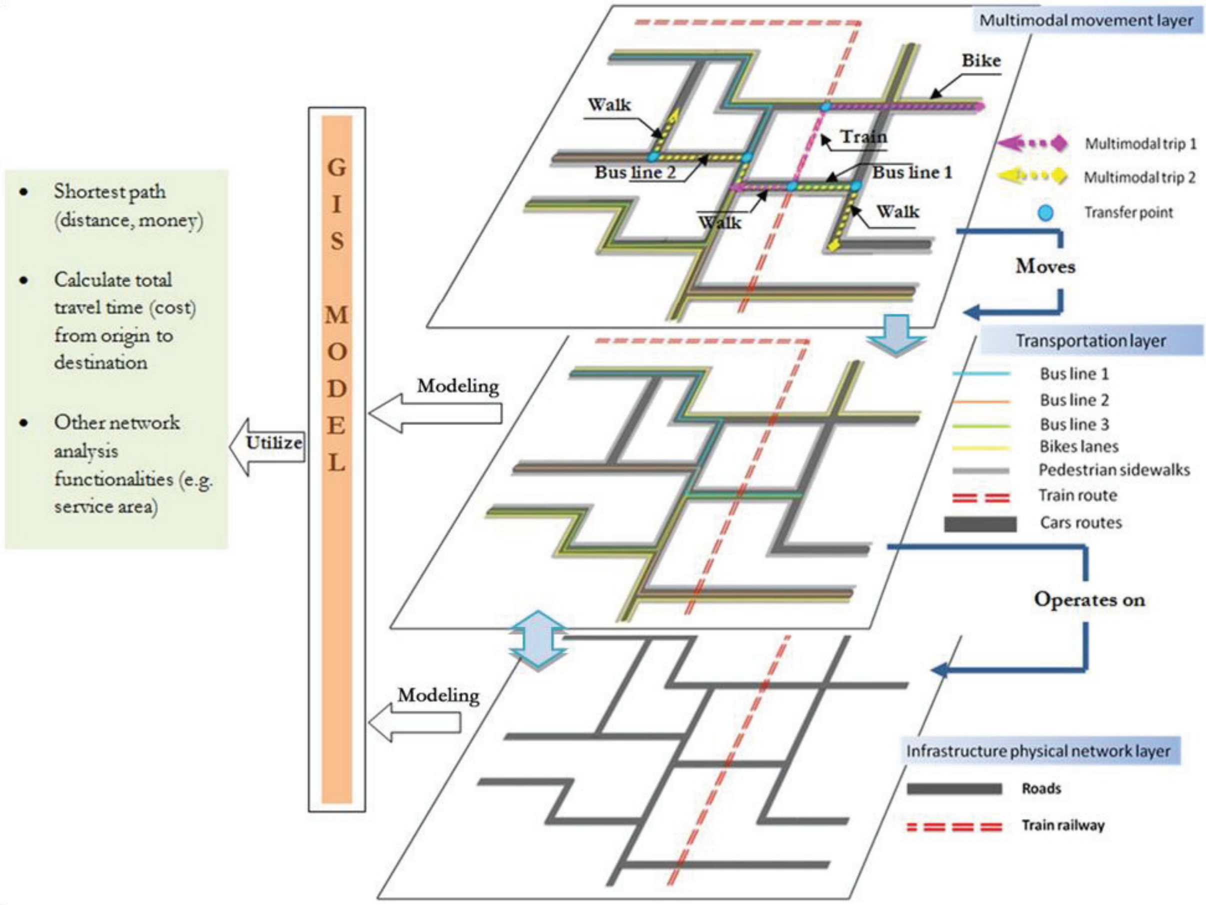



Figure 1-1: Conceptual representation of a multimodal transportation system

## 1.6. Operational plan and research design

Figure 1-2 shows the operational plan of the research as well as steps and methods used in answering research questions and reach the objectives.

First stage of the research is concerned with sub objectives 1 and 2. It will be conducted by reviewing literature in order to answer two categories of questions: The First related to sub objective 1, about defining and understanding the components of a multimodal transportation system and how they interact (i.e. Modes networks, routes and the transfer action). The second category related to sub objective 2, discusses existing models for multimodal transportation systems, reviewing the approaches mentioned in literature and the techniques used in modelling this kind of systems and the suggested improvements in order to choose the techniques to be used later on in developing the model. This is the scope of literature reviewing in chapter 2. Once the techniques are chosen, the model functional requirements are subsequently identified which lead to the second stage of the research.

The second stage of the research is about incorporating the different techniques found in literature into one modelling concept (sub objective 3 and 4). This is the scope of chapter 3 (Methodology and modelling concept) discussing the modelling concept adopted in the research in details.
Existing GIS software will be used in building the model because they have already ready and standard tools capable of helping in preparing the data and providing basic network analysis functionalities. As platform ArcGIS developed by ESRI will be used. It is a widely used GIS system with basic network analysis functionality which can be used as base for the model under research.

The third stage is about testing the model workability in a real life case. Chapter 4 (Implementation), reviews the process of implementing the modelling concept discussed in chapter 3 with Enschede dataset. Available data of Enschede transportation modes will be prepared to fit the model requirements. A multimodal transportation model will be implemented using synthetic data of Enschede city considering the city local bus lines, bikes' paths, pedestrian sidewalks and the portion of the railway system serving the city (sub objective 4).

Integrating cycling in the transportation network is one of the key stones in this research that was the main reason for choosing Enschede (as a Dutch city) data to implement the model. Having its own infrastructure (bike lane network) and high rate of usage, cycling is one of the main components of the transportation system in Netherlands what will make the developed model of importance more than in the case of another place where people don't depend on cycling as much as Dutch cities. Another reason is that the transportation system works following fixed rules in operation (e.g. bus only stop at bus stops) which make it easier to define the modelling rules.

The fourth stage of the research will be the operationalization and testing of the model (sub objective 5); the main functionality to be tested for the model is its ability to find route with the least cost with different modal combination, also to be flexible to allow all possible changes between modes. For a pair of source and destination, least cost route is identified and the total travel cost(s) are calculated. Chapter 5 (Results) shows some outputs routes of the modes showing it ability to perform all possible modal combinations and modal transfer.
Finally chapter 6 (conclusion and recommendation) reviews the research conclusion, limitations and recommendation.

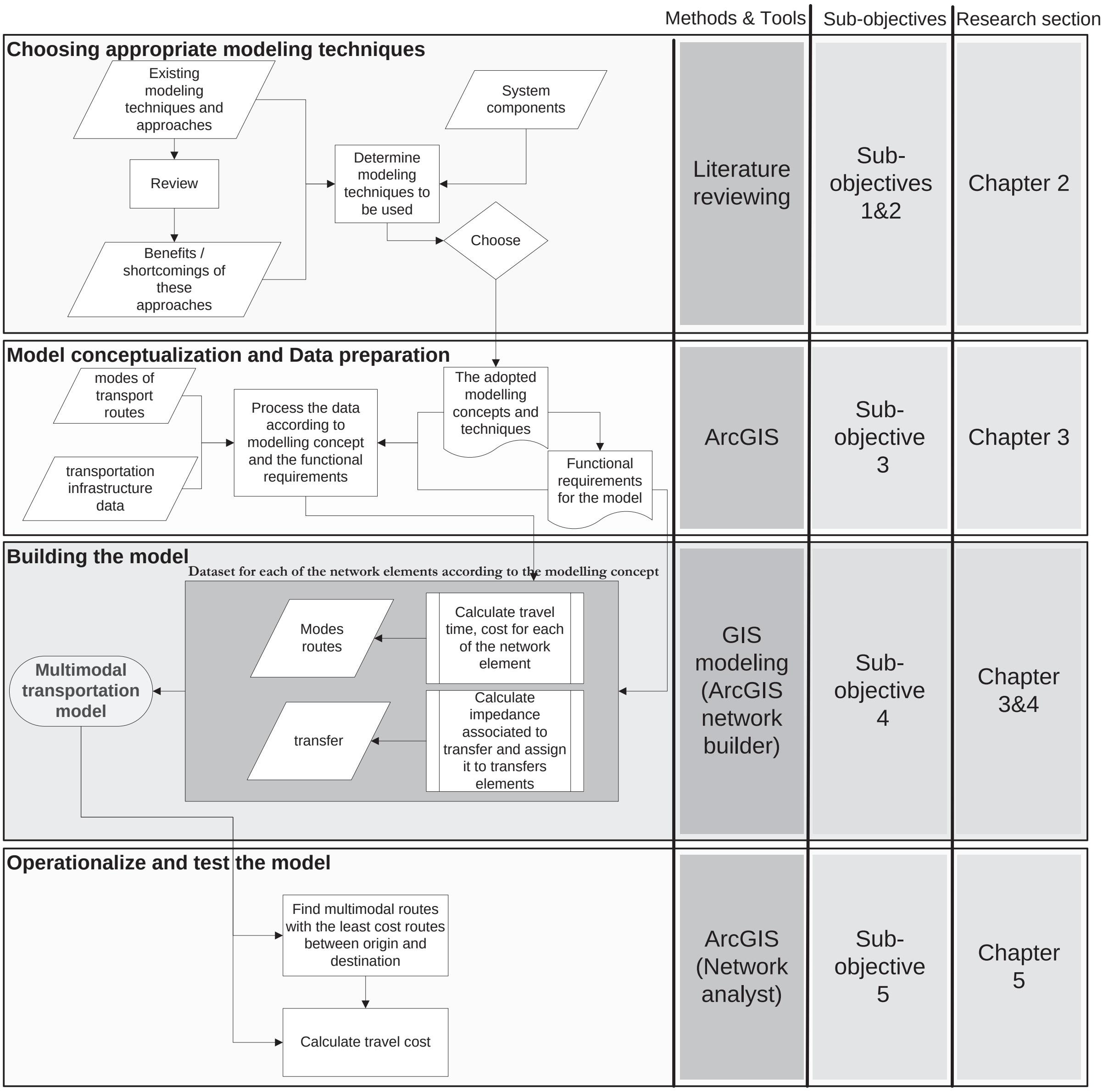



Figure 1-2: Operational plan

# 2. MODELLING MULTIMODAL TRANSPORT AND GIS

## 2.1. Introduction

This research is about modeling multimodal transportation systems using GIS. But before multimodal transport systems can be modelled within a GIS environment it is necessary to clearly describe and define the different aspects which do play a role.This chapter will review these different aspects in three sections. The first section discusses transportation systems generally then focuses on the multimodality nature of the system. After that multimodal transportation systems' components are reviewed to be able to model them in a system, its components should be identified and understood. The second section discusses the role that GIS can play in modeling a multimodal transportation system, benefits and challenges. The final section reviews some approaches and techniques discussed in literature to model a multimodal transportation system with GIS and concludes on the usefulness of these approaches.

## 2.2. Transportation systems

Generally, transportation's main goal is to change the geographical location of freight, people or information, from an origin to a destination (Comtois, Slack, & Rodrigue, 2009; Liu, 2011).
Hensher & Button (2001) argue that a transport system is too complex to have a clear and straight forward definition as it depends on the perspective. It can be seen from the modes of transportation point of view, by the different infrastructures point of view, the operators or by the users point of view (Zuidgeest, et al., 2009).

Some authors described a transport system in terms of its components. Tolley & Turton (1995) define transport system as "the assemblage of components associated with a specific means of transport". The components of the transport system are: network, routes, nodes and terminals. The network is defined as "the framework of routes within a system" while a route is "simply a single link between two points which is a part of larger network". Nodes and terminals are the contact or exchange points where it is possible for people to change from one mode to another (Zuidgeest, et al., 2009).
Zuidgeest et al. (2009) also describe the system as a collection of sub systems, each sub-system representing one mode of transport. Each mode sub network is composed of routes that connect to the other sub networks through contact or exchange points at nodes or terminals. These are the places where people change from mode to mode.

This definition brings the perspective of the system multimodality. The transport system is defined from a multimodal perspective by Mandloi & Thill (2010) as the network in which the movement of people may occur by two or more different modes from the point of origin to the point of destination. Chen et al. (2011)also describe the multimodal transport system as "the use of two or more modes involved in the movement of people or goods from origin to destination". Since the human mobility within an urban area actually always happens in a multimodal transportation network (Liu, 2011), it would be more accurate to describe a transportation system as a multimodal transportation system.

### 2.2.1. Components

In order to model a system its key elements/components should be identified and understood. From the previous definitions multimodal transportation systems' key elements can be identified as:

- Transportation infrastructure on top of which transport modes operate
- Modes of transport: networks representing different modes routes and paths
- Multimodal trips: This is the use of people for these modes with different combinations
- Transfer points: allowing people to change from one mode to another

#### 2.2.1.1. Modes of transport

Comtois et al. (2009) define transportation modes as "the means by which people and freight achieve mobility". These modes can be private like cars and taxis or public like different types of buses, train, tram, underground. Table 1shows the modes classification as adopted by Liu (2011). He didn't classify the modes as simply public and private but also as motorized and non-motorized and by the physical infrastructure it operates on.

Table 1: modes of transport classification (Liu, 2011)

| Mode type | Mode (abbr.) | Transportation network | |
|---|---|---|---|
| | | **Functional type** | **Carrier type** |
| **Private** | Walking (W) | Pedestrian-allowed | Road |
| | Car driving (D) | Private car-allowed | |
| | Bicycle riding | Bicycle-allowed | |
| | Motorbike | Motorbike-allowed | |
| | Taxi | Taxi-allowed | |
| **Public** | Bus taking | Bus line | |
| | By underground train (U) | Underground line | Railway |
| | By suburban train (S) | Suburban line | |
| | By tram train (T) | Tram line | |

Classifying the modes helps in choosing the appropriate technique in modelling. Modes with similar characteristics can be modelled using the same technique.

#### 2.2.1.2. Infrastructure

Mandloi & Thill (2010) argue that describing a multimodal transport network involve mentioning the use of different transportation infrastructures like road, rail, water or air. Transportation infrastructures represent the means of carriage for the modes of transport. A single infrastructure can even support different modes like the roads can serve public bus system and cars simultaneously.

#### 2.2.1.3. Multimodal trips

According to Van Nes (2002) a multimodal trip is "when two or more different modes are used for a single trip between which the traveller has to make a transfer". Hoogendoorn-Lanser et al. (2006) also define a multimodal trip as "a trip when it involves at least one transfer between – not necessarily different – mechanized modes".

This brings us to the definition of the trip chains, trip chain as defined by Rietveld, et al. (2001) as "an ordered sequence of trips where the endpoint of each trip is equal to the starting point of the subsequent trip in the chain. The starting point of the first trip is the starting point of the chain, and the endpoint of the last trip equals the endpoint of the chain" (Zuidgeest, et al., 2009). However, in the case of passenger movements, Zuidgeest et al. argue that in a multimodal travel context for this definition to be valid, a passenger should not engage in any intermediate activity and that the term transport chain is more valid.

A multimodal trip is typically composed of an access leg, egress leg and a main leg. According to Hoogendoorn-Lanser et al. (2006) the access trip is "the trip part from the origin to the boarding railway station" whereas the egress trip is "the trip part from the alighting railway station to the destination".

However, Zuidgeest et al. argue that this definition is not generic because it considers the train as exclusively the main mode. So, they proposed another definition which is more general because it accounts for public transport generally as the main mode. Zuidgeest et al. define access trip as "the trip part from the trip origin to the first entry point of the public transport system" and the egress as "the trip part from the point of alighting the last public transport leg to the final destination" (Zuidgeest, et al., 2009). From that we can define the access leg as the part of the trip from the origin to the entry point of the first main mode of transport and the egress leg as the part of trip from the exit point of the last main mode to the destination.

#### 2.2.1.4. Transfer or mode switching action

Another important concept in a multimodal transportation system is the transfer between modes (Wang, et al., 2009) which occurs at the so called "switch points". These are described by Tolley & Turton (1995) as "points on a network where several routes converge, and often act as the focus of transport services or for the exchange of traffic between two modes of transport". Liu also defines switch points as "the spots where transferring from one mode to another takes place", examples for that in real life can be parking places, park and ride lots, bike and ride lots, public transit stations (Liu, 2011).

Transfer points are considered important because connectivity between two modal networks is established only at these transfer points. So even if two network modes have routes that are geometrically coincident switching between these 2 modes can only be done at transfer points. Also the activity of switching modes produces extra cost which is in case of modelling associated with these transfer points (Mandloi & Thill, 2010).

## 2.3. The need to model multimodal transportation systems

In literature, models for multimodal transportation systems are used for a wide range of functionalities. They can be used for assessing the current performance of a transportation system like assessing the regional accessibility of a neighbourhood (Waddell & Nourzad, 2002). It can also act as a decision support tool for transportation policies such as assessing the overall performance of the transportation system of an area after introducing a new route or line for a specific mode of transport.. For example, (Martens, 2007) used a similar model to assess the introduction of more bike and ride facilities at bus stops in Dutch cities. A model for multimodal transport can also help measure the benefits of integrated transport system like assessing the benefits of integrating non motorized transport with public transport which can only be performed in a multimodal context (Zuidgeest, et al., 2009).

Finally such models can also assist in route planning. Commuters need improved means to solve the problems affecting their journey in a multimodal context aiming to find the optimal route between the source and the target of the trip using different modes of transportation (Wang, et al., 2009). Providing commuters with path finding options or the optimal route with the least cost as well as the overall travel cost is expected to help in trip planning and route choice. Such information can only be obtained by a model encompassing all modes in one network.

Most of commercial GIS software contains applications which solve the conventional route planning problem, but without taking into account the integration of multiple transport modes. Also, some of route planning systems are making efforts to integrate more transportation modes, e.g. Google Maps added "Walking", "By public transit", and "Bicycling" options besides "By car" in its Get Directions function for some areas but the problem that the route planning is performed totally separately for each mode, i.e. one mode at time (Liu, 2011). However, Mandloi & Thill (2010) argue that a GIS data model designed to support route planning in an urban environment must be able to model different modal combination for it to be effective.

The model suggested in this research will integrate the different modes of transport of an urban area in one network model representing its multi-modal transport system. This is believed to be capable to generate routes between origins and destinations, over the network, making use of different modes in order to find the routes with the least cost.

## 2.4. GIS in multimodal transportation systems modelling

In this section the use of geographic information systems (GIS) in modelling multi modal transportation network is discussed. First the suitability of GIS to model such system is discussed, followed by a discussion on the data models and theories behind network modelling in GIS. This is followed by a summary of the challenges that are encountered when modelling such networks. Finally reviewing different approaches from the literature to model multimodal transportation networks using GIS and finalizing with a discussion how these approaches are forming the base for the model adopted in this research.

### 2.4.1. GIS as a suitable platform to model multimodal transport system

Among all the supporting technologies of transportation and navigation, GIS always plays an important role (Liu, 2011). GIS at its very basic definition being a spatial database that is capable of storing, analyzing and visualizing spatial data (Zuidgeest, et al., 2009) can serve well the modelling of a phenomenon like transportation that has both spatial and attributable sides. A specific expression for that is GIS for transportation (GIS-T) which is an expression that encompasses all the activities that utilize geographic information systems for some aspect of transportation planning and management.

GIS is also capable to deal with a large amount of data efficiently specially in a system like multimodal transportation network that accommodates a variety of data including street, bus, rail (metro), walking or cycling service routes and their interconnections (Chen, et al., 2011).

Choi & Jang (2000) Argue that GIS is a tool that can provide a better consistency and accuracy for the data and to be more labour efficient when building a transport model. The advantages of GIS as mentioned by Wang et al. (2009) also include analytical capabilities, visual power, efficiency of data storage, integration of spatial databases, and capabilities for spatial analysis.

### 2.4.2. GIS Network data models

The modelling of a phenomenon in GIS which is representing the components of a system and the relations between them requires a data model (Zuidgeest, et al., 2009). A data model as defined by Goodchild (1998) is "the set of entities and relationships used to create a representation of some real phenomenon". Therefore understanding the data model behind the representation of the modelled system its capabilities and limitations determines the analysis and functions that are possible with that system (Brussel & Zuidgeest, 2010).

In everyday life, transportation networks are the most common and easy to identify type of networks among physical networks (Choi & Jang, 2000). Therefore, in GIS, transport systems are usually represented as networks (Brussel & Zuidgeest, 2010). And modelling a network requires a data model capable of defining connectivity between the network elements, direction of flow in the network and other values assigned to network elements like amount of the flow and impedance. Bielli, et al.(2006)argue that viewing these relationships as graph structure is helpful in many cases.

#### 2.4.2.1. Graph theory

The mathematical theory that is concerned with how networks can be encoded and their properties measured and analyzed as a graph is known as graph theory (Brussel & Zuidgeest, 2010).
Graph theory states that a network can be modelled as a set of edges and vertices. A graph consisting of encoded edges (segments, links or lines) and vertices (nodes) can define direction and define connectivity (Comtois, et al., 2009). For example the bus network can be represented as a graph where the bus stations are the graph vertices and links between stations as the graph edges.

A graph can also have other properties that serve the network modelling. A graph can be labelled by attaching labels (attributes, values) to its edges and vertices. A graph can also be directed if the directions of its edges are defined by the start and end vertices. In case that any direction of the edges is disregarded, the graph is referred to as an undirected graph (Liu, 2011).

Another important characteristic of a graph for the transportation network is that a graph can be weighted. Liu defines the weighted graph as the graph that numerical label (value) or weight is assigned to each of its edges. In case of transport modelling, this weight is the way of representing the cost of travelling from a point (vertex) to another (Liu, 2011).

Following the definition of graph theory and the characteristics of a graph, this way of representing a network fits well the modelling of a transportation network. Based on the ability to weight a graph, the shortest path finding in a network is applicable. The shortest path is the path that the summation of the cost (weight) of its edges is the least among the others. Also following the concept of directed graph, the direction of a network flow can be defined.

#### 2.4.2.2. Node arc data model

As mentioned before, in GIS a transportation network is modelled as a network of interconnected nodes and links. There is a vector data model behind that with the ability to store topological relationship and connectivity which is called the node arc data model (Mandloi & Thill, 2010).

The node arc data model uses the directionality of arcs to store the connectivity also by enforcing rules such that every arc is bounded by a start node and an end node. Also introduction of a new node requires an arc to be split at that node (Mandloi & Thill, 2010).Nodes define the topological relation (connectivity) and can also carry attributes (Zuidgeest, et al., 2009).

#### 2.4.2.3. Transportation and Network data model

However, modelling all features of transportation networks in an edge/vertex structure, i.e. a graph is not an easy process as the real transportation networks are often highly complicated (Liu, 2011). A GIS usually stores a transportation network as it exists on the surface of the earth in two dimensions (2D) (Mandloi & Thill, 2010). GIS systems, being typically 2-dimensional in the nature of their data structure have difficulty in modelling non planar graphs (Brussel & Zuidgeest, 2010).

An addition is made to the data model to allow for the modelling of non planarities. A "turn table" which is a table used to define the connectivity rules and the turning restrictions (Wang, et al., 2009) is used to regulate particular turns in a transport network (Zuidgeest, et al., 2009).

However, Brussel & Zuidgeest (2010) argue that modifications and additions over the last 20 years made on the GIS basic network data model gave it the ability to deal with non-planar networks. These modifications like turn tables and additions like linear referencing and dynamic segmentation which makes it possible to handle one to Many relations (giving different description or values for each part of the same segment); which is not possible in the strict arc-node model.. Also this includes the definition and implementation of the route concept, lanes, flows and dynamic data. (Brussel & Zuidgeest, 2010; Butler, 2008; Goodchild, 1998; Miller & Shaw, 2001).
This leads to the discussion of next section about challenges in modelling transportation network with GIS and its data models capabilities.

#### 2.4.3. Challenges in modelling multimodal systems

The challenges facing modelling is divided to two parts: one related to the modelling approach and modelling technique used and the other related to the data used in the modelling. In the same sense, modelling transport systems with GIS face difficulties that arise from the limitations imposed from GIS but also from the available data needed for the modelling. Liu (2011)sees that the lack of a high-quality dataset and of effective modelling and path-finding approaches are the bottleneck for the modelling of a multimodal transport.

Although GIS has potentials in modelling transport, limitations exist in computerized GIS data modelling and representation concepts in representing the complexity of the transport system and the richness of its properties and characteristics and to cope with the dynamic nature of the applications of transport model systems (Brussel & Zuidgeest, 2010).

For instance, the node-arc data model, although being suitable for many modelling tasks, needs some modifications to be able to represent the complex reality of some situations such as those arising from non-planarity due to the three-dimensional (3D) nature of the network like bridges and tunnels and other apparent intersection. Apparent intersections are those that are happening physically but are not used in the movement over a network. For instance 2 bus lines routes might intersect at some points other than stations or even overlap at some parts but this does not mean that the flow between the two routes can make use of this apparent intersection/overlap because moving between the 2 routes happens only at designated locations (bus stops/stations). Hence additions have been made to the basic planar network data model by extending it using turn tables to model specific connectivity at an overpass or by using Z level attribute values associated with street segments(Mandloi & Thill, 2010) or by defining the connectivity rules of the network.

Movement over the road network within a transportation system is modelled as linear layer carrying impedance that represents the movement cost along each part of this layer (line/segment). Moving over a road can be done by several modes. A road is used to walk, to cycle and the bus uses the same road network too. However, possible routes within a network need to be modelled as separate entities, because there is a need to distinguish one route from the other to be able to relate attributes to these entities. Though, the ArcGIS geodatabase structure, is able to overcome such problem by allowing the movement and interaction among its constituent layers representing routes (Zuidgeest, et al., 2009).

Another important issue in modelling generally is the data. Generally, multiple modes of transportation systems lead to a complex transportation network where representation and integration of data becomes a large and not straight forward process (Chen, et al., 2011).

Choi & Jang (2000) discussed the issue of data availability and required data preparation. They argue that typical problems are encountered in the preparation of the transportation network data. For example, available stops in a transit network are not always spatially coincident with intersections of the road network and are sometimes located in the middle of links. This will make it impossible to use the vector topology database provided by GIS network database. To understand this problem we need to know that topological relationship between a line and a point occurs if the location of this point over the line is at one of the line vertices (start, end or middle). So for the problem mentioned here, if the stations are located in the middle of a line with no vertex of the line at the same location, connectivity between the line and the point can't be established. Therefore some steps are required to transform the road network to the format needed for transit network data generation and modelling. GIS softwares provide tools to do similar editing, but it is still an issue to be considered when preparing the data for modelling.

Liu (2011) also mentioned the data but from the interoperability point of view. A multimodal system composed of different modes corresponds to various datasets provided by different organizations. According to Liu, the challenge lies in the integration of these datasets in one containing all the necessary geometric, topological and semantic information.

For that reason, connectivity between some elements cannot be directly established. Data of different elements of a transportation system are provided by different operators with different format. Having, for example, road network from one source and bus lines and stations from another source make them sometimes geometrically not coincident with each other. They need to be snapped to each other before thinking about their connectivity. However GIS can do such corrections easily.

Routing as an important and main functionality performed with a transport model cannot be mentioned without mentioning optimal path finding. The network-modelling method and path-finding algorithm design are closely related to each other (Liu, 2011).
An optimal or shortest path as defined by Liu is "the path(s) through the network from a known starting point to an optional ending point that minimizes distance, or some other measure based on distance, such as travel time".

The appropriate optimal path finding algorithm is always an important issue to consider when developing a transportation system. However the path finding algorithm is out of this research focus as this research uses the built in path finding algorithm of ArcGIS, the modelling environment considered in this research.

From that we can summarize the main challenges facing modelling a multimodal transportation system as

1. Available data and its format
2. Overlapping routes of both similar and different modes
3. Modelling transfers
4. Integration of travel cost in the model

## 2.5. Different approaches of modelling mutlimodal transport system using GIS

Mandloi & Thill (2010) describes the traditional way of modelling a multimodal transportation system as storing a set of sub networks following the arc-node data model for each mode of transport in a GIS database. Then build a logical network where connectivity between sub networks (Modes) is established. This approach's main advantage that it is easy to build and implement especially if data for existing modes routes is already prepared. If data is not necessarily prepared at the same time, different services providers can prepare their data and after that it is only a task of integration.

However, this approach is criticized by raising the database integrity issue. Each mode network is edited independently from the other and away from the roads infrastructure network. Mandloi & Thill (2010) argue that this can be addressed using topological editing tools while editing but this requires a lot of effort and time at data integration in case of different data provider which refute one main advantage of the approach. Also, data redundancy and visualization problems appear for overlaying routes and different segments geometrically coincident. Such model's aim is to help travellers determine their options and plan their routes which won't be an easy job with several bus lines sharing many segments and overlaying with cars routes and metro lines for instance.

Mandloi & Thill (2010) adopted a modified traditional approach to address some of its disadvantages. The approach uses the capabilities of the GIS software (ArcGIS 9.1) in topological relationship building to build a network with 3D elements. This approach makes use of the ArcGIS object oriented network data model and the 3D capabilities of the software. The object oriented concept of connectivity groups incorporated in the data model of the software is used to define connectivity between different network elements (objects) having different elevation values. In ArcGIS connectivity group concept, connectivity can be established based on the elevation value of the participating objects, i.e. objects (Datasets) having same elevations are connected. A set of sub networks are developed based on the arc-node data model. These sub networks can be at different elevations.

The authors argue that the physical separation between modes' networks enable the modelling of physical transfer between modes and the modelling of impedance associated to this transfer by assigning the impedance value to these transfer arcs (Mandloi & Thill, 2010). However the part of using the 3D concept was applied by the authors in the context of an indoor modelling context. Brussel & Zuidgeest (2010) discussed the application of a similar approach but in the context of multimodal network transportation of Pune city, India.

Brussel & Zuidgeest (2010) review traditional approach of modelling multimodal transportation network differently. According to the authors, traditionally when modelling trips following the arc node data model, each part of the trip (access, main, egress) is represented by separate linear feature(s). Stops are represented by point features and every boarding or alighting action at each stop is represented by a linear feature diverging or converging carrying the impedance associated with such action.
For example, modelling a bus line route using this approach would represent each link (the part of the route from station A to station B) of the route by a linear feature and the bus stops by a point feature and the boarding and alighting actions at these stops presented by linear feature from the boarding/alighting point to the route. This line carry the cost of boarding/alighting, waiting time and any extra cost related to this action. However, lines coming out and towards a node (stop) are overlapping and crossing each other (in graph not physically) which requires extra modelling to represent this non planar relation (Brussel & Zuidgeest, 2010).

Also, with large systems with big number of stops and lines, it is not an easy job to create all the lines representing the transfer (boarding/alighting) action and assign them the corresponding cost. Another problem emerges when many bus lines routes (for example) overlap in some parts as they operate on same roads. Brussel & Zuidgeest (2010) suggest that placing bus routes parallel to the existing route network this can overcome the overlapping problem. But they also argue that such a solution requires a big effort in digitizing to avoid clustering of line segments. It is also poor in visualizing the system especially at the part where many modes' routes overlap.
Another solution suggested by the authors is the use of dynamic segmentation to address the issue of several routes (of different or same mode) sharing the same underlying road. Dynamic segmentation

allows the storage of data for a part of existing arc node structure without changing the structure. So for each part of the road (line) and without introducing new node and disturbing the existing structure, different information is stored. This is also more efficient in term of database usage as there is no need to duplicate a road several times to represent different kind of information and routes (Brussel & Zuidgeest, 2010).
However, the need for separate entity for each mode is still there. So storing one entity like roads representing several modes will not work, but still, linear referencing can be very efficient in generating different modes' routes from one entity. Also the issue of availability of the data required for the dynamic segmentation (event table) is an obstacle facing the use of dynamic segmentation. Such data is not always available which requires extra work for collecting or preparing such data.

The approach adopted by the authors however is based on the advances in GIS and spatial database that introduce more 3D capabilities. Its main idea is physically separating bus routes from the underlying road network by assigning different elevation values to each bus line route corresponding to the bus line number. Switching between bus lines is presented by linear feature carrying the transfer cost (Brussel & Zuidgeest, 2010).

The main advantage of this approach as stated by the authors that it provides a better visualization for such overlapping routes especially at stations that serve several bus lines.
The approach adopted in this research is basically a combination of Zuidgeest, et al. (2009)and Mandloi & Thill's (2010) approach. It relies mainly on the technique of physically separating sub networks representing each mode of transport also in making use of the 3D capabilities introduced in GIS softwares.

An important issue in the modelling is the size of the modelled system and data and its complexity. A multimodal transportation system for some cities comprises a huge number of overlapping intersected routes and transit points. This is the result of numerous modes of transport and operating systems (NMT & PTs). For that, some researchers considered the amount of data and the complexity of the system when choosing the appropriate modelling approach. For a transportation network, path finding is a main function. Path finding in such a large amount of data requires an efficient database organization method for structuring the multimodal transportation network and to speed up the computation of a minimum cost path (Bielli, et al., 2006).

The hierarchical approach is the one adopted by many addressing the issue of large amount of data (Bielli, et al., 2006; Van Nes, 1999; Wang, et al., 2009). However, hierarchical approach is translated differently in literature. Jing, et al. proposed an idea that consists of partitioning large graph into smaller sub graphs and organizing them in a hierarchical fashion (Jing, et al., 1998).

Many authors define three hierarchical levels for a transportation network. Bielli, et al. (2006) used a data model that structures the transportation network in a hierarchical fashion that defines three levels: a physical level which is the spatial coordinates and actual positions of the network elements, logical level where the graph representation of the transportation network is defined and finally the applicative level which consider the applications dependent modelling.

The above mentioned researches used a hierarchical graph structuring method dealing with large amount of data. Others adopted the hierarchy conceptually. Wang, et al. (2009)also defined the same three levels as Bielli, et al. (2006) but for Wang, et al. it is not only a way of structuring data but also to generate data efficiently. In Wang approach he makes use of the hierarchy concept, dynamic segmentation and linear

referencing techniques as well. The first level, “the physical level “, is the street network. It is also the linear referencing system of the network. The second level, the logical level is the roadway level where the roadway network is defined. Intersections and turn tables are defined in this level as well. The third level is where the paths and stations of public transport networks are defined. These networks inherit form the roadway network (Wang, et al., 2009).
The modelling is done as a directed graph G (V, E), where V is the set of nodes (vertices) and E is the set of edges. At the first level, the streets level, the edges are the streets and streets’ end points are the nodes of the graph. The roadway network is composed of roadways (edges), intersections (nodes) and turning table (defining the direction of the graph). On top of that is the application level where the elements related to transportation modes are defined. Wang, et al. divided this to 2 categories: public network with fixed station, schedule and routes like bus and metro network, and private network which is not bounded to any restriction like taxi and private cars (Wang, et al., 2009).

Choi & Jang also represented a method to generate data necessary for transit network modelling from existing street network (Choi & Jang, 2000). For the work done at this research, the roads centre lines are used as well to generate all the data of the modes operating on the roads.
Liu (2011)argues also that efficient transportation network data organization can be applied by either partitioning the network vertically which is the hierarchical network organization or horizontally that consists of graph decomposition and clustering. The author adopted the horizontal partitioning. He argues that different functionalities of a transportation system which are different modes are modelled as a set of separate standalone graphs corresponding to the functionality of the mode the graph represent. This concept is defined by Liu as the *mode graph*. Liu distinguishes different modelling methods for public and private modes (Liu, 2011).

The road network is modelled into several graphs representing different modes operating on the road network. This multi graph representation is because networks of different modes are different in topology and edge cost functions. In the raw dataset available and used by the author in his model, one physical street is available as one feature line. It is corresponding to several modes but such data is stored as attached attribute to this feature line. Attributes indicating the type of modes (traffic) allowed in this street. These attributes are used to generate the network of different modes. For example, by selecting those lines where the attributes indicated that auto is allowed the private cars network is established. Pedestrian network is generated the same way but the authors highlight the issue of the scarcity of data available about pedestrian paths so that he had to collect the data manually to make a detailed pedestrian network (Liu, 2011).

The stand alone graphs of modes are pluggable to each other through switch points. Switch point are the locations where transferring from one mode to another is applicable.

This (the network topology) is described by the authors as the static component of the system. For the dynamic part of the system which is the time dependent components of the network like timetable (mode frequency) and waiting time, they are modelled within switch points.
The anchor point in modelling public transit modes is the time table. In the approach adopted by Liu, time dependent schedule is incorporated in the switch points. A main technique in modelling public transit modes in this approach is the separation of direction or overlapping stations. For example, if at one location, which is present in the raw dataset as one point, many stations co-exist or a station serving 2 directions, this is modelled as separate points. The same for the link between 2 stations, if it is a 2 way link, it is separate to 2 links each for one direction. Also constraints can be applied to the switch points to control the behaviour of multimodal path finding like for example that in a driving – parking switching

point, to restrict that the switch can be applicable only if there are vacant places in the parking lot (Liu, 2011).

The problems arising from the data preparation whether about large size and repetition of operations or about the need for a long process can be addressed by automation of the data preparation process. In this research an automated process for preparing is suggested (Chapter 3). Especially that GIS software provide a set of tools concerned with topological editing, checks, snapping and other needed tools for data consistency.

As a summary from the previous approaches, using the 3D capabilities of GIS as well as the physical separation for the modes graph address most of the challenges facing the modelling. The 3D solution address many issues, first the problem of overlapping routes or network elements but also the visualization problem. Combining the 3D approach adopted by Zuidgeest et al.(2009)and Mandloi & Thill (2010) with the physical separation concept adopted also by Mandloi & Thill (2010)form the core of the approach adopted in this research. According to Liu (2011)concept of mode graph, each mode operating on the road has a separate graph (set of edges and nodes). Modes sharing the same road segment are separated horizontally this would be like representing each lane of the road by one line instead of representing the road with all its lanes with one line. This is described in the methodology chapter (chapter 3) in details as the parallel lanes concept. For the bus lane which serves many bus lines, the vertical separation is used to separate the overlapping bus line operating the same lane.

Like Mandloi & Thill's approach, establishing connectivity and defining topological relationships between these physically separated sub networks (horizontally and vertically) is established by the object oriented connectivity groups of ArcGIS software. Also connector lines are used to model transfer and the boarding and alighting actions.

# 3. METHODOLOGY AND MODELLING CONCEPT

## 3.1. Introduction

In this Chapter, the methodology and the modelling concept adopted in this research are described in details, how to combine the different modes in one multimodal network making use of the techniques reviewed in the previous chapter. For that, the nature of each mode should be understood in order to model its own network in the right way and also to understand the interchange possibilities with the other modes. The focus of the model described in this research is public transport. Specifically in the case of the study area it is bus and train. Cycling and walking are vital modes in themselves, but are also important feeders in urban transport (Brussel & Zuidgeest, 2010). So, walking and cycling are considered in the model as access and egress modes for public transport and also as separate modes of transport used for the whole trip.

Modelling is an abstraction and simulation of reality. So when trying to model a system, its main components should be identified as well as understanding how they work and interact together. From the definition and discussion of chapter 2 section 2.2, the multimodal transportation system's main components (layers) are identified as:

- Transport Infrastructure (roads, railway…)
- Modes operating on this infrastructure (bus, train, bike …)
- Trips made by people using these modes (unimodal, multimodal, least cost, least time ….)

In this case, roads and railroads as the transport infrastructure layer are used to delineate the different modes' routes and networks. Train routes are delineated using railroads. For the train with one mode operating on a separate infrastructure, the use of railroads to define train paths is simple. But a problem arises when one infrastructure is used by more than one mode of transport. Specifically for the roads it is more complicated. Pedestrian paths are not available separately, neither cycling. They are all considered as parts of the roads functionalities (lanes). Also, bus shares the same roads with cycling and pedestrian. But all modes operating on the roads cannot be represented by only one set of lines. Separate sets of lines are needed for each mode's paths to establish connectivity properly. For that, roads are used as the base for the generation of modes' paths operating on top of it.

Roads are available as a set of line elements representing roads centre lines. But in reality, a road is more of a polygon than a line. More specifically, a group of parallel polygons (lanes) composing one bigger polygon (a road) (Figure 3-1: Road detail). For the sake of simplification and other technical issue, like that a network can be built only with lines; an abstraction to the road polygon has to be made. But for the case of this model, a road is rather simplified to several parallel lines representing its different lanes instead of only one (Figure 3-2: Road abstraction).

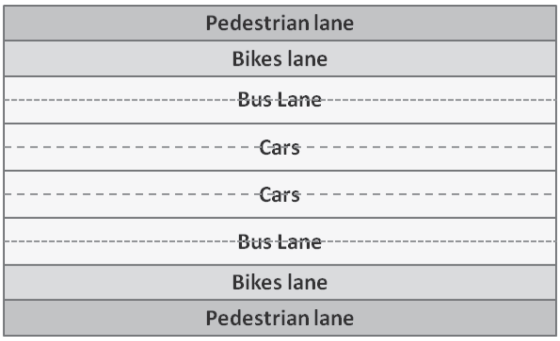



Figure 3-1: Road detail

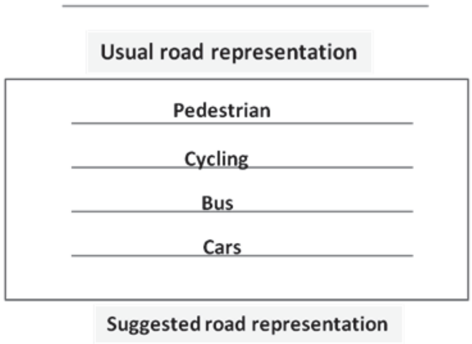



Figure 3-2: Road abstraction

Separating the lanes in which each mode operates and representing each with one separate dataset solves the problem of the overlapping routes of different modes operating on the same infrastructure. But the problem of overlapping routes of the same mode is still present. All bus lines operate on the same lane and by applying the previously discussed techniques of lanes, bus is represented by one set of lines. Now how one set of lines can represent the numerous bus lines? The solution of having separate dataset for each line will result in many overlapping lines which will make the process of establishing connectivity between lines that are geometrically completely, coincident impossible. For that, the modelling concept of this research suggests the use of 3D capability of ArcGIS to solve that. If the modes were separated horizontally, modes overlapping routes can be separated vertically (Figure 3-3).

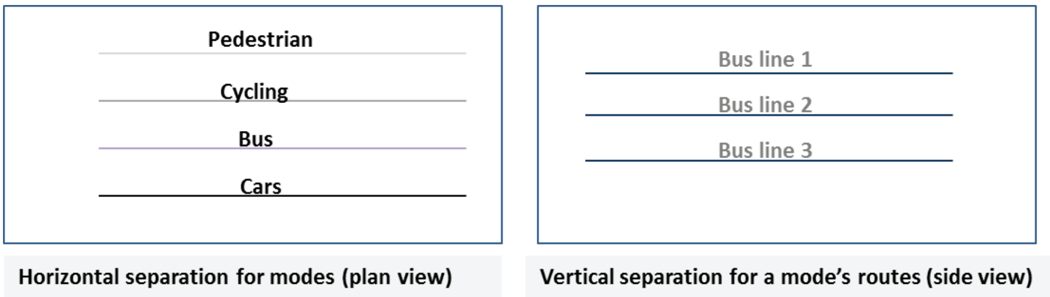



Figure 3-3

For each lane mode, one separate dataset for pedestrian, one for cycling and one for bus. For each Bus line segments an elevation value equivalent to the bus number is assigned in order to separate each bus line from the other vertically. Each dataset preparation will be discussed separately in detail in the following section.

The third layer in MMTS is the trips made by people using different combinations of modes according to their preferences. Mode combination brings the concept of transfer; transfer between modes or within the lines of the same mode (like the bus). Transfer is seen at this model as the physical movement of a person from one mode/mode's route to another and the associated impedance caused by this transfer. In other words, changing mode in this model is incorporated in 2 forms: a feature representing the change and a value (attribute) representing the associated impedance.

## 3.2. Modes

In this section, the modelling concept and the preparation for each mode dataset is described in detail. Modes considered are walking, cycling, bus and train. This following data are assumed to be available at the start of the process:

- Roads centre lines dataset

- Bus lines routes
- Bus stations
- Railroads
- Train stations
- Bus lines frequency
- Train frequency
- Average Speeds (walking, bus, train, cycling)

### 3.2.1. Walking

Walking, besides being an access/egress mode for public transport, is sometimes used alone for a whole trip from origin to destination. In both cases walking must be part of this model, if not as separate mode, it is necessary in the multimodal context as the backbone that connects all the modes together. One needs to go back to the pedestrian network to take another mode. Actually, this is not just a modelling concept but it is the case in real life that the model is simulating. Walking main characteristics as a mode of transport that its flow is continuous, it is not bounded to some transfer locations. People can change from/ to without any extra cost. It is also not bounded to any schedule. The moment that you decide to walk you start walking.

To have the walking sub network, all the paths available for walking are needed. It is true that pedestrian paths are not available separately, but as discussed in the previous section, roads can be used to represent pedestrian paths. Some roads in the dataset may have an attribute indicating if pedestrian is allowed on it or not. For the available roads dataset, such information is not available, so by excluding highways, an assumption is made that all the rest of roads are available for walking. In section 2.1 the preparation process is described in details.

### 3.2.2. Bus

Bus is a completely restricted mode of transport. It has fixed routes, bounded by time schedule and can be accessed only at specific locations (stations). In Netherlands, bus operates on a specific lane (bus lane), stops only at its stations and its frequency is accountable.
From that we can identify bus network main geometrical components as bus routes and bus stations and other non geometrical information needed as bus schedule (bus frequency) and bus speed per bus line. For that we need to have for each bus line, a set of lines representing its links (a link is a connection between 2 bus stations), bus stations that serves this bus line, frequency of this bus line and bus speed.
Available data about bus routes are paper maps indicating bus lines. Following the parallel lanes concept described before, the bus routes can be prepared from the roads dataset also. The bus however does not operate on all roads segments. Also, sometimes many bus lines operate on the same road segment which results in overlapped routes (Figure 3-4).

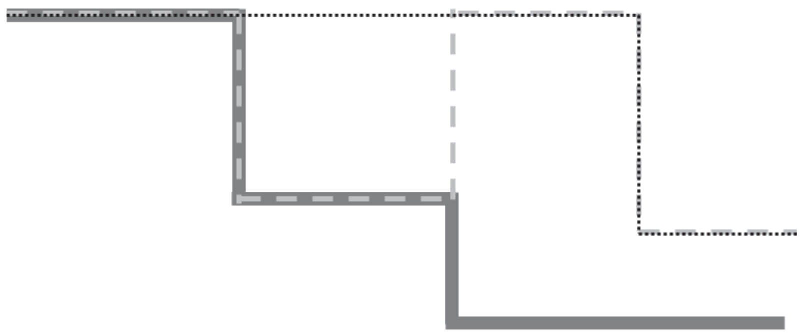


Figure 3-4

This problem is tackled by the 3D solution. Each bus line set of lines are assigned a different elevation value equivalent to its (unique) bus line number. This way the overlapped routes problem is avoided and connectivity can be established between 2 segments of different bus lines sharing the same road segment (Figure 3-5). The preparation process is described in details in section 2.2.

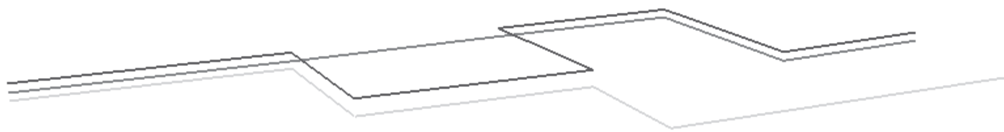


Figure 3-5

#### 3.2.3. Cycling

Assuming that cycling operate on a separate lane like the case of Enschede, Cycling operates on a separate lane in most parts of the road network. In some roads with low rank, bicycle lane is not defined but still bicycles are allowed. This makes cycling like walking that it is available everywhere in the city. However it is different than walking in that changing mode from/to cycling is not as simple as walking. One must park his bike to switch mode. This requires the availability of bike parking facility and costs the traveller extra time for parking.
But should cycling network be represented by another parallel lane to pedestrian, following the parallel lane concept discussed before? Or should it be considered as alternative for walking mode therefore it can be in the same XY locations of pedestrian network with an elevation value that makes cycling network exactly on top of pedestrian network. Technically the second option is more feasible as it results in less topological and editing errors. So it is the concept that is adopted in cycling modelling.

#### 3.2.4. Train

The train is like the bus, a mode restricted to time, access locations and time but is different because it operates on a separate infrastructure. In a city level there is no need to define many train routes. The train simply goes back and forth sequentially on all the train stations within the city. So the 3D concept adopted in the bus lines routes is not needed here for the scale considered in this search but in other cases where there are several bus routes at a regional or national level of a transport network, the 3D routes can be implemented. For this research's case, train network is built based on train route, which is delineated using the available railroads line features, and train stations.

### 3.3. Transfer

This section describes how the transfer between modes is modelled. For a passenger to switch mode, he has to physically change location: from walking pathway to a bus, from a bus to another bus, from a train to a bike. But also to encounter extra impedance due to this transfer like time, money and even comfort. In the model, transfer is presented in its physical form as transfer point features and connectors lines. Its impedance form is present as cost attributes associated to these (physical) features. Table 2 shows the cases of all possible transfers scenarios From/To the modes considered.

Table 2: Transfer cases

| | Walking | Bus | Train | Bicycle |
|---|---|---|---|---|
| Walking | - | Case 1 | Case 2 | Case 3 |
| Bus | Case 4 | Case 5 | Case 6 | Case 7 |
| Train | Case 8 | Case 9 | - | Case 10 |
| Bicycle | Case 11 | Case 12 | Case 13 | - |

### 3.3.1. Case1: from walking to bus

A person moving along pedestrian paths and wants to take the bus, walks to the bus stop and then embark to the bus. From that we can say that bus stations are accessible from pedestrian paths. So bus stations are located on pedestrian network. Knowing that pedestrian and bus network and independent of each other, features are needed to represent the physical link made by people's movement in case of transfer. Bus Connectors data set represents a line dataset that connects pedestrian network to bus lines routes at bus stops (Figure 3-6) embarking and disembarking penalties are assigned to these connectors.

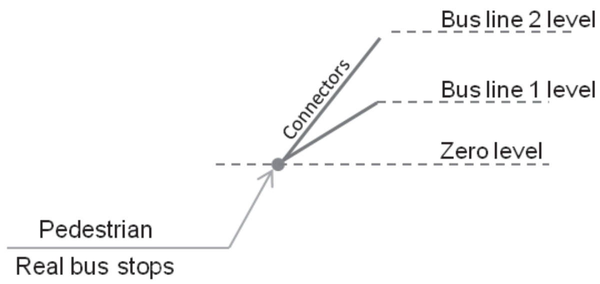



Figure 3-6: Bus Connectors (side view)

As arc node model in the underlying concept for network modeling in ArcGIS, connectivity between two edges (arcs) is established through a point (node) feature. For that, False Bus Stops dataset is needed at the intersection between Bus connectors and Bus lines. It represents the projection of real bus stops, located on pedestrian paths, on bus lines (Figure 3-7).

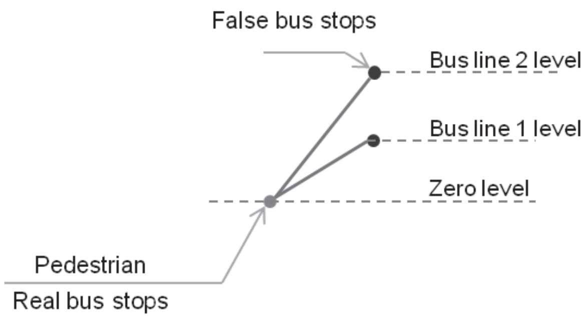



Figure 3-7: Walking-bus transfer (side view)

Pedestrian network -> Real bus stops
Real bus stops -> Bus connectors
Bus connectors -> false bus stops
false bus stops -> desired bus line

### 3.3.2. Case2: from walking to train

A passenger walks to the train station where he can take the first train to his destination. So train stations must be accessible from the pedestrian network. But for the available pedestrian network that was prepared from the road network, the pedestrian walking segments do not always reach every train station (Figure 3-8).


Figure 3-8 Figure 3-9

For that train connectors features are needed to fill the missing parts of pedestrian network that leads to train stations. These connectors line are added and considered part of the pedestrian (Figure 3-9).
Pedestrian network -> Train stations
Train stations -> Train network

#### 3.3.3. Case3 & 11: Walking /bicycle

This case is not applicable therefore is not considered in the model. It is not common that if somebody is using a bicycle will park his bike and start walking to his final destination.

#### 3.3.4. Case 4: From bus to walking

A person on board of a bus who wants change to walking does that simply by alighting at a bus stop. In more details, the bus stops on its route at the location of the bus stop, the person physically moves from the bus to the pedestrian network via the bus stop. This is how the model solves it as well.
bus line -> false bus stops (bus stop location but projected on bus line route)
false bus stops -> Bus connectors (representing passenger physical movement and where alighting impedance is assigned)
Bus connectors -> Real bus stops
Real bus stops -> Pedestrian network

#### 3.3.5. Case5: from bus to bus

A passenger who is on board of a bus and wants to change to another line has to disembark at a bus stop where he can embark again the other bus (Figure 3-10).

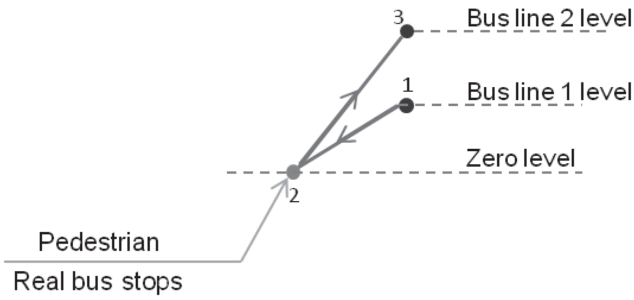



Figure 3-10: Transfer between bus lines (side view)

Starting bus line -> false bus stops (at the starting bus line)
false bus stops -> Bus connectors

Bus connectors -> Real bus stops
Real bus stops -> Bus connectors
Bus connectors -> false bus stops (at the other bus line)
false bus stops -> the other bus line

#### 3.3.6. Case6: from bus to train

A person on board of a bus and wants to switch to train has to go back to the pedestrian network through bus stop. From the pedestrian network he can reach the access point of train network: the train connectors or if applicable train stations directly (in the case that train station is intersected with pedestrian network no train connector in needed as it intend only to link train stations to the pedestrian network) (Figure 3-11).


Figure 3-11: Bus - train transfer

Bus line -> false bus stops
false bus stops -> Bus connectors
Bus connectors -> Real bus stops
Real bus stops -> Pedestrian network
Pedestrian network - > Train stations
Train stations -> train network

#### 3.3.7. Case7: from bus to bicycle

Cycling although seen as alternative for walking has different characteristics. A traveller who is walking and wants to change mode has to be only at any access point for the other mode network and transfer is made with no extra obstacles but for parking this is not enough. One must also park his bike before changing the mode. So the passenger cannot switch between cycling and another mode without having a parking facility at the transfer points. In other worlds connectivity between cycling network and public transport networks is not established at their access points (stations & stops) unless parking facility is available there.

But how to model this restriction? One of the model's main concepts is that to change mode one has to go back to pedestrian network. In other words the access point of any other network is on pedestrian paths. So in this case a person who is cycling has to ride his bike at the bus station (if available) which is on the pedestrian network. Figure 3-12 shows the modelling concept of this case.

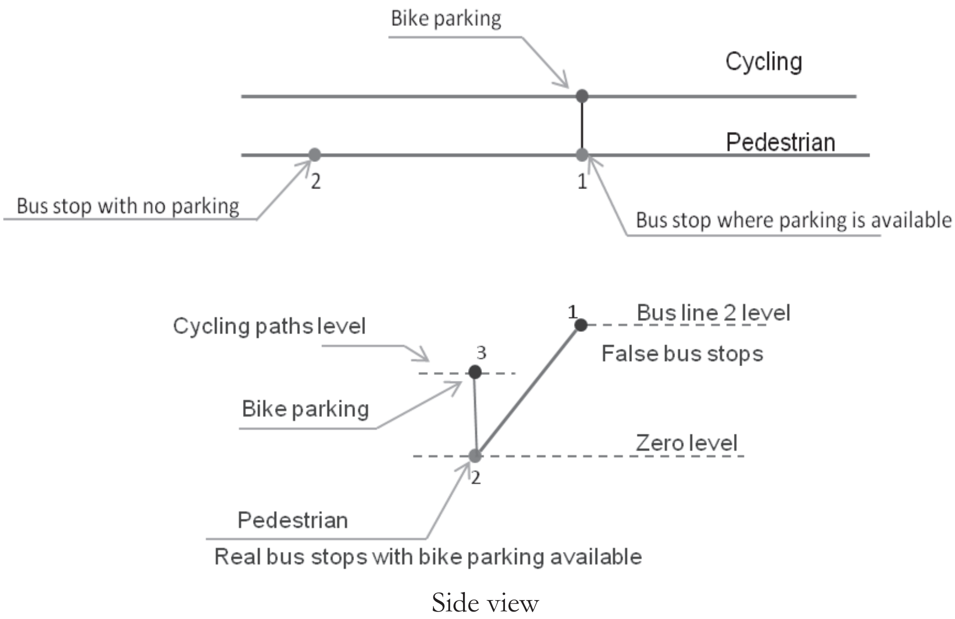



Figure 3-12: cycling walking bus transfer concept

Bus line -> false bus stops
false bus stops -> Bus connectors
Bus connectors -> Real bus stops
<u>if cycling is allowed:</u>
Real bus stops -> Cycling connectors
Cycling connectors - > Cycling parking
Cycling parking -> Cycling network

#### 3.3.8. Case 8: from train to walking

A person on board of a train and wants to switch to walking has to alight at a train station from where he can access the pedestrian network (at the nearest point through train connectors).
Train network -> Train stations
Train stations -> Pedestrian network

#### 3.3.9. Case 9: from train to bus

A person switching from train to bus alights at a train station use the pedestrian network to the nearest bus stop where he can access the desired bus line (Figure 3-11).
Train network -> Train stations
Train stations -> Pedestrian network
Pedestrian network -> Real bus stops
Real bus stops -> Bus connectors
Bus connectors -> false bus stops (at the desired bus line)
false bus stops -> The desired bus line

#### 3.3.10. Case10: from train to bicycle

An assumption is made that at all train stations parking is allowed. So a traveller willing to switch from train to bicycle alights at a train station takes the bike and access the cycling sub network from there (train and cycling sub networks are connected at the train stations/parking locations) (Figure 3-13).

Train network -> Train stations
Train stations -> cycling connectors
cycling connectors -> cycling parking
cycling parking -> cycling network

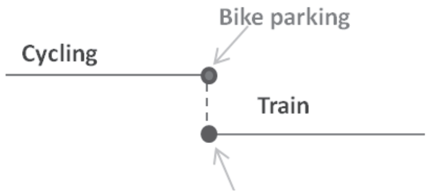



Figure 3-13: Train- Bike transfer

### 3.3.11. Case 12: from bicycle to bus

For a passenger to switch from bicycle to bus, he must park his bike. This requires the presence of a bike parking facility at the bus stop which is not available at all bus stops. So using the bus stops that bike parking is available, bike parking locations are identified and are used as the location where bicycle and bus network are connected (Figure 3-12).
Cycling network -> cycling parking
cycling parking -> cycling connectors
Cycling connectors -> Real bus stops
Real bus stops -> desired bus line

### 3.3.12. Case 13: from bicycle to train

A person cycling on the bicycle network reaches the train station, parks his bike and takes the train
Cycling network -> Cycling parking
Cycling parking -> Cycling connectors
Cycling connectors -> Train stations
Train stations -> Train network

## 3.4. Data preparation (Model requirement Vs existing data)

This section describes the data preparation details for the features dataset needed in building the model. In order to determine the required data and the format that matches the model requirements, the researcher start building a synthetic dataset to test the concept from. This is also to exclude the factor of data problems while testing the concept. Figure 3-14 shows the overall work flow which consists of three phases: data preparation, building the model and using the model. This section is about the first phase. Data preparation is divided to 4 blocks, one per mode consisting on the preparation process of all the dataset that are needed to model the mode sub network and possible transfer from/to this mode.

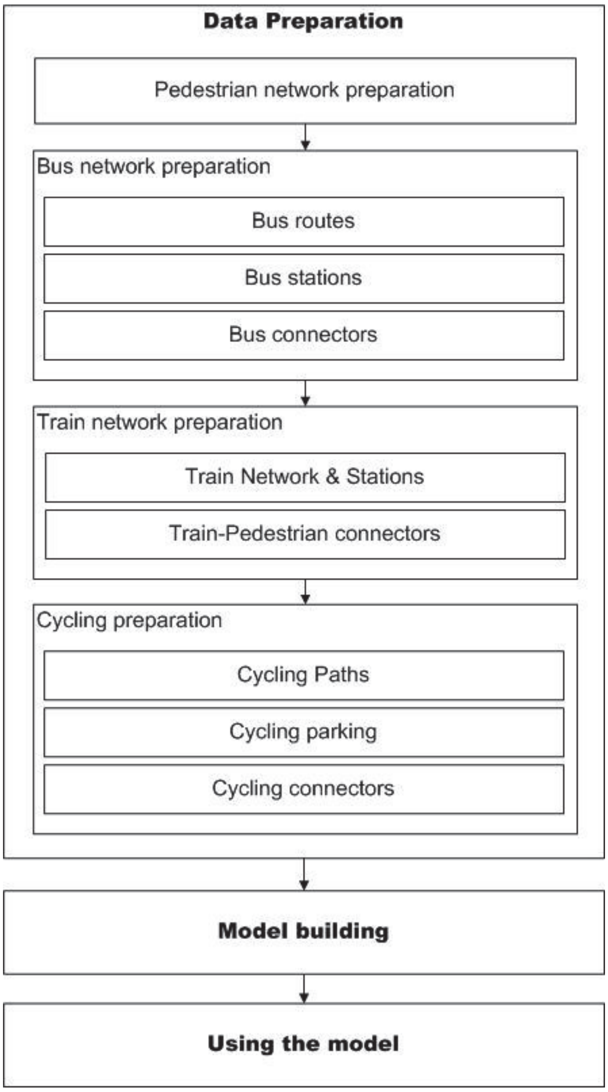



Figure 3-14: Work flow

### 3.4.1. Pedestrian

Figure 3-15 shows the details of first block which is the preparation process of a separate dataset for the pedestrian from existing roads dataset. The roads centre lines are used to represent the pedestrian paths. The diagram (Figure 3-15) shows the steps to prepare the roads centre lines to represent the pedestrian paths in the model. The first step is to check the given road centre line dataset for topological errors.

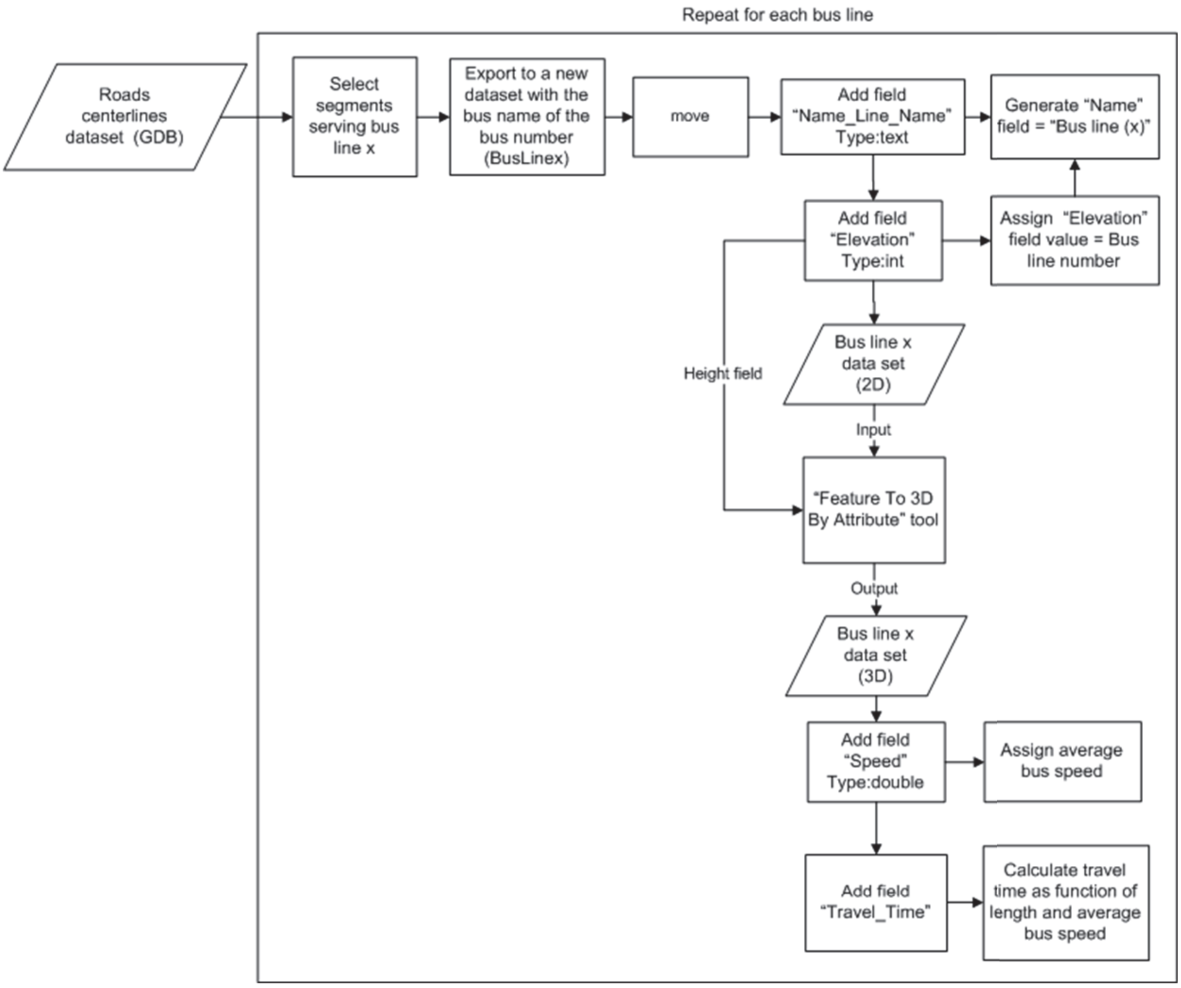



Figure 3-15: Pedestrian paths preparation

As some of the datasets involved in the model will have elevation value. It means that the rest of datasets also should have elevation value even if it is Zero because ArcGIS will establish connectivity through elevations of datasets. The prepared pedestrian lines dataset is assigned zero elevation value and is transformed to 3D features. After that, other needed attributes are added: Name, speed and travel time.

### 3.4.2. Bus

Second block is about preparing all required datasets for bus sub network and to model transfer from/to bus network: Bus lines, real bus stops, false bus stops and bus connectors.

#### 3.4.2.1. Bus lines

Following the parallel lane concept discussed in section 3.1 of this chapter, bus lines are to be represented by a parallel line dataset to the pedestrian paths. Road centre lines available dataset are used to delineate bus line routes. The following steps are to be repeated for each bus line. First step is selecting roads segments serving a bus line and export them to a different (new) dataset. Bus line number is assigned as the name of this line. Also, bus line number is assigned as the elevation value of this line. Bus line number is assumed to be unique so there will never be two bus lines at the same elevation. Exported dataset are all shifted with the same X and Y amount. Now that the bus lines are parallel to the pedestrian paths (or roads centre lines they are the same), the bus lines are then transformed to 3D dataset based on the elevation value assigned before. Now having the 3D bus lines dataset other needed impedance attributes like speed and travel time are added and calculated. Figure 3-16 shows the preparation process for bus lines dataset from the available roads dataset.

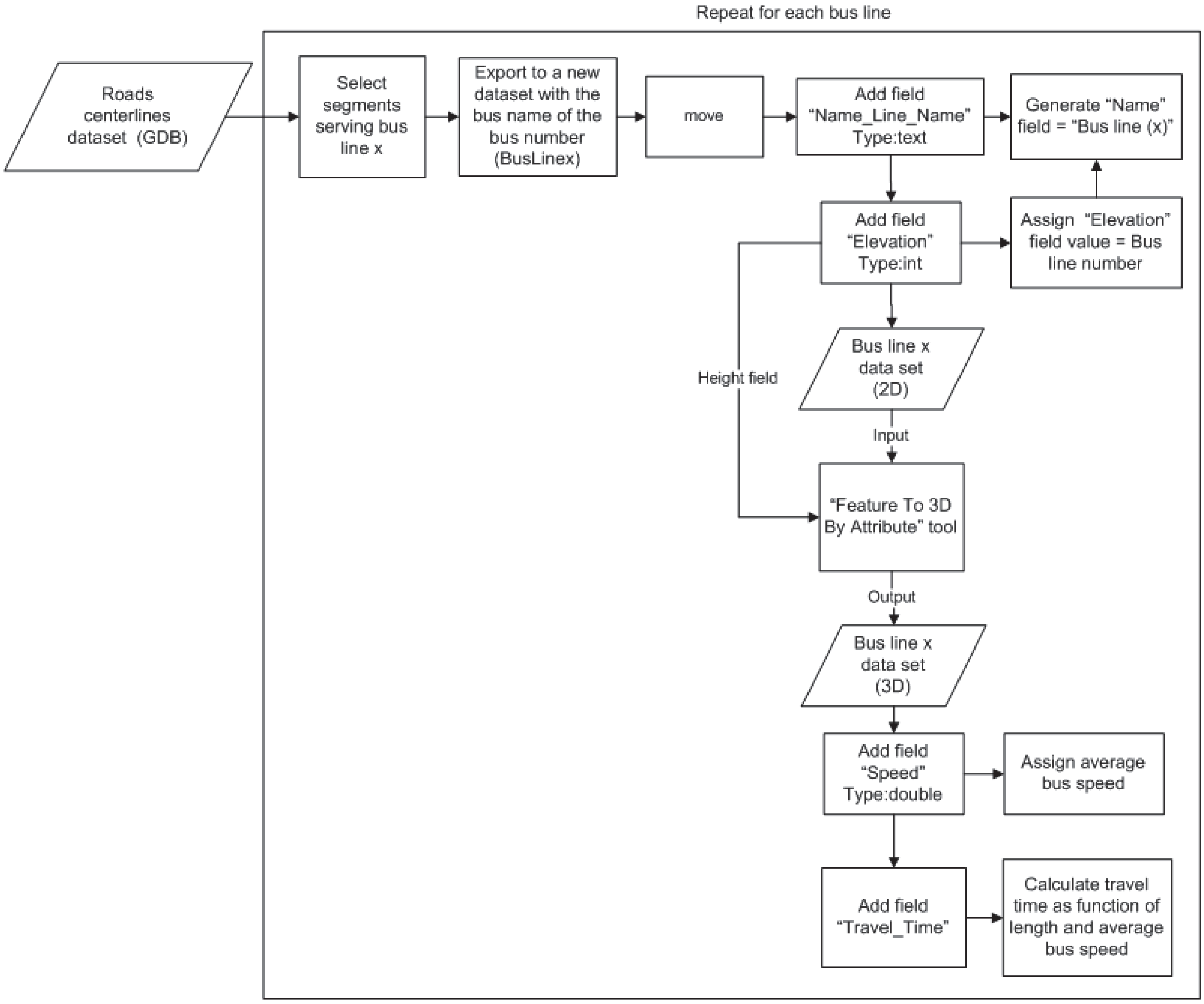


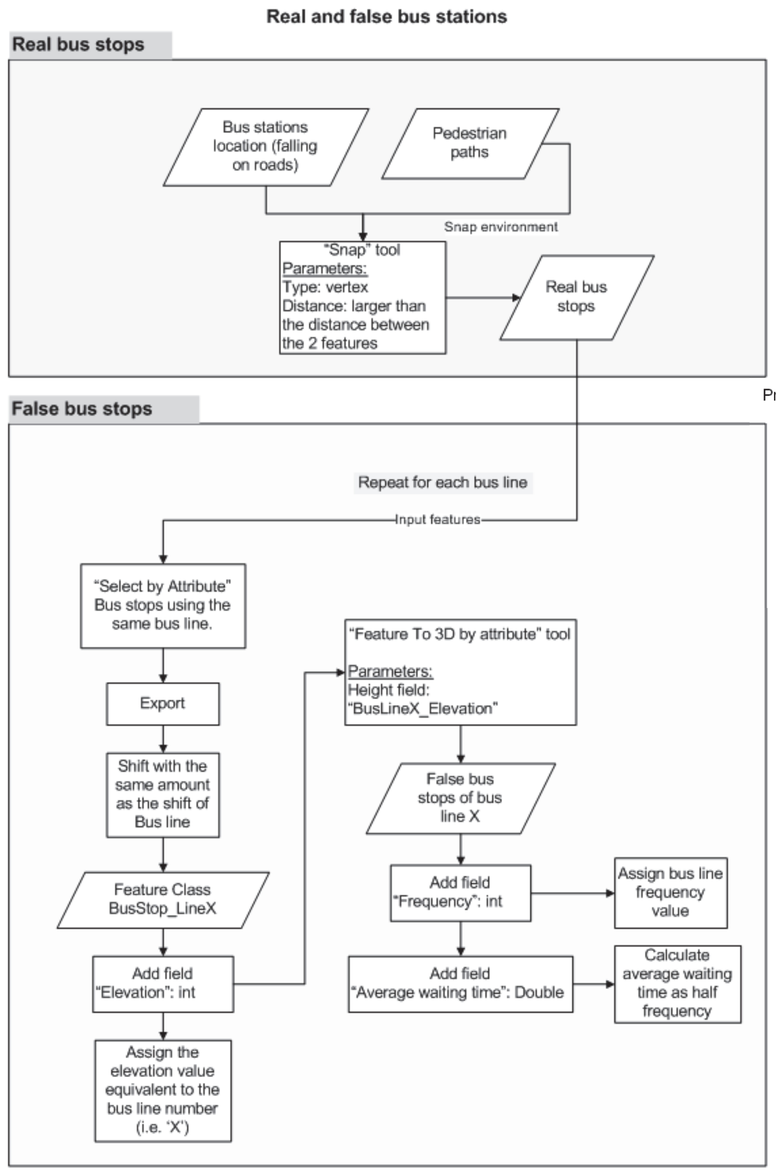

Figure 3-16: Bus lines preparation process

#### 3.4.2.2. Bus stops

Assuming that bus stations locations and names are available in digital format. The first step is to snap them to the pre-prepared pedestrian paths. In real life, a station is usually on pedestrian sidewalks so that passengers can wait there safely and also reach it on foot. Only at the moment when the bus arrives, a passenger move from pedestrian to bus network through bus stations. From that concept, bus stations should be geometrically coincident with pedestrian paths. Also, there should be a connection between pedestrian network and bus routes at the locations of stations to model people physical movement (mode change) from a station (pedestrian mode) to the bus (bus mode). Modelling people's transfer between bus and walking needs the following three datasets:

1- Bus stops: point feature coincident on pedestrian network representing real bus stops that enables the transfer between walking and bus mode. Throughout the work it will be named "real bus stops".
2- Bus connector: line feature connecting real bus station (on the pedestrian path) to its projection on the bus line.
3- False bus stop: points features coincident on a bus route, representing the projection of "real bus stations" on the bus route.

The preparation process for the bus stations to comply with the model concept (Figure 3-17) is presented in Figure 3-18. The first part about the real bus stops preparation, it consists of snapping the given bus line points to the pedestrian paths, then add elevation field with value equal to zero. Based on this field the points are transformed to 3D elements (with zero value).
Second block is about preparation of "false bus stops" those representing bus stops locations on the bus route. The first step is selecting the bus stops serving each bus line and exports them to a separate dataset. Then shift it with the same X and Y amount of the shift of the bus lines. After that, elevation field is added with a value equivalent to the bus line number. This field is used to transform the false bus stops to 3D elements. After that the waiting time field is added with value equivalent to half the frequency of the bus line.



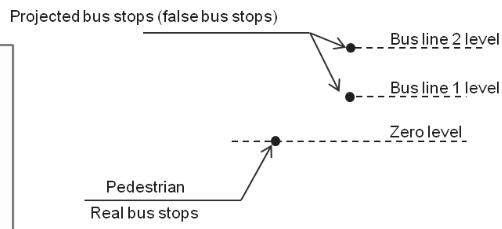



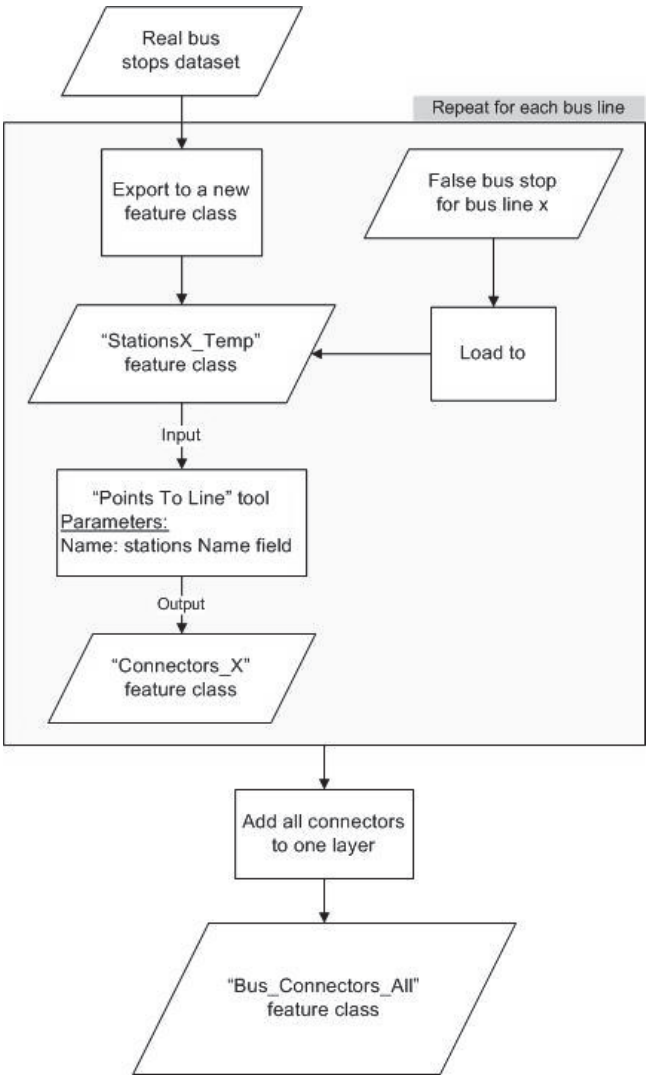

Figure 3-17

Figure 3-18: Real and false bus stops preparation process

#### 3.4.2.3. Bus Connectors

Third step is the generation of the connectors between real and false bus stops that model the physical movement of a person from/to bus (Figure 3-19). Also, boarding and alighting impedances are assigned to these connectors. Using point to line tool a line is drawn between each couple of real and false bus stop at the same location (with the same name). Figure 3-20 shows the preparation details.

The "Points to line" tool has as input a point dataset (feature class) and a field name. It draws a line between every couple of points having the same value at the given field. For that, a temporary feature class is prepared containing the real bus stops and the false stop of a bus line. This temporary feature class is used as input for "Points to line" tool. The false bus stops feature class is a subset of the real bus stops, so for the bus stop (at real bus stops feature class) and its projection (at the false bus stop) the name is the same. Therefore the "Points to line" tool can draw a line (connector) between them. This process is repeated for each bus line. All the connectors are afterwards collected in one feature class representing the bus connectors between real bus stops (on pedestrian paths) and the different false bus stops of the different bus lines.



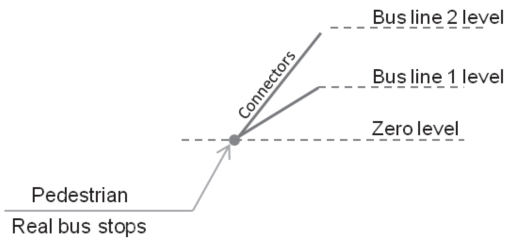




Figure 3-19

Figure 3-20: Bus Connectors generation process

### 3.4.3. Cycling

This section describes the preparation process for cycling mode. First part is the preparation of cycling paths then the following part about bike parking facilities available at transfer points (bus stops and train stations) and last part about the links that connect the cycling network to the pedestrian network.

As mentioned in section 3.2.3 and the introduction part of this chapter, cycling network location in the model is on top of pedestrian network. So, assigning an elevation value to the pedestrian network lines and using this elevation to transform it to 3D attributes will provide us with the cycling network paths. Speed and travel time attributes are added after that. Figure 3-21 describes the preparation steps for the cycling network paths.

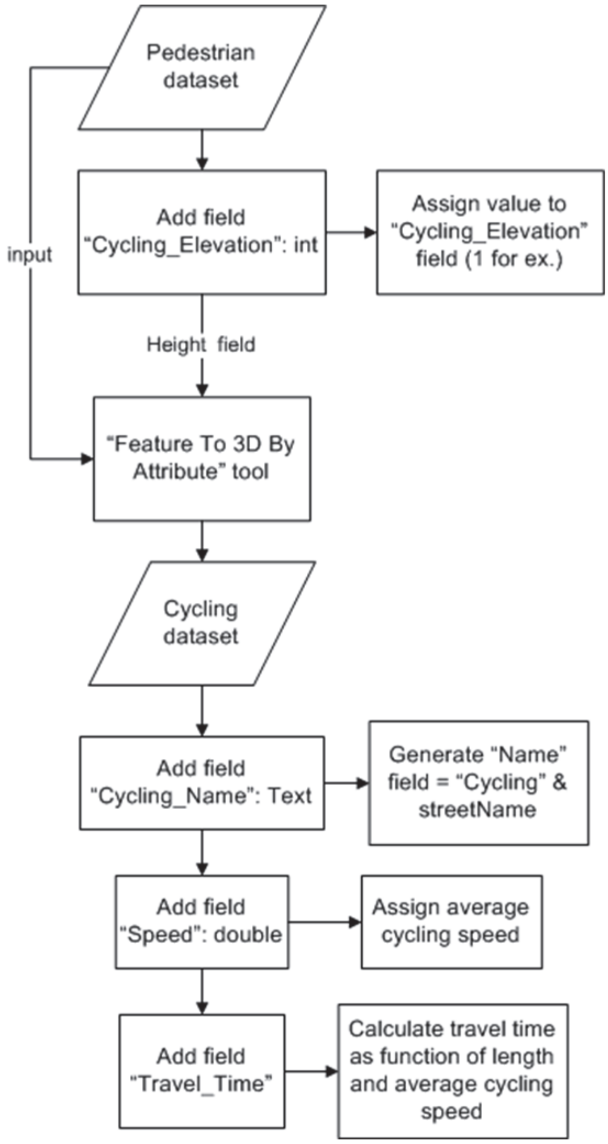



Figure 3-21

The model considers only bike parking facilities that are available at transfer points (bus stops and train stations). Bike parking facilities are considered in the model in first place to enable connectivity in case of its existence between cycling and the other mode at the transfer point. Assuming that in Netherlands, at any train station there must be a place to park bike. All train stations are considered as locations where bike parking is available. For bus stops, some have this facility and others don't. So, an attribute having such information about each bus stop helps select those that have bike parking facility.

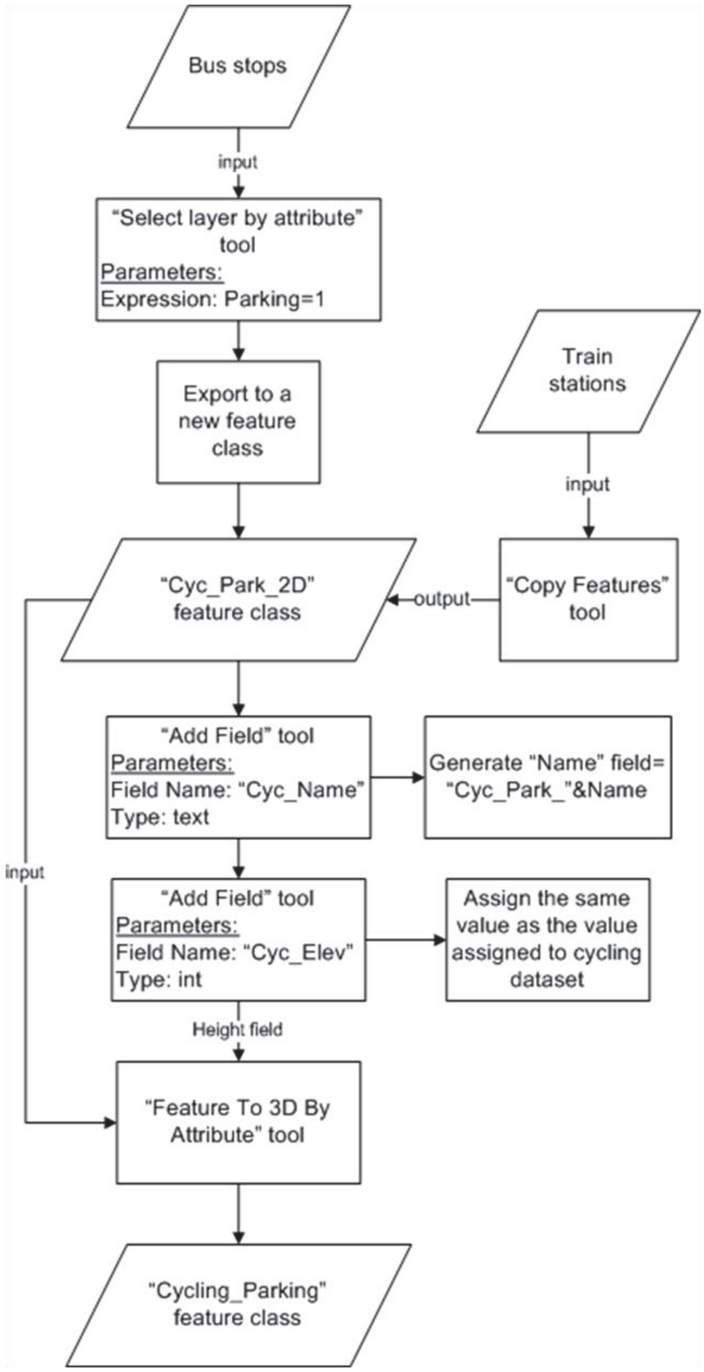



Figure 3-22: Cycling parking generation details

Adding those selected locations to train stations location will give all transfer points with available bike parking facility. After that an elevation value equivalent to the one of the cycling network is assigned to these locations. Based on this elevation value bike parking locations at transfer points are transferred to 3D features at the same level of the cycling network (Figure 3-22).

Final part is the generation of links between bike parking and transfer points. This is done by the "Points to line" tool that draws a line between each couple of points having the same name. A bike parking and transfer point at the same location have the same name as they were originally one before the 3D transformation. Parking time and the time needed to ride the bike again and go is assigned to these links (Figure 3-23).

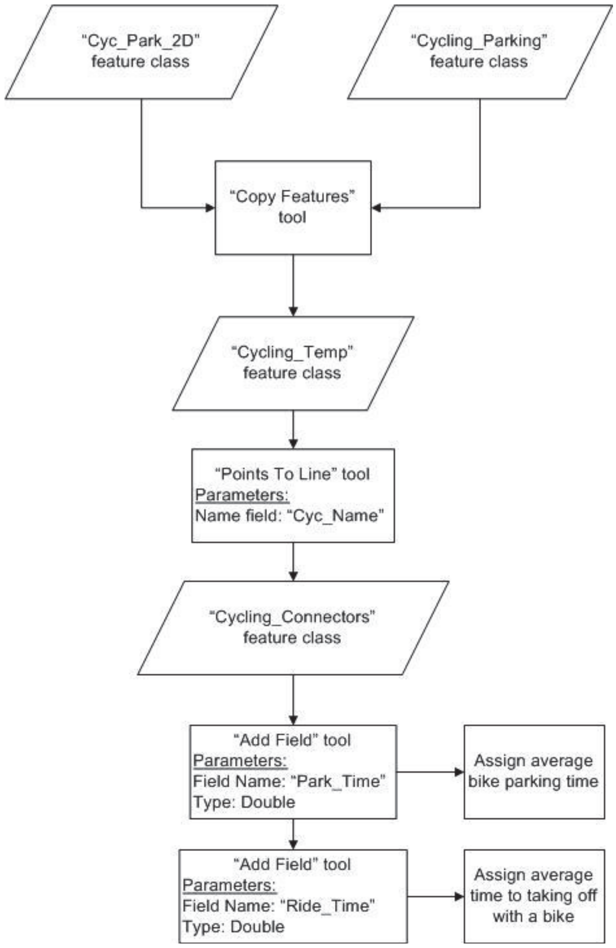


Figure 3-23: Cycling connectors' generation details

#### 3.4.4. Train

Figure 3-24 shows this preparation made on railroads to work as the train network. It simply consists of adding travel time field as travel cost and assures the existence of a name field.

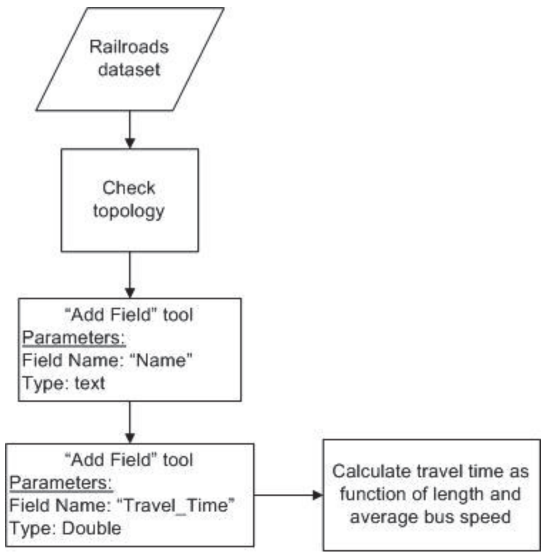


Figure 3-24: Train network preparation

For the train stations, Figure 3-25 describes the preparation process. First step would be check that train stations points are coincident with railway lines. After that, some fields are added, the name field (in case it does not exists), waiting time field with value equal to half the train frequency.

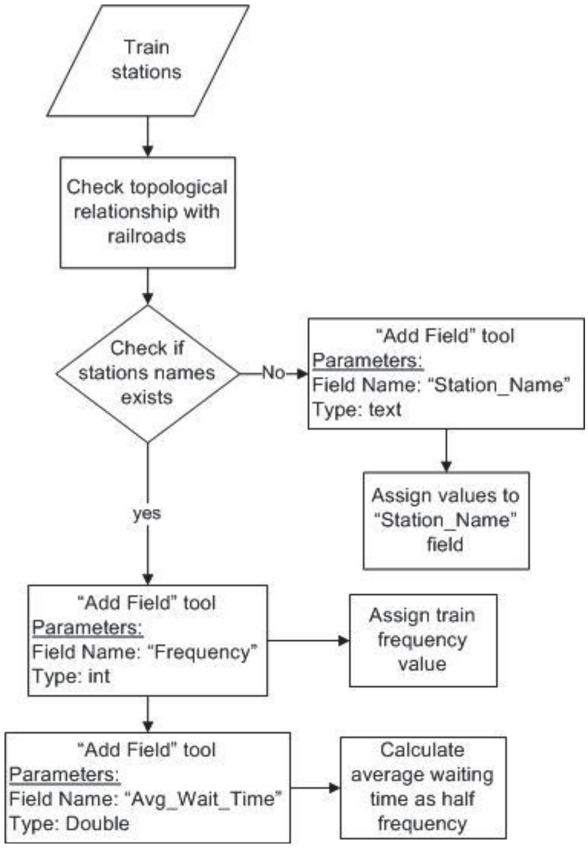



Figure 3-25: train stations preparation

Train stations are accessible through pedestrian paths. Pedestrian paths here are represented by the road center lines. However, it is not necessary that the given roads center lines are linked to the train stations as the source of both datasets can be different. For that, and to ensure that the train stations falls on one of the segments of the pedestrian paths, lines connecting the train stations to the nearest line of pedestrian paths is created and added afterwards to the pedestrian paths. Figure 3-26 shows the steps of creating those lines. The "Generate near table" tool takes two feature classes as input (one as "input features" and another as "near features"). It generates a table with the nearest locations to the input features on the nearest features. This means it calculates the location (x, y) of the nearest point on the pedestrian paths to the train stations. For the train stations, the x and y information are added using the "Add XY coordinates" tool. Joining the two tables, the output of the "Generate near table" tool and the train stations, gives a table having the x and y for each train station and the x and y of the nearest point to it on the pedestrian paths. Using this table as input for the "XY to line" tool would generates the desired lines.

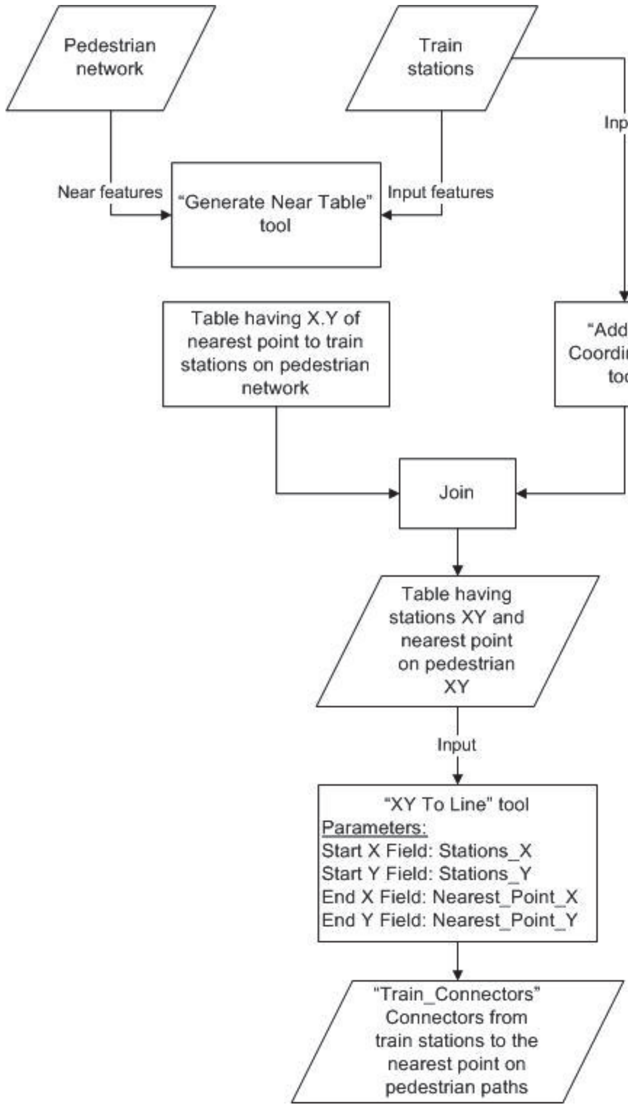



Figure 3-26: train stations connectors to pedestrian

## 3.5. Automating the data preparation process

It is clear that the data preparation process described in the previous section is long and in some parts repetitive too. In case of a large data size, the preparation process becomes even more inconvenient. A suggested way to automate the data preparation process is making use of the ArcGIS model builder. The ArcGIS model builder allows the automation of a process as a sequence of tools is one model that can be repeated. As described in the previous section, all the steps are done using the standard ArcGIS tools, so each of the diagrams of section 3.4 is converted to a model in model builder. Each of these models give as final output one of the feature classes to participate in the network. The developed models are available at Annex1.

## 3.6. Building the multimodal network:

Network dataset in ArcGIS following the below steps:

1- New network dataset
2- Feature classes participating in the network dataset (with sample of only 3 bus lines):
    - BusLine1
    - BusLine2

- BusLine3
- Bus_Connectors
- Cycling_Connectors
- Cycling
- Pedestrian
- Railroads
- Cycling_Parking
- FalseBusStops_Line1
- FalseBusStops_Line2
- FalseBusStops_Line3
- RealBusStops
- TrainStations

3- Connectivity is set using the connectivity groups of ArcGIS. A connectivity group is a group of one edge element and a number of junction elements. Connectivity between groups is established if they share junction elements. Table 3 shows how the elements are connected together following the connectivity group concept. A column represents one connectivity group. The shaded rows are edge elements.

Table 3: Connectivity table with a sample of 3 bus lines

| | G1 | G2 | G3 | G4 | G5 | G6 | G7 | G8 |
|---|---|---|---|---|---|---|---|---|
| BusLine1 | √ | | | | | | | |
| BusLine2 | | √ | | | | | | |
| BusLine3 | | | √ | | | | | |
| Bus_Connectors | | | | √ | | | | |
| Cycling_Connectors | | | | | √ | | | |
| Cycling | | | | | | √ | | |
| Pedestrian | | | | | | | √ | |
| Railroads | | | | | | | | √ |
| Cycling_Parking | | | | | √ | √ | | |
| FalseBusStops_L1 | √ | | | √ | | | | |
| FalseBusStops_L2 | | √ | | √ | | | | |
| FalseBusStops_L3 | | | √ | √ | | | | |
| RealBusStops | | | | √ | √ | | √ | |
| TrainStations | | | | | √ | | √ | √ |

4- This model's main idea is the use of 3D capabilities of the software to overcome the problem of overlapping routes, all the features participating in the network are 3D features having an elevation value even if it is zero like the pedestrian and the train stations. So all feature classes have elevation field and the elevation connectivity would be modelled on these elevation fields.

5- Set up of impedances (cost) attributes
Impedances considered in this model are time and distance. In section 2 of this chapter, time cost for each part of the network is described and Table 4 how the cost attributes is assigned to the network.

Table 4: Travel impedances (time and distance) as assigned to different network elements.

| | Time | | Distance | |
|---|---|---|---|---|
| | From-To | To-From | From-To | To-From |
| BusLine1 | Travel_Time | Travel_Time | Shape_Length | Shape_Length |
| BusLine2 | Travel_Time | Travel_Time | Shape_Length | Shape_Length |
| BusLine3 | Travel_Time | Travel_Time | Shape_Length | Shape_Length |
| Bus_Connectors | Emb_Time | Disemb_Time | --- | --- |
| Cycling_Connectors | Park_Time | Ride_Time | --- | --- |
| Cycling | Travel_Time | Travel_Time | Shape_Length | Shape_Length |
| Pedestrian | Travel_Time | Travel_Time | Shape_Length | Shape_Length |
| Railroads | Travel_Time | Travel_Time | Shape_Length | Shape_Length |
| Train_Connectors | Travel_Time | Travel_Time | Shape_Length | Shape_Length |
| Cycling_Parking | --- | | | |
| FalseBusStops_L1 | Average waiting time | | --- | |
| FalseBusStops_L2 | Average waiting time | | --- | |
| FalseBusStops_L3 | Average waiting time | | --- | |
| RealBusStops | --- | | --- | |
| Train_Pedestrian_Junctions | --- | | --- | |
| TrainStations | Average waiting time | | --- | |

Time cost is the combination of all the spent time using a mode or changing modes.”Travel_Time” attribute of a mode is the ravel time along a line segment of this mode as calculated by this formula: Travel_Time=D/V where D is the shape length of the segment (distance) and V is the mode speed. Connectors model the switch between modes so different time impedances like waiting time and the time necessary to embark and disembark is assigned to the connectors and transfer points. For the bus connectors, “Emb_Time” is the time necessary for a person to embark to a bus while “Disemb_Time” is the time necessary for a person to disembark. Time cost for cycling connectors are “Park_Time” and “Ride_Time” representing the time necessary for a person to park his bike and the time to ride it again and go. The average waiting time is assigned to the stations (bus and bike).

For the distance cost, length of different modes routes segments represents the distance impedance. For different connectors, length does not represent anything. They only represent the transfer between modes so it has time and cost impedances but no distance impedance as transfer happens in the same point with no extra distance required.

# 4. IMPLEMENTATION

To test the model, it is constructed following the methodology described in the previous chapter using a real dataset of Enschede city, Netherlands. This chapter describes this implementation to transform the available transportation data for Enschede to a multimodal transportation network using ArcGIS then test the model with some network analysis functionality in a multimodal context.

## 4.1. Available data and data preparation

The data used for Enschede city for this research is prepared by the researcher. The implementation is mainly done to test the working of the concept and methodology discussed in the previous chapter, therefore the data used does not require being of high geographical accuracy. The data should represent the different modes of transport such that it represents a multi modal transport system correctly for the study area

In this section the data preparation process is reviewed. It consists of 2 phases: the first is preparing the raw data set which represents the actual geographical features of the roads, bus stations, bus lines, train stations and train railway. The second is preparing them according to the model requirements like generating connectors or calculate the required attributes (travel cost).

### 4.1.1. Phase 1

At the beginning of this phase, the available data were:

- Road center line dataset for Enschede in digital format (Source: ITC)
- A paper map for the bus network (Connexxion, 2011)
- The part of the railway crossing Enschede and train stations serving Enschede in digital format also (Source: ITC)
- A paper map showing the cycling paths in Enschede (Gemeente Enschede, 2008)

The required output of this phase is to have a separate feature class for the actual geographical features of each mode:

- Pedestrian paths
- Bus lines routes (one feature class for each)
- Bus stops
- Cycling paths
- Bus stops and train stations where cycling parking is available

The methodology described in the previous chapter uses the road centre lines as the base to generate the different edges of the network (bus routes, pedestrian paths, cycling paths) representing the different modes which operate on the roads (buses, walking and cycling). For that the first step is to prepare the road center lines. A dataset for the roads center lines was available. Some modifications were performed to fix topological problems like duplicated lines (Figure 4-1) or to delete lines which are not parts of the road centre line, like those lines which were just paths inside parks not roads (Figure 4-2). In brief, it was modified so that each road is presented by one line in the dataset. Figure 4-3 shows the roads center lines produced and the available one.

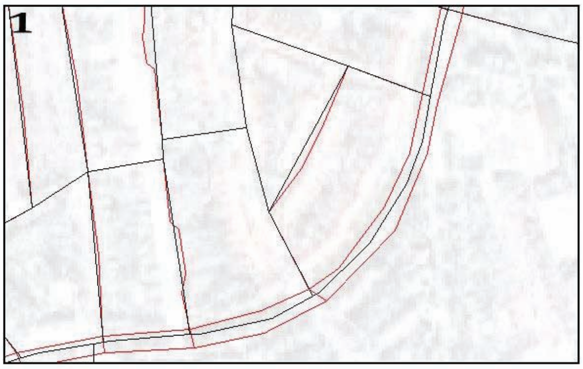



Figure 4-1


Figure 4-2

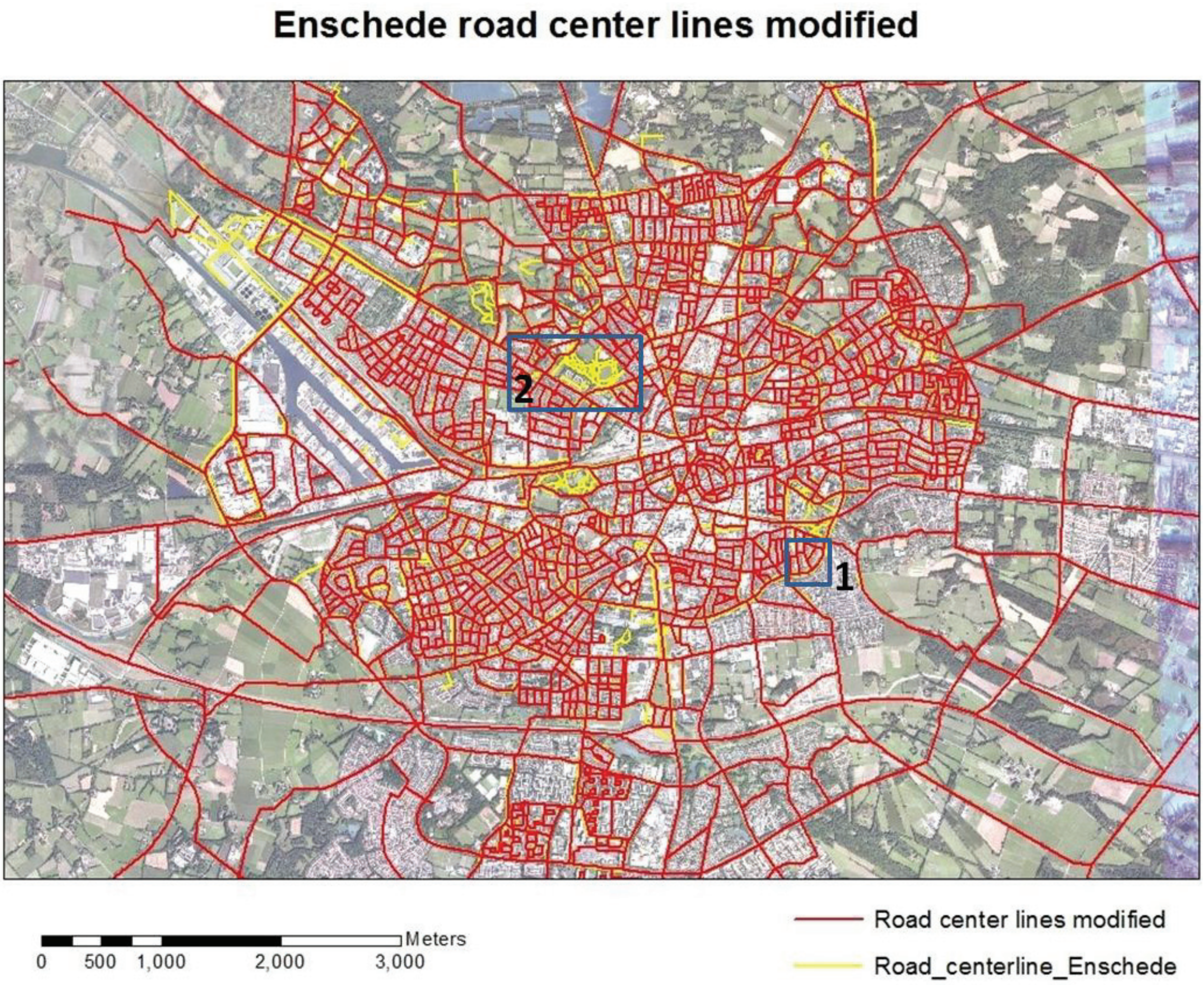



Figure 4-3

Roads are the infrastructure on top of it operates the bus so it is used to delineate the bus lines. Having Enschede road centre lines ready, and with reference to the paper map of bus network of Enschede (Figure 4-4), the roads centre lines representing one line route are selected and exported as a separate feature class. That way a single feature class for each bus line route is prepared.


Figure 4-4: Enschede bus network (Connexxion, 2011)


Also this paper map is used to prepare the feature class of the bus stops. Bus stops locations are obtained as points feature (Figure 4-5) from open street maps. Using the paper map as reference also, stations were prepared by assigning to each bus stop its name and the bus line or lines it serve after deleting unnecessary or duplicated points. After that the final points (bus stops) were snapped to the roads centre lines.
Figure 4-5 shows the output of this process which is Enschede bus stations.

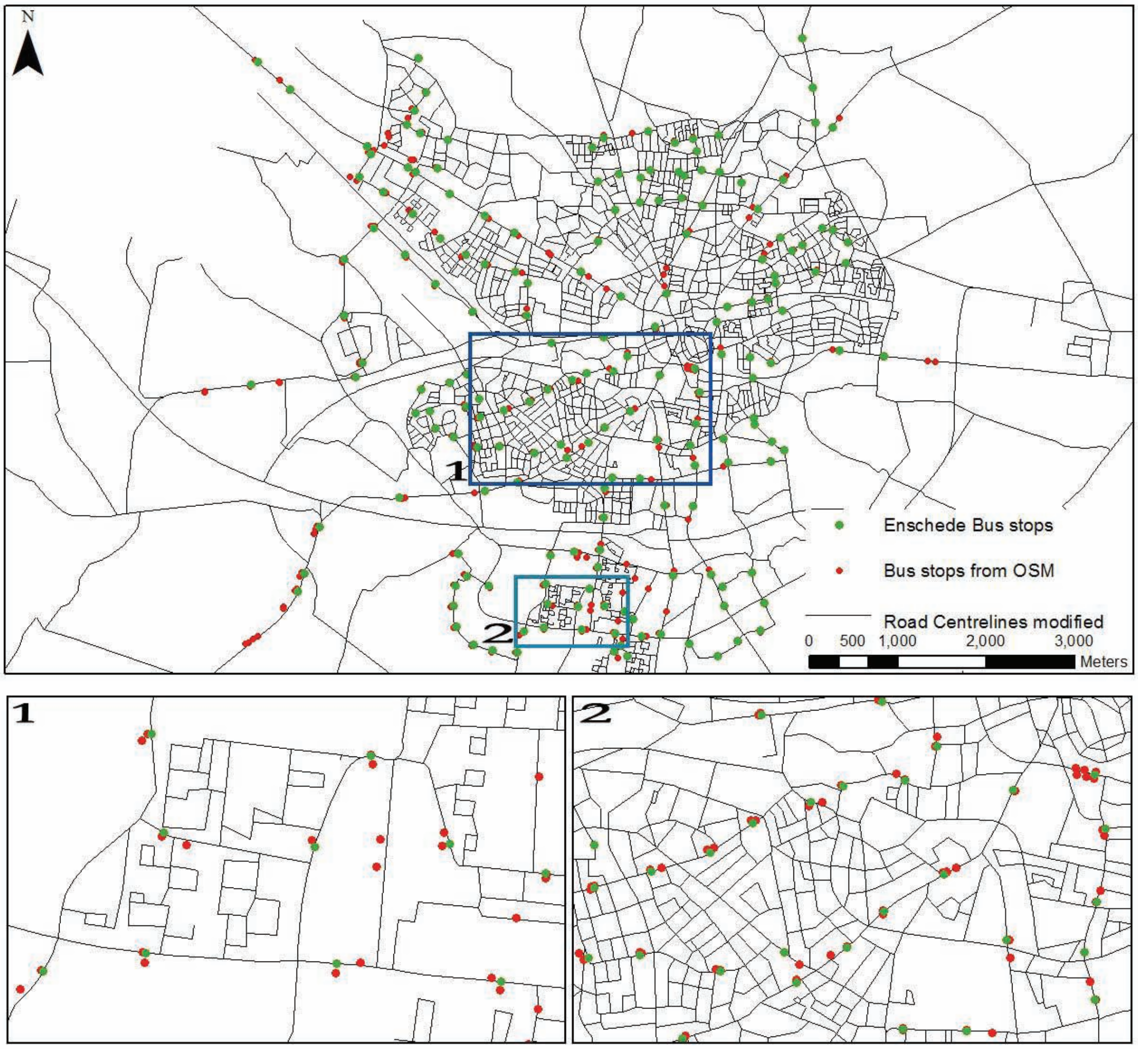



Figure 4-5: Enschede Bus stops

Figure 4-6 shows a paper map for the cycling network of Enschede city. Using this paper map of the cycling paths, the matching roads centre lines to these paths are selected and exported as cycling network. Figure 4-7 shows the output, the produced cycling network of Enschede city.

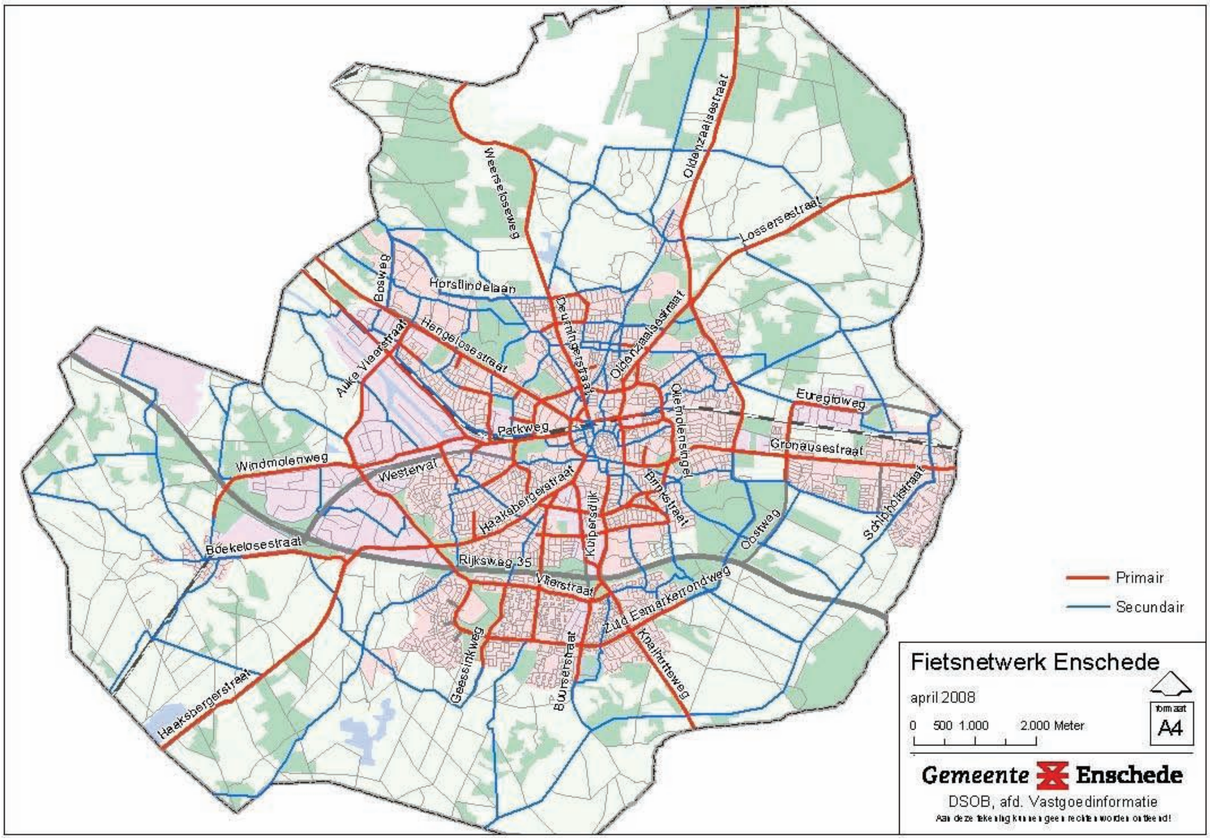



Figure 4-6: Cycling network (Gemeente Enschede, 2008)

Enschede cycling paths with stations having bike parking facility

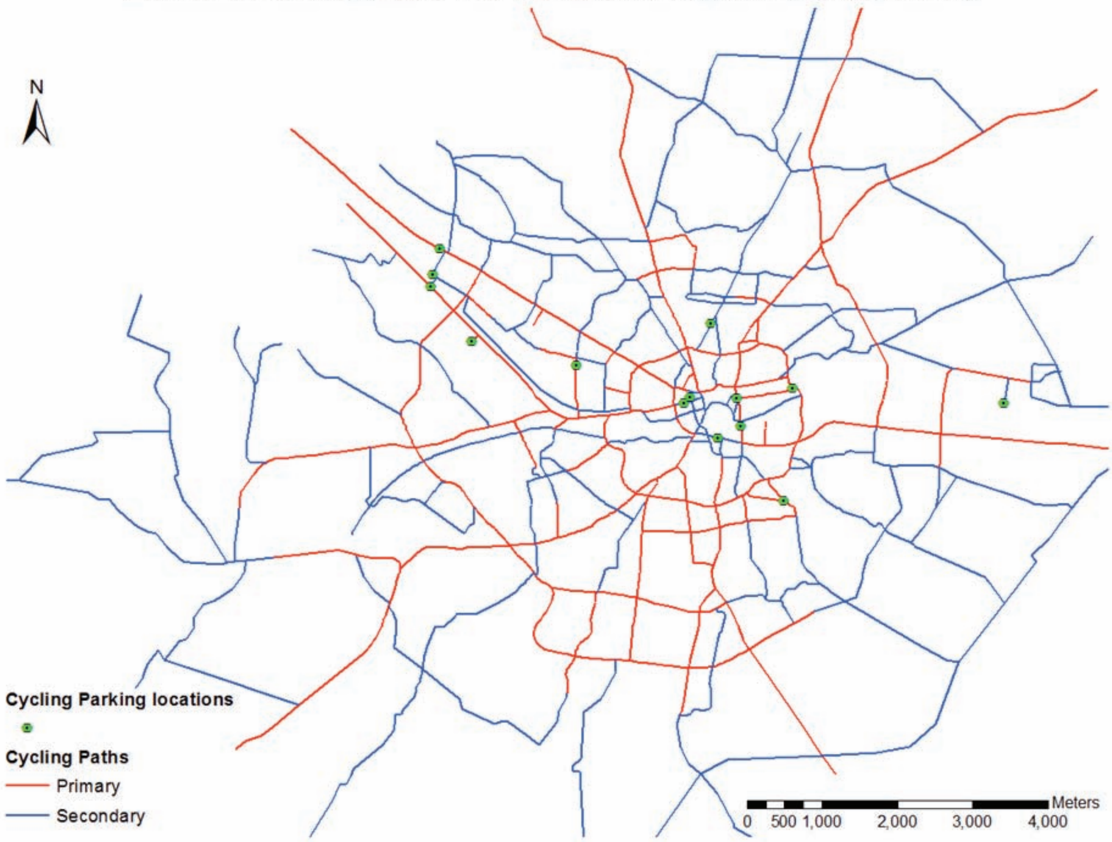



Figure 4-7: produced cycling paths

To produce the transfer points (bus stops, train stations) where bike parking facility is available, a survey was done for bus stops to check which ones have bike parking (Figure 4-8). Later those bus stops with bike parking available were selected and exported as the bike parking points in addition to the train stations which all have bike parking facility. A topological check is made after that to check that all cycling parking points are coincident with cycling paths. Some points which were not snapped with the bicycle paths like the train stations for instance were connected with cycling paths. Figure 4-7 shows the produced bike parking facility available at transfer points.


Figure 4-8: bus stations where parking bikes is available

Railway feature class was already available as well as train stations. The output of this phase is an ArcGIS geodatabase containing feature class for Enschede for the following:

- road centre lines
- real bus stops: a feature class containing all the bus stops (names, served bus lines, availability of bike parking)
- 18 bus lines (one feature class for each)
- railway
- train stations
- cycling paths
- cycling parking at transfer points(stops/stations)

Figure 4-9 shows the output of phase 1 of data preparation which is the different modes paths of Enschede city.

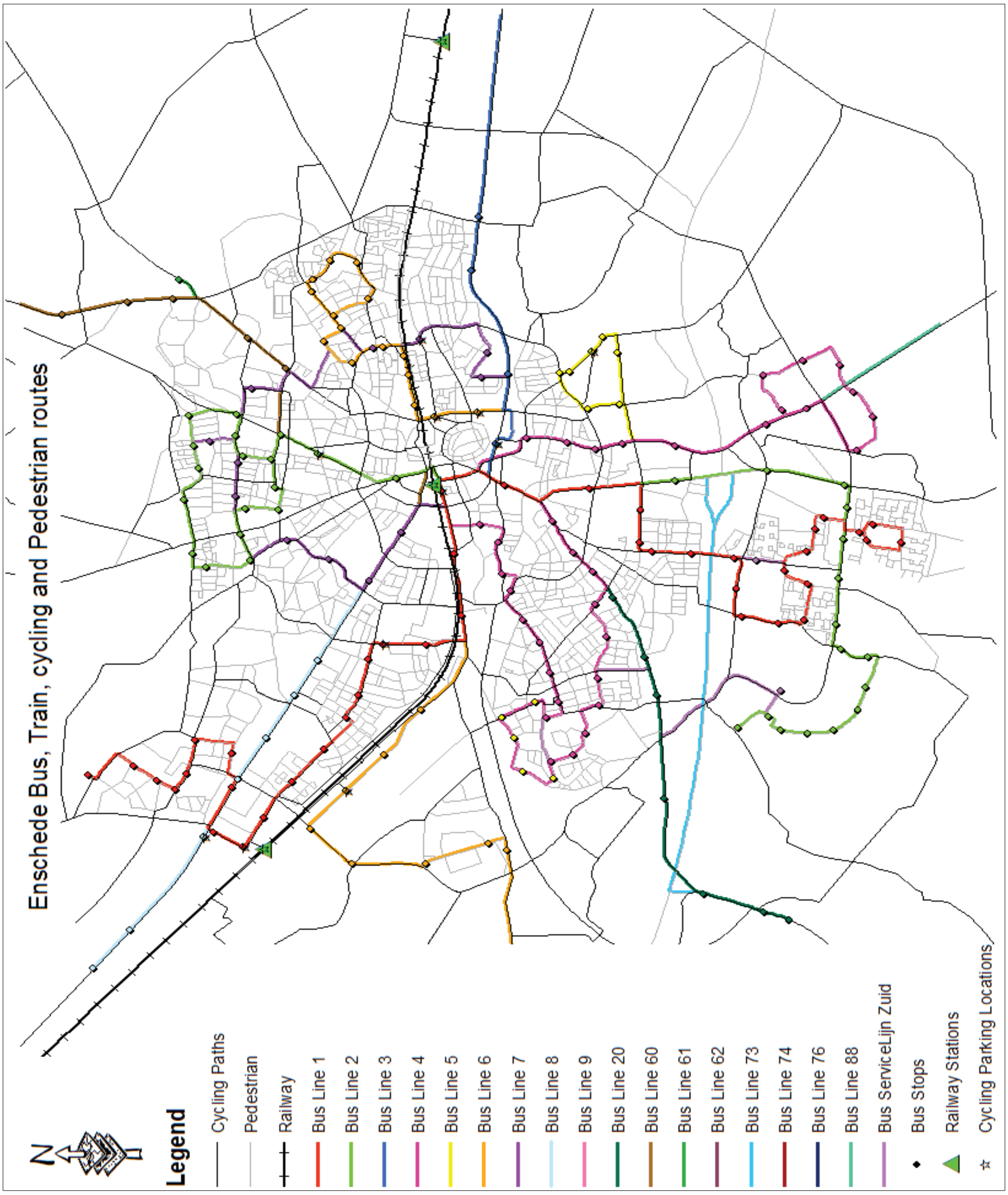



Figure 4-9: Enschede modes paths

#### 4.1.2. Phase 2

This section is about preparing the data to meet the model requirement. Following the methodology described in Chapter 3, the data was prepared to meet the modelling requirement described. The data preparation process described in diagrams in chapter 3 is implemented using ArcGIS tools.

##### 4.1.2.1. Train

Railway feature class is converted to 3D with Z-values of zero as well as train stations. Railway feature class is prepared to be in the format that each link between two train stations is one separate line. The following attributes has to be attached to the railway feature class:

- Elevation: with a value of Zero
- Speed: with a value of 60 (km/h) which is assumed to be the average train speed
- Travel time: in minutes calculated as function of the speed with this formula (ShapeLength * 60/Speed*1000) derived from the basic function of speed (speed=distance/Time)
- Name: calculated as "train from (station A) to (station B)"

Train stations are accessible through pedestrian paths. So train stations should be connected to the pedestrian network. Connector lines between train stations and nearest edge of the pedestrian network is generated and added after that to be part of the pedestrian network. "Generate near table" tool is used to generate a table with X and Y information of the nearest location on pedestrian network to the train stations. Using "Add XY Coordinates" tool the X and Y information of train stations locations is added. Joining the generated table with the train stations the X&Y of the train stations and the X&Y of the nearest point on pedestrian network is available at one table. This table is used as the input table for the "XY to Line" tool to generate line connectors between train stations and pedestrian. This tool takes a start X and start Y and an end X and an end Y which are the X and Y of the train stations and the nearest points on pedestrian. These generated lines are added to the pedestrian network.

##### 4.1.2.2. Pedestrian

According to the methodology, the road centre lines is used as the pedestrian paths, however some more steps are required for it to match with the model. For example, for connectivity issues, pedestrian network must be split at bus stops location. This is because the connectivity between pedestrian network and bus network is done through 3 elements:

- Real bus stops (at pedestrian lines)
- False bus stops (at bus lines routes)
- Connectors connecting real and false bus stops

So real bus stops locations should be at a vertex of pedestrian network therefore pedestrian network is split at bus stops locations (Figure 4-10).

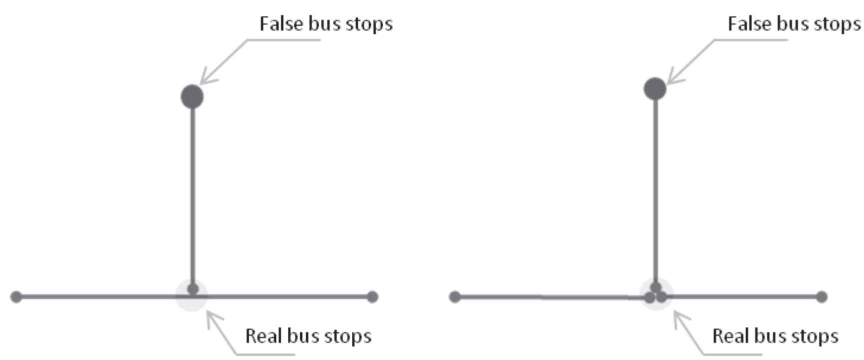



Figure 4-10: split for connectivity

One important step that is to be performed for every feature class is to convert it to 3D features. In this network model, connectivity is established based on the Z value of the participating feature classes, therefore it should have a Z value.. This can be obtained by converting the feature class to a 3D feature class. This is performed by the "Feature to 3D by Attribute" tool. This tool converts the feature class to 3D based on a field value. For the pedestrian and according to the setup discussed before, pedestrian is at Z-value Zero.
A number of attributes have to be at the pedestrian feature class. First the elevation value based on it the feature class acquires its Z value. Also for all the features participating in the network, travel time value is needed to work as the travel cost. Another travel cost considered is the distance, but it does not require extra attributes as it is already calculated for every line geometry at a field named "shapeLength". The following attributes (fields) are added to the pedestrian feature class:

- Elevation: with a value of Zero
- Speed: with a value of 5 (km/h) which is assumed to be the average human walking speed
- Travel time: in minutes calculated as function of the speed with this formula (ShapeLength * 60/Speed*1000) derived from the basic function of speed (speed=distance/Time)
- Name

#### 4.1.2.3. Bus

From preparation phase 1, 18 feature classes are prepared one for each bus line route carrying the segments representing its route. Following the parallel lanes concept described in chapter 3, bus lines routes are modelled as parallel lines to the pedestrian (roads centre lines) line features. Therefore, bus lines feature classes are shifted in the X and Y direction. The relation between the pedestrian and the bus lines can be seen in Figure 4-11. Also a copy of the bus stops is shifted with the same amount as the bus lines.

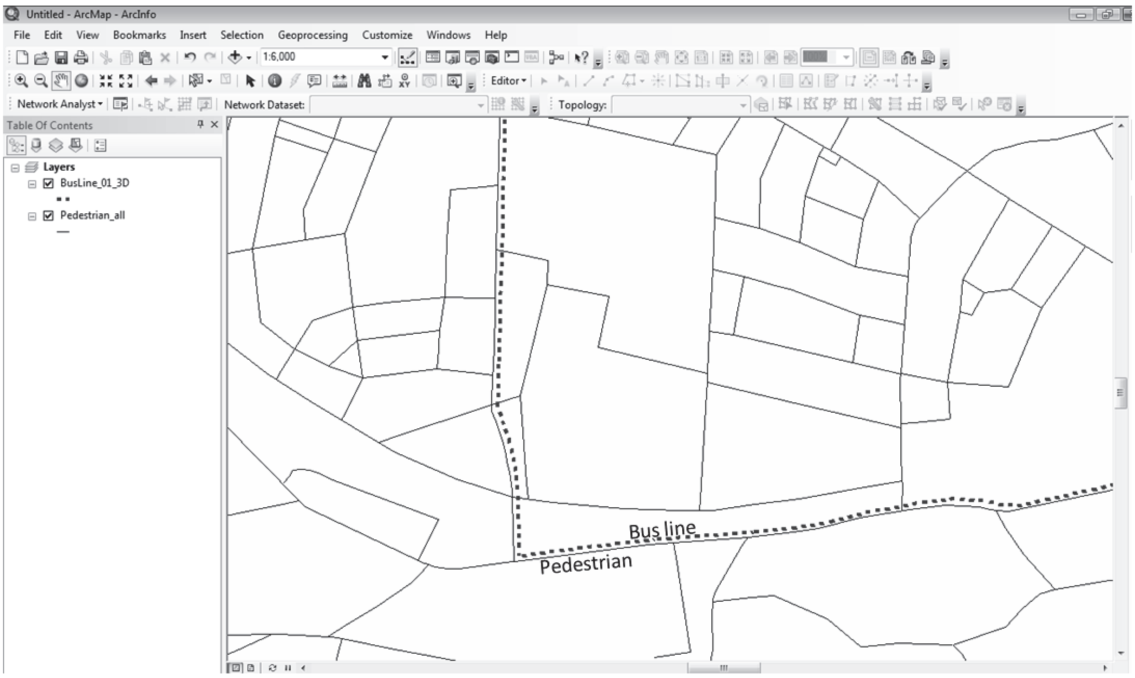



Figure 4-11: The relation between bus line route and pedestrian paths

Now a separate feature class for each bus line stops is produced. Bus stops serving the same bus line are selected and exported to a separate feature class. Bus lines route (line feature) are connected with the rest of the network edges through the so called "false bus stops" which are coincident with bus line and are

the projection of "real bus stops" coincident with the pedestrian edges. Therefore and for the sake of connectivity, each bus line route (line feature class) has to be in the format that every link between two bus stops is a separate segment. So each bus line route is split at the "false bus stops" of the same line. For example, feature class of bus line 2 is split at the location of bus stops 2. This is done using the "Split Line at Point" tool.
Then comes the step of the 3D, each bus line route and bus stops of the same line are assigned an elevation value equivalent to the bus line number. Bus line 2 has an elevation of 2 using "Feature to 3D by Attribute" tool.
The following attributes has to be calculated for each feature class of each bus line route:

- Elevation: with a value equivalent to the bus number
- Speed: with a value of 45 (km/h) which is assumed to be the average bus speed
- Travel time: in minutes calculated as function of the speed with this formula (ShapeLength * 60/Speed*1000) derived from the basic function of speed (speed=distance/Time)
- Name: with the value "bus line number (x)"

For the "false bus stops" the following attributes has to be calculated for each feature class:

- Elevation: with a value equivalent to the bus number
- Name
- Average waiting time: calculated as half of the bus frequency which is assumed to be 15 Minutes for all

"Real bus stops" is the feature class produced at data preparation phase with all the bus stops of Enschede city. It is geometrically coincident with the pedestrian paths, however some attributes has to be attached to it:

- Elevation: calculated as Zero like the pedestrian paths
- Name

It is converted to 3D also based on the "Elevation" field.
Having false bus stops and real bus stops ready bus connectors can be generated. Bus connectors are the line connecting the false bus stops and the real bus stops therefore connecting bus lines to pedestrian paths. For each bus line, a temporary feature class is made consisting of real bus stops and the false stops of one bus line. Using the "Points to Line" tool, connectors are generated with this temporary feature class. It has pairs of points with the same name (one from the real bus stop and the other from the false bus stop).the tool draws a line between each pair having the same name (Figure 4-12).

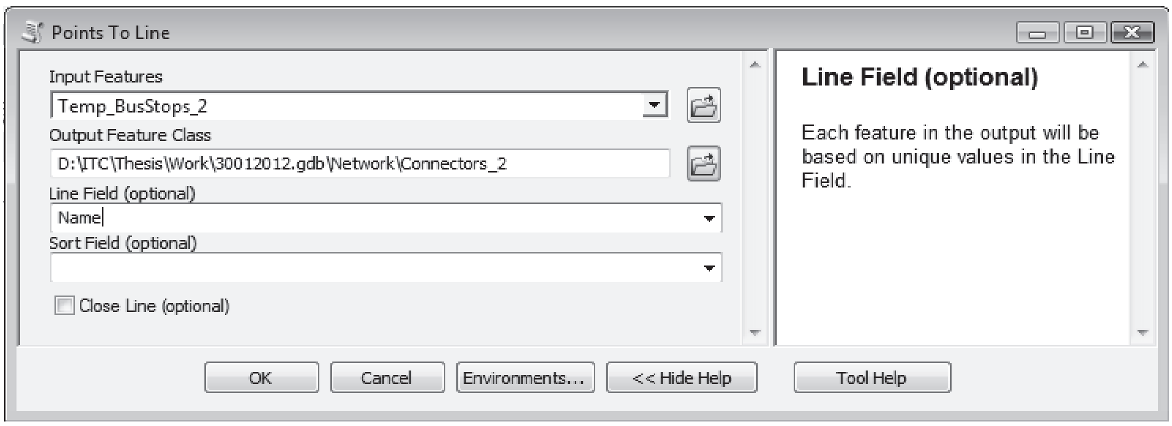



Figure 4-12: Points to line tool to generate bus connectors

The connectors produced for each bus lines are all added in one feature class. For this feature class having all the connectors between all the bus lines and the pedestrian, the following attributes have to be calculated:

- Name: calculated as "bus connector at station" & the bus stop name
- Boarding time: equivalent to the time necessary to board a bus (assumed to be 0.5 min)
- Alighting time: equivalent to the time necessary to alight from a bus (assumed to be 0.5 min)

#### 4.1.2.4. Cycling

Cycling paths are converted to 3D based on any value other than zero (the elevation value of the pedestrian) because the important that it be on different elevation than the pedestrian. "Elevation" field (attribute) is added to Cycling paths feature class and assigned a value of 5. The following attributes also have to be calculated for the cycling paths feature class

- Elevation: with a value different than the one of the pedestrian (here the value 5 is used)
- Speed: with a value of 20 (km/h) which is assumed to be the average cycling speed
- Travel time: in minutes calculated as function of the speed with this formula (ShapeLength * 60/Speed*1000) derived from the basic function of speed (speed=distance/Time)
- Name

The prepared cycling parking feature class prepared at data preparation phase 1 is also converted to 3D with the same value of cycling paths. That way they are at the same level. Cycling connectors are generated afterwards using the same technique used in generating bus connectors. Only for cycling connectors the points used are the cycling parking points before and after the 3D conversion (points at level 0 and at level 5). The following attributes also have to be calculated for the cycling connectors feature class

- Elevation: with a value different equivalent to the one of cycling paths
- Name: calculated as "Cycling connector at" & the bus stop or train station name
- Riding time: equivalent to the time necessary to ride the bike and start moving (assumed to be 0.5 min)
- Parking time: equivalent to the time necessary to park the bike (assumed to be 0.5 min)

The output of this phase is a geodatabase with the following feature classes:

- Pedestrian
- Real bus stops
- Railway
- Train stations
- Cycling
- Cycling parking
- Cycling connectors
- 18 bus lines: line feature classes one for each bus line route
- 18 bus stops: points feature class one representing bus stops of each bus line
- Bus connectors:

### 4.2. Building the network

After preparing the data set to match the model requirement, this section describes the multimodal network building. The network is built using ArcGIS network builder. This is performed by creating a network dataset in which the participating network elements (features classes) are defined, how they are connected to each other and the impedance value for each of the network elements.
The feature classes produced in the previous phase are used as the input network elements (edges and junctions). The connectivity of the network elements is defined with the so called "connectivity groups". A connectivity group is a group of one edge element and a number of junction elements. Connectivity between groups is established if they share junction elements.
The connectivity in this multimodal network is working as following. Pedestrian paths (edge element) are connected to the "real bus stops" (junction element) and the railway stations (junction element) which are both accessible through pedestrian paths and geometrically coincident with it. Railway stations are also connected to railway lines (edge element). This way, pedestrian and railway are connected to each other only at railway stations locations (Figure 4-13).

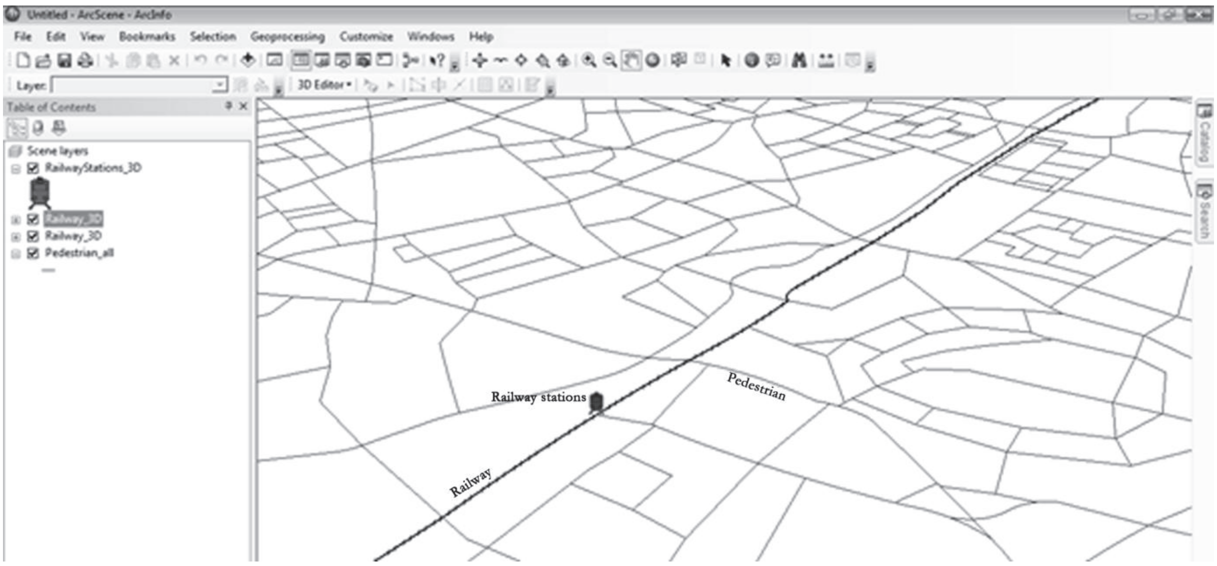



Figure 4-13: the connection between pedestrian paths and railway through railway stations

The other junction element connected to the pedestrian paths is the "real bus stops". Real bus stops are connected to the edge element "bus connectors" which connects the pedestrian paths to the bus lines through two junction elements: real bus stops and the false bus stop of the connected line. Figure 4-14 shows the relation between bus connectors and real bus stops from one side and different false bus stops from the other side.

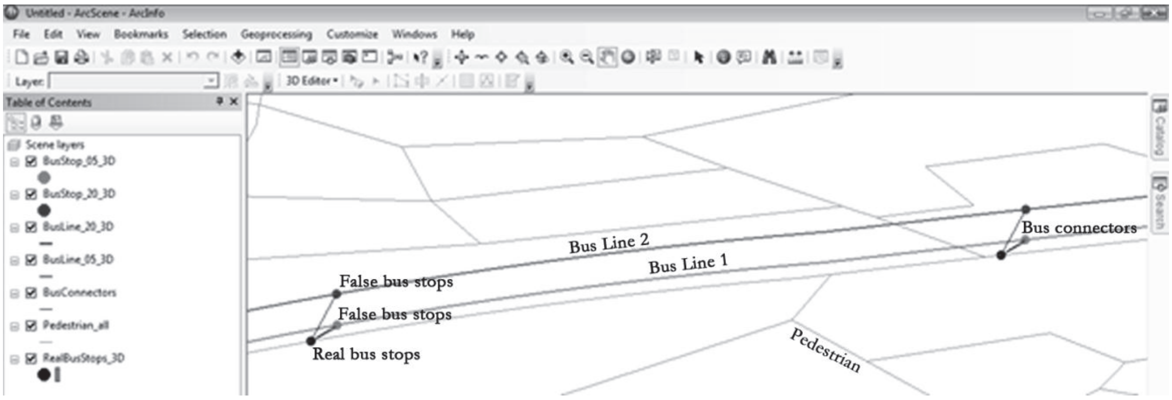



Figure 4-14: Relation between false bus stops, bus connectors and real bus stops

For each bus line there is a connectivity groups consisting of the bus line path and its false bus stops. This way a bus line is connected to the bus connectors through its false bus stops, and the bus connectors is connected to the pedestrian paths through real bus stops. This makes the pedestrian paths and the bus line path connected together and changing from on to the other is applicable only at the bus stops locations (Figure 4-14).

Cycling paths (edge element) form a connectivity group with the cycling parking (junction element). Cycling parking is at the other side in another connectivity group (i.e. connected) with the cycling connectors which connects the cycling paths to the pedestrian paths. Cycling connectors is in a connectivity group with cycling parking from one side and the real bus stops and train stations from the other side. This is because Real bus stops and train stations are the locations where cycling parking (and therefore changing to/from cycling) is available. This way, cycling connectors connects to the cycling paths through cycling parking feature class (junction element) from one side and connects at the other side to the pedestrian paths through real bus stops and train stations (Figure 4-15).

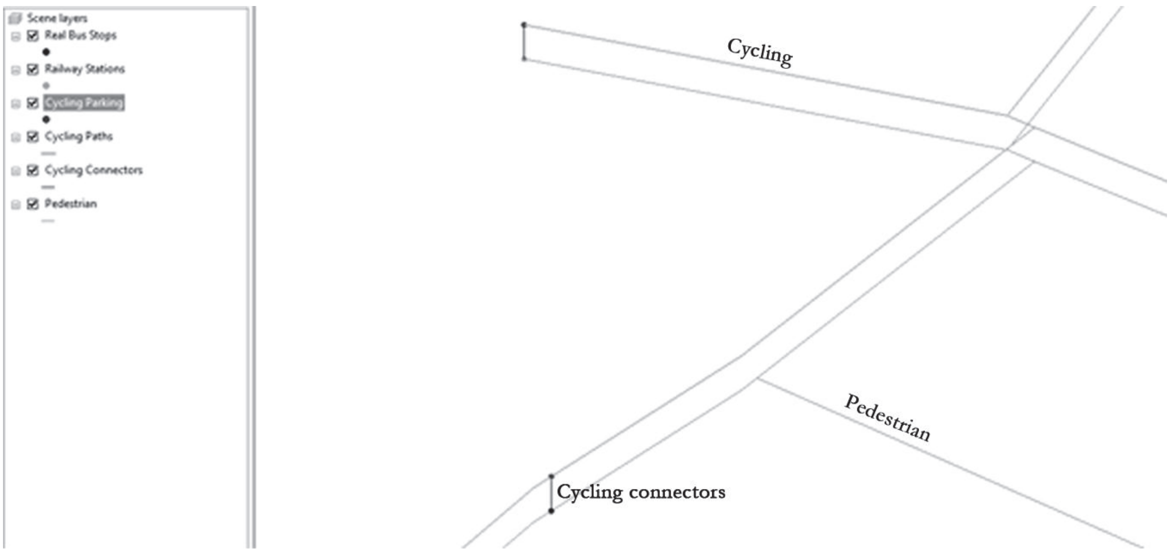



Figure 4-15: pedestrian - cycling connection

This way the modelling concept that pedestrian is the backbone that connects all the modes together is achieved as we see from the connectivity. Pedestrian paths are connected to the bus elements through real bus stops, to the train through railway stations and to cycling elements through real bus stops and train stations where cycling parking is available. Figure 4-16 shows the connectivity table of the network.

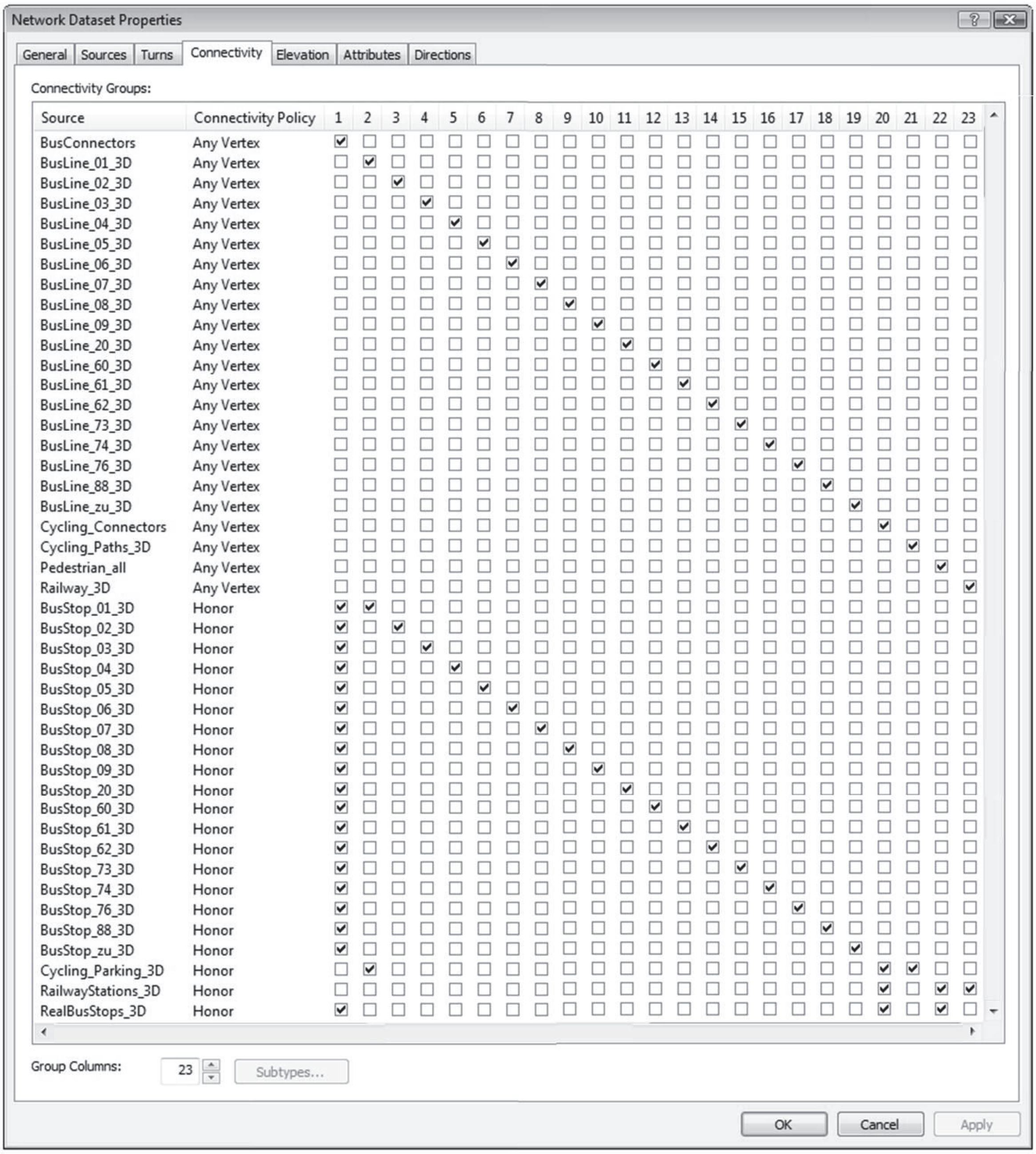



Figure 4-16: Network connectivity table

Another decision to take at the connectivity table is the connectivity policy. For edge elements it has 2 options: any vertex or end point. "Any vertex" means connecting to this edge element is done through any vertex on the line while "end point" restricts connectivity at the lines end points only. For junction elements, connectivity policy is either "honor" or "override". Override gives this junction element the priority over other junction element in case of conflict.

The final step in building the network is assigning the travelling cost to the different network elements. The impedances considered in this research are distance and time. Distance is a cost that is assigned only to edge element and is simply equivalent to the length of the travelled element. But time cost is different part of the time cost is assigned to edge elements and other to the junction element depending on the nature of the cost.

For the pedestrian mode, the time impedance associated to moving on such network is simply equivalent to the travel time calculated as function of the average walking speed and the length of the part travelled of the network. This is calculated in minutes to all the pedestrian paths feature class segments as "TravelTime" attribute. For the use of the bus, time impedance is composed of the time spent inside the bus from the start station to the end station and the time spend to wait for the bus from the moment and also the boarding and alighting time. The time spent in the bus is associated to the bus line path (edge element), the waiting time is assigned to the bus stop and the boarding and alighting time as a 2 way cost is assigned to the bus connector. Because a 2 way cost (from/to) should be assigned to an edge element as junction element allows the assignment of one directional cost.

Time cost to move over a cycling network has 2 parts too. One concerning the time needed to traverse a path of the network, this is assigned to the cycling paths feature class and calculated in minutes as function of the average cycling speed and the length of the path travelled of the network .The other resulting from the time needed to park the bike or to unlock it, mount it and start moving with over the cycling network which is assigned to the cycling connector as "ParkingTime" and "RidingTime" attributes.

# 5. RESULTS

The output of this research is a network model for part of the multimodal transport system of Enschede considering train, cycling, walking and bus modes. It is an ArcGIS network model capable of performing the different standard ArcGIS network analysis functionalities in a multimodal context.

However the focus of the research is the optimal route finding functionality among other available standard ArcGIS network analysis functionalities and which the model is also capable to perform. The effectiveness of the modelling concept is tested by using the model to provide the best route between an origin and a destination making use of different modes incorporated in the model.

For the optimal route finding functionality the model has the following capabilities:

- Provide the route between an origin and a destination using a combination of different modes to attain best route.
- Gives the ability to change from one mode to another or form bus line to another only at designated locations. Changing from bus line to another is performed only at common bus stops between the 2 bus lines and not at any physical intersection. Also entering or leaving a bus line happens only at a bus station. Also entering the railway happens only through train stations. Switching from/ to cycling paths, happens only at bus stops or train stations where bike parking is available.
- Having different entities for each bus line makes it more flexible to assign different bus speed and frequency (and consequently waiting time) to each bus line separately.
- Identify for the route found the locations of mode switching and the number of transfer.
- Provide detailed travel cost for each part (mode) of the routes, for each travel cost considered in the mode, in this case the distance and time. Also the overall travel cost.

The model has the capability to solve route using all possible combination between the modes integrated in the model to achieve the optimal route in terms of travel cost. However some results do not seem to be logic in real life. In the following part some examples output routes with different multimodal combinations are reviewed and discussed.

But before reviewing some examples of the output routes, some characteristics of the ArcGIS route solver are highlighted. Route finding is one of the standard functionality of the ArcGIS network analyst extension. The first step to find the best route is to define a new route for which at least 2 points (origin and destination) has to be defined as the “route stops”. The network analyst finds the optimal route between these defined stops. This is the very basic route definition. However a route can have more properties. For instance, restrict which elements of the ones participating in the network can be used to allocate the stops. When a route stop is defined (whether by digitizing it or using existing point) it is automatically allocated on one of the network elements. The option of excluding some elements of this allocation is used in this research to disallow that the start of a trip can be at the middle of a bus line or the railway. Excluding the bus lines and railway from the allocation makes the model snaps to the nearest network element allowed which are in this case are the pedestrian or cycling.

Another option in locating bus stops is "closest" or "First". Closest locate the stops to the closest network element while first using the order of the network elements. Closest option is the one used for all the coming examples. However this network has 3D elements with different elevations. so closest option always leads to locating on pedestrian because when picking (digitizing) the stops points they are at the zero level, so at the closest option the points are the pedestrian paths (at zero level too). But digitizing is not the only way to define route stops. Existing points can also be used as the route stops. So a point with an elevation equivalent to the one of cycling paths will explicitly locate this stop on the cycling paths. This technique is used to provide the option of the bike availability at a certain stop. For example if we want to find a route between 2 points considering that a bike is available at the start point then the start route stop is assigned an elevation equal to the cycling paths.

**Routes with different multimodal combinations**

**Walking -> bus -> walking**

For this pair of origin and destination (shown in Figure 5-1) considering that no bike is available, the route is solved as shown in Figure 5-1. It starts with walking to the nearest bus stop (Stevenfennestraat station) then use bus line 20 to the nearest station to destination (Kerk station). Then walk to destination with a total travel time of 12 min (see detailed directions in Annex2- 1).

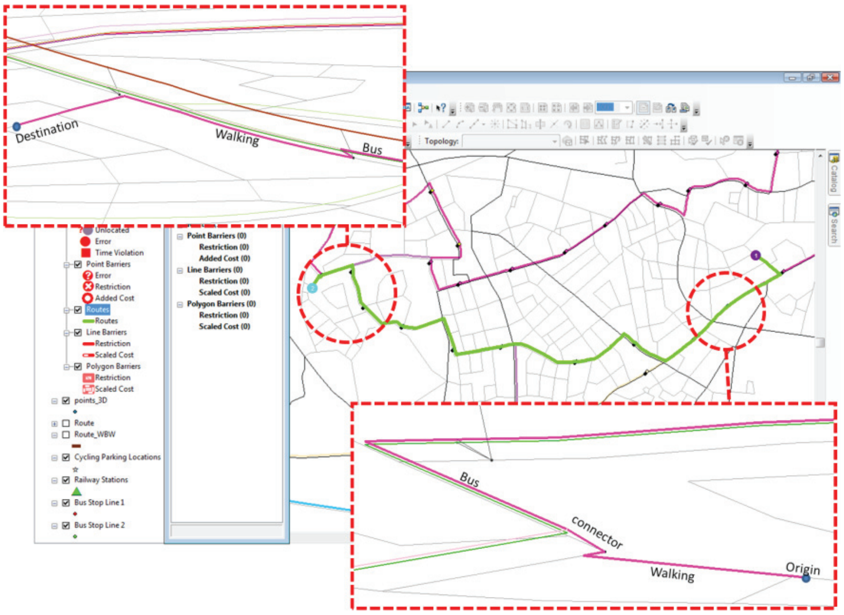



Figure 5-1

**Cycling -> bus -> cycling**

But when considering the availability of a bike at the origin and destination (for the same origin and destination), the route solving is different. The whole trip is made by bike with a less travel time of only 10 minutes.

**Walking -> bus -> cycling OR cycling -> bus -> walking**

For the pair of origin and destination sown in Figure 5-2 the option of bike availability is provided. The origin point is allocated on cycling paths but at the destination point location there is no cycling path available, so destination point is allocated on pedestrian paths. The route is solved as following: starts with a bike, park the bike, use the bus and walk to the destination.

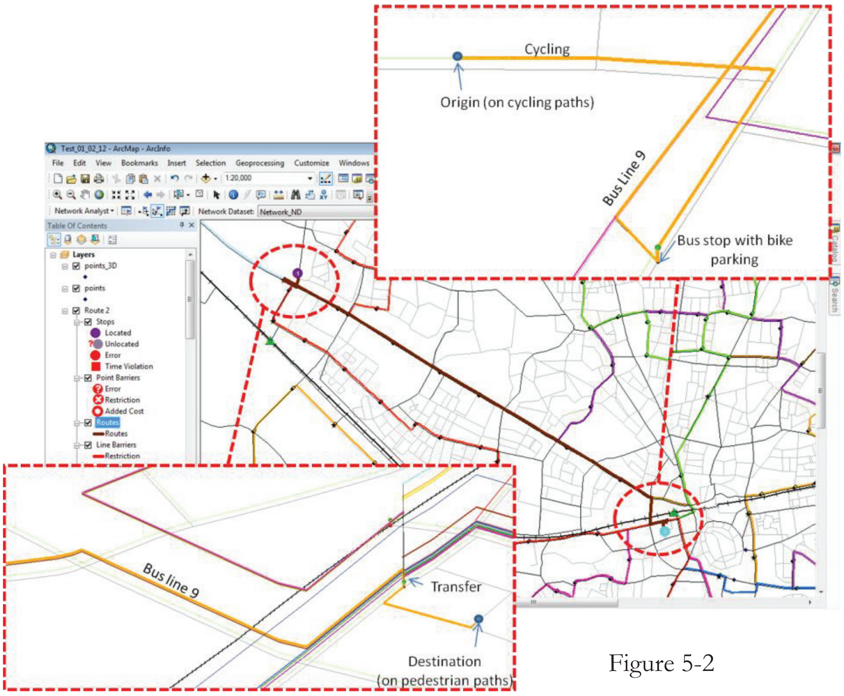



Figure 5-2

**Walking -> bus -> bus -> walking**

For the pair of origin and destination (points 1 and 2) in Figure 5-3 the best route found is shown in the figure. It start using pedestrian paths to the nearest bus stop (Vanekerstraat)then take bus line 2 till MST Haaksbergerstraat stop where it change to bus line 20 till stop Borgbos and reaches the destination using pedestrian paths also (see Annex2- 2 for the complete detailed route).

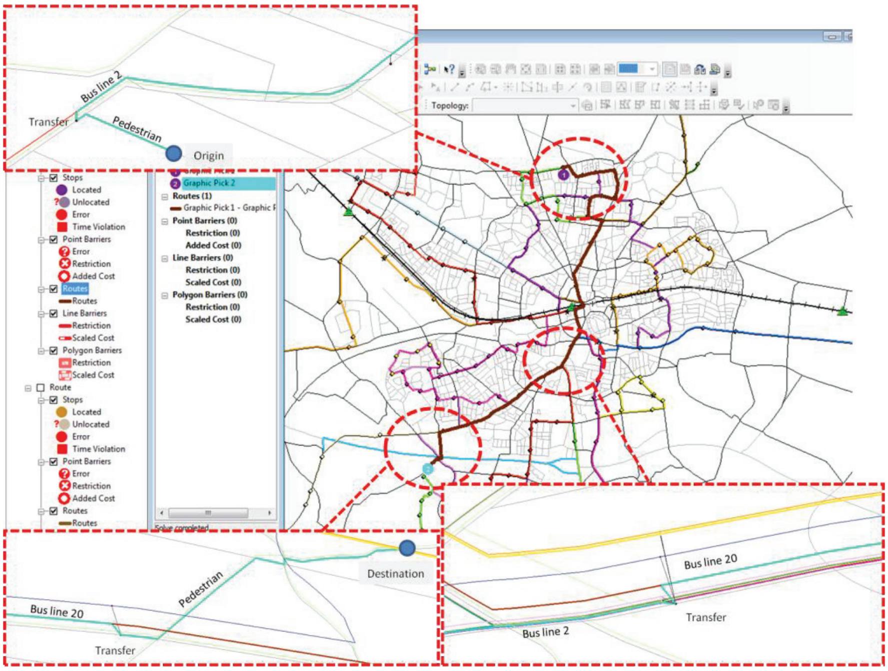



Figure 5-3

**Cycling -> bus -> bus -> cycling**

However, for the same origin and destination, when considering the availability of a bike at the start and at the end of the trip, the route details changed. It start with pedestrian also as it is the only available network at the start point then use bus line 2 then finally take the bike till the destination (see Annex2- 3). It is true that this second solution is faster, the total travel time is 21 minutes compared to the first solution with 22 minutes but it is not logic in real life. A person who will use the bus system will continue using it to the nearest point to the destination as long as the bus system covers it which is the case here. So solution one seem to be more realistic although scoring longer travel time

**Walking -> train -> walking**

Another example shows the use of the train. For the pair of origin and destination (points 1 and 2) shown in Figure 5-4 the route provided is solved as shown: pedestrian till Enschede central station, use the train till Enschede-De Eschmarke train station and finally go to destination point using pedestrian paths too (see detailed routes instruction Annex2- 4)

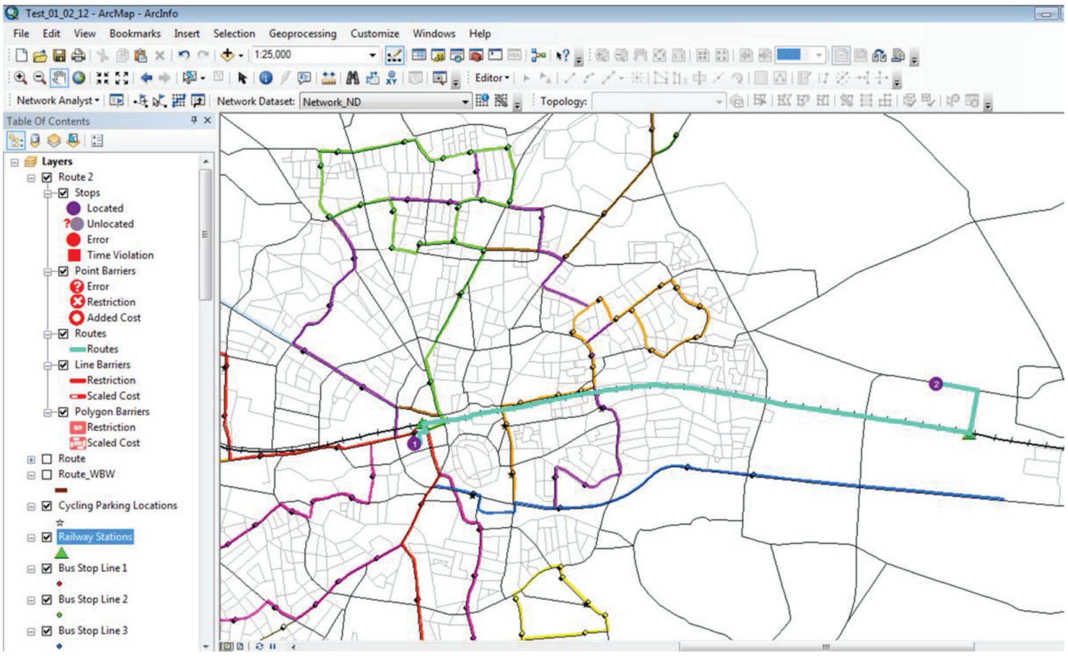



Figure 5-4

**Walking -> train -> cycling OR cycling -> train -> walking**

For the same pair of origin and destination, if the option of a bike is available at origin and destination, the route is solved differently. The start of the trip is still done using the pedestrian paths because no cycling paths are available at the start location, then use the train and finally use the cycling paths till the destination (see Annex2- 5 for the detailed route directions). From that we can conclude that to use the bike 2 conditions have to be fulfilled, the bike availability (at the model, done by locating the bike at the elevation of cycling paths) and the availability of a cycling path at the point (start/end/switch).

**Cycling -> train -> cycling**

Therefore, if the start point is also at a cycling path like the case of Figure 5-5, the solution will be: Cycling -> train -> cycling (see Annex2- 6 for the detailed route directions). This is because the 2 conditions are fulfilled in this case; available bike and available cycling path (Figure 5-6).


Point 1 at pedestrian path    Point 1 at cycling path

Figure 5-5

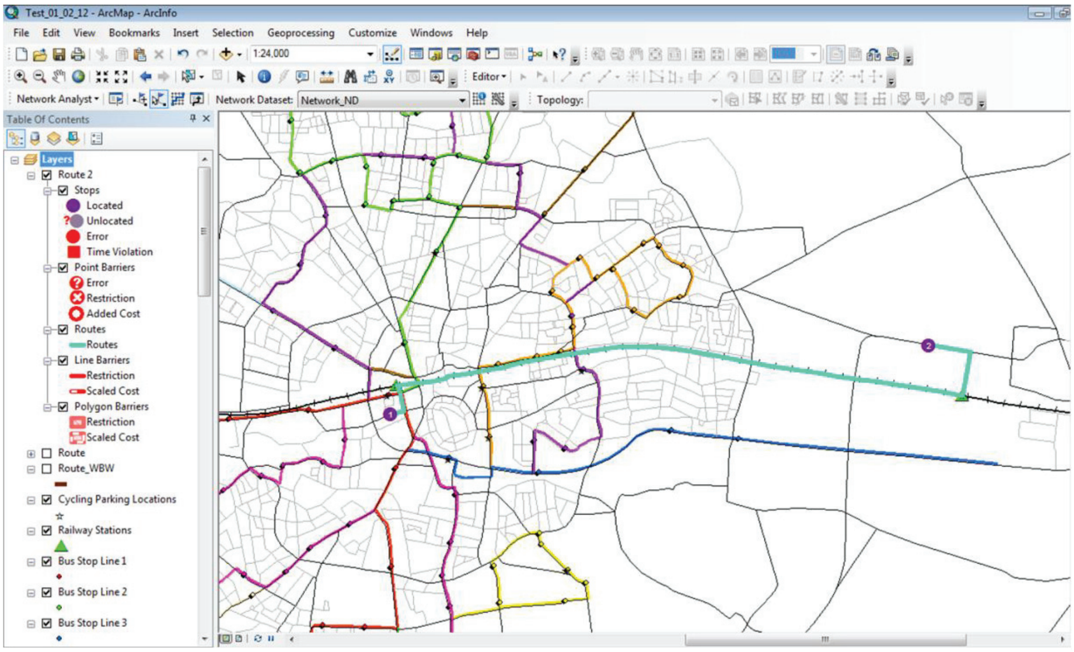



Figure 5-6

**Walking -> bus -> train -> walking**

The combination of walking, bus and train is applicable at the model. For the case shown in Figure 5-7, the location of the destination (point 2) is not served by any bus line so the nearest transport mode is the train. But also at the start point (point 1) the train is not nearby. So the route is solved as following: start at pedestrian path to reach nearest bus stop (Jupiterstraat), take bus line 1 to Enschede central where the train is accessible. After that the train is used till Enschede-De Eschmarke train station then using the pedestrian paths, the destination is reached. (See Annex2- 7 for details route direction).

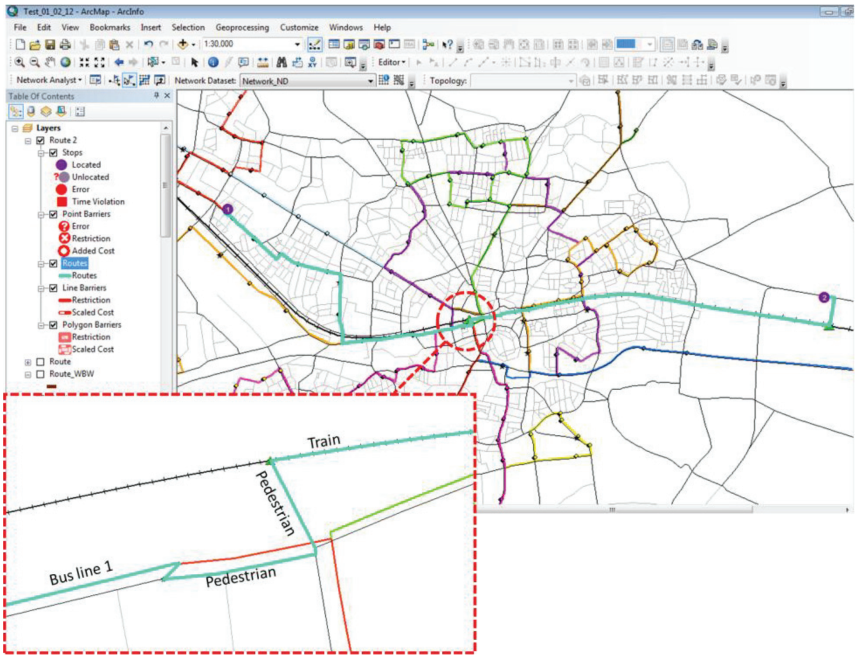



Figure 5-7

Providing bike at the start and the end of the trip for the same origin and destination as previous route gives different route. At the start point location only pedestrian paths are available, so the start of the trip has to be made at pedestrian paths to reach the nearest bus stop then take the train (as previous route), the different is that the rest of the route is made by bicycle (see Annex2- 8 for the route details).

**Cycling -> bus -> train -> cycling**

Moving the origin (start) point to a very near location where a cycling path is available (Figure 5-9) changes the modal combination. Figure 5-8 shows the output route.

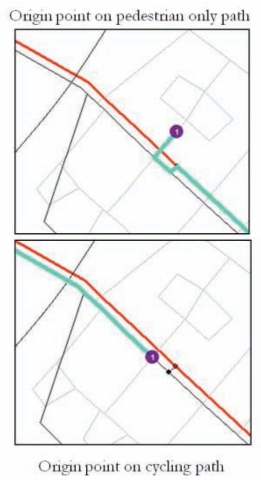


Figure 5-9

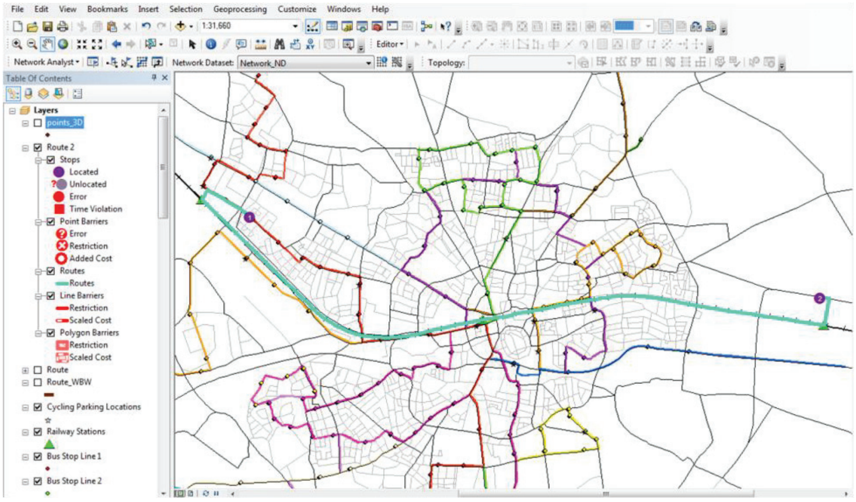


Figure 5-8

The route starts at cycling path but to a near train station. It's true that there is a bus stop which is nearer but considering that train is faster than bus and that the destination is near to a train station which means that train should be used anyhow, going to the nearest train station is fastest for the overall route especially that biking to the train station in this case is faster to walking to the nearest bus stop (like the case of previous route).

# 6. CONCLUSION AND RECOMMENDATION

The objective of the research is to develop a GIS data model for a multimodal transportation system combining different modes in one network that allows different modal combination in route planning. The modelling concept adopted in this research in order to fulfil this objective consists mainly on having a separate entity (layer, feature class...) for each mode route and physically separating each of these entities. The separation is vertical for different modes and horizontal for the different routes of the same mode. Connecting these separated entities is done through connectors entities representing the transfer action from one route to the other. Applying this concept at the ArcGIS platform, a multimodal network model is built.

The model developed has proved satisfaction in finding route over a multimodal network using the suitable modal combination that achieves the least cost path. The developed model is also able to simulate all the possible transfer scenarios between the integrated modes and to integrate the cost associated with the different elements, the cost of travelling and the transfer cost. The whole route details including the step by step directions and the detailed as well as the overall cost are also provided with the route.

However, after implementing the concept, some limitations are found. For instance, the travel impedance assignment is fixed, this suits some travel costs like the distance but for the time cost, some components need to be variable. The waiting time for the bus as a components of the overall travel time cost is calculated here as half the frequency, but the frequency is not the same throughout the day and may change from day to day (weekends and working days).

As the implementation aim in this research is testing the workability of the model, travel time assigned to different elements were mostly estimates. It is true that all the travel time components (e.g. time spent inside the bus, waiting for the bus, boarding, alighting ...) are considering but feeding the model with more accurate and real life data would result of more realistic travel cost estimate. For future work, other travel impedance can also be incorporated in the model like monetary cost or comfort. This will provide different alternatives for the route finding.

Considering that other transport systems could be more complicated than Enschede, the automation of the data preparation process can help but for future work, the automation of building the model would offer more help as well. Defining the connectivity rule between for a large number of entities is not an easy task. It is true that the number of modes remains limited at the end, but the idea of having separate entities for bus lines makes the number grow enormously. Enschede has only 18 bus lines other city might have a hundred. Defining connectivity rules manually for such a large number will not be easy or accurate work. So extending the automation process for building the network could be a good addition for the work. Also, since the model is built with the standard ArcGIS tools and functionality, so by using the same ArcGIS objects, a customized system with a user friendly interface can be developed to help people find their route but in more customized way.

The modes considered are non motorized modes, namely walking and cycling and two public transport modes:  train and bus. However the model is extendable, some other modes can be incorporated in the model using the same technique and concept. The tram and the bus for example are similar in many ways. The tram uses also the road and has a separate lane like the bus (in Netherlands). Tram route is accessible only at the designated stations; it is also accessible directly through pedestrian paths.

However other modes specifically private modes like cars and taxis requires a different technique. Modelling private modes in which the commuter provides the mode (car or bicycle) by himself should have a different technique that allows the condition of the availability of the mode at the start point or in case of change to this mode.

Since the model is able to perform one of the basic GIS network analysis functionality which is path finding, therefore it should be able to do other network analysis functionalities. The data model presented in this research can be a platform for other transportation network based types of analysis.

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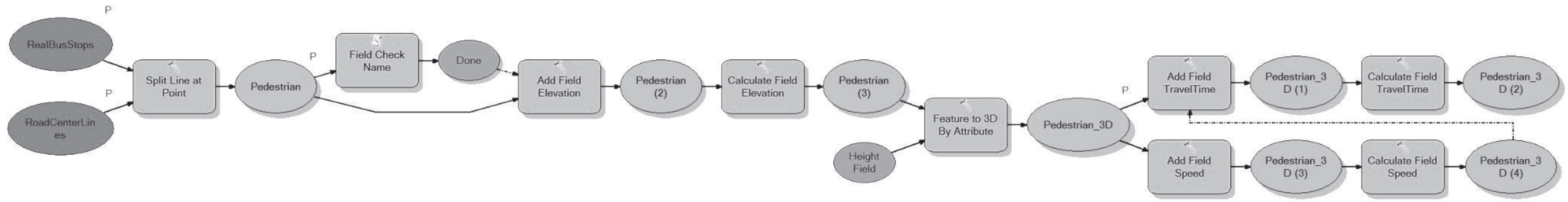
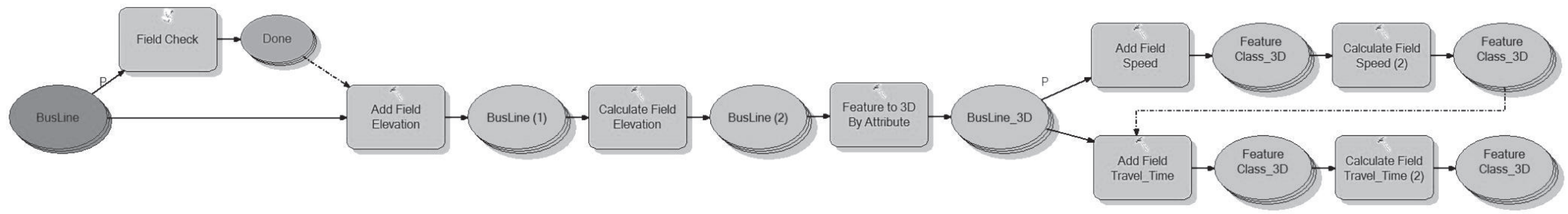
# ANNEX 1: DATA PREPARATION AUTOMATION MODELS

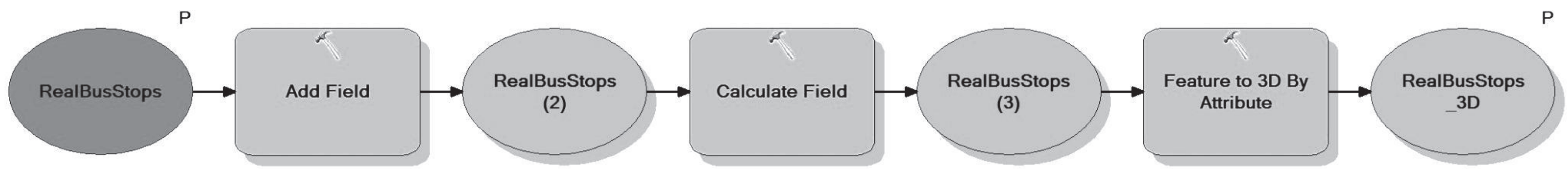
## Pedestrian



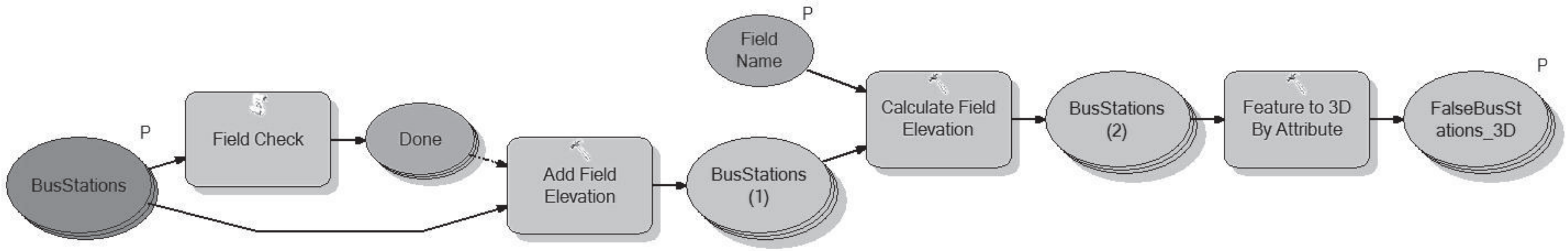

## BusLines_3D



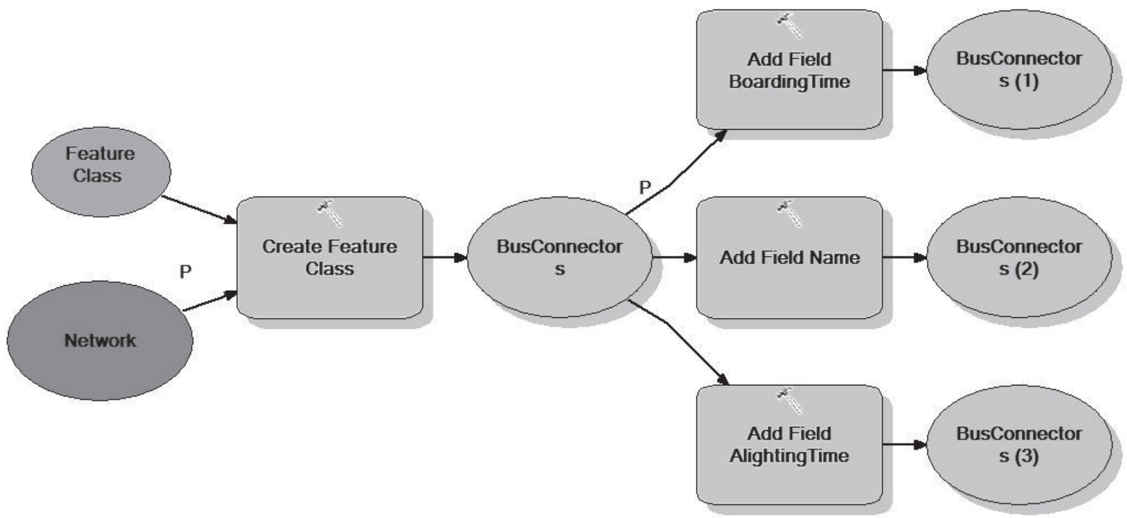

## Real Bus Stops



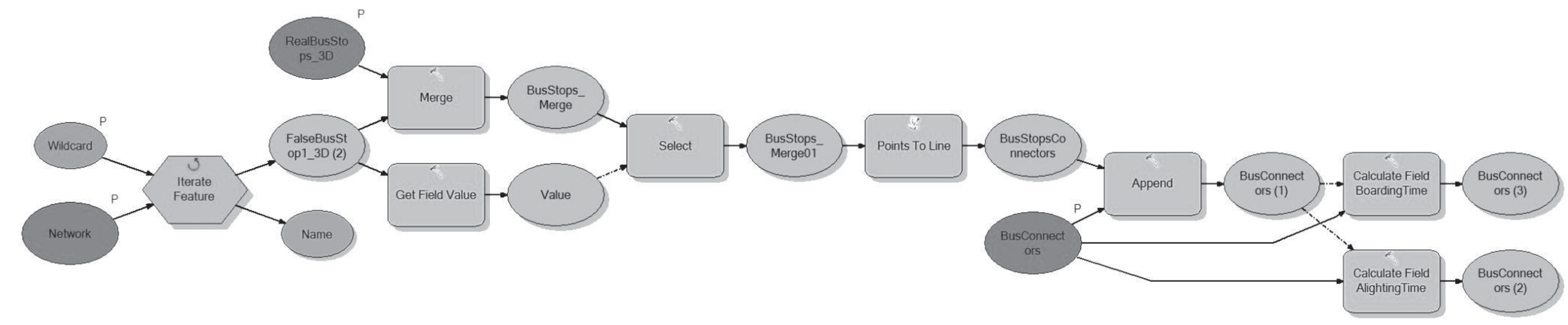
FalseBusStops3D



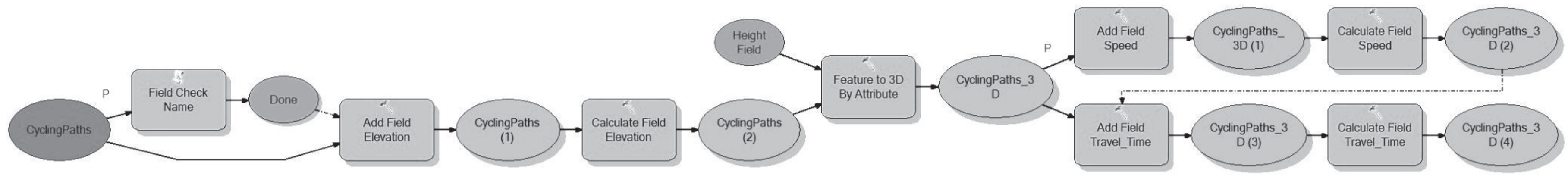

Create Bus Connector feature class



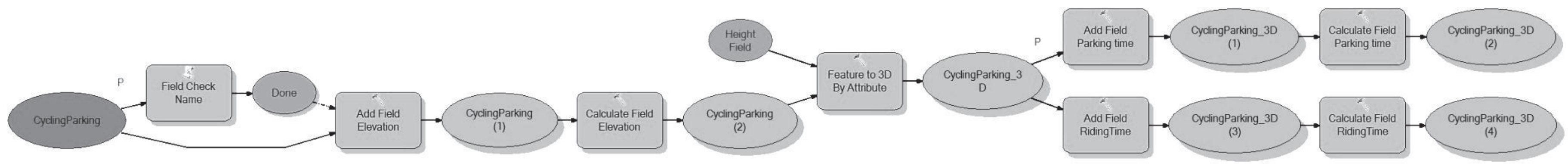
## Bus Connectors



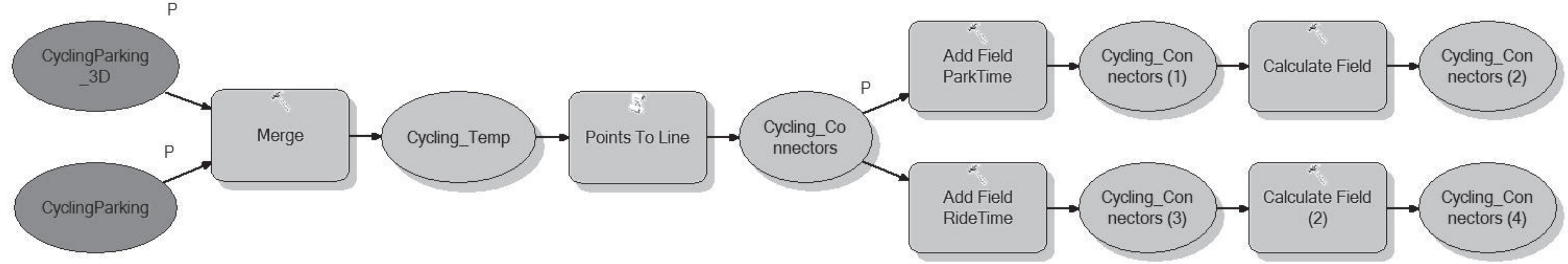

## Cycling Paths



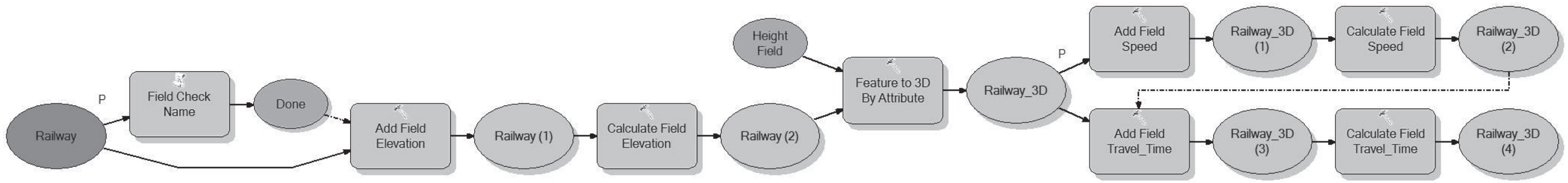

## CyclingParking3D



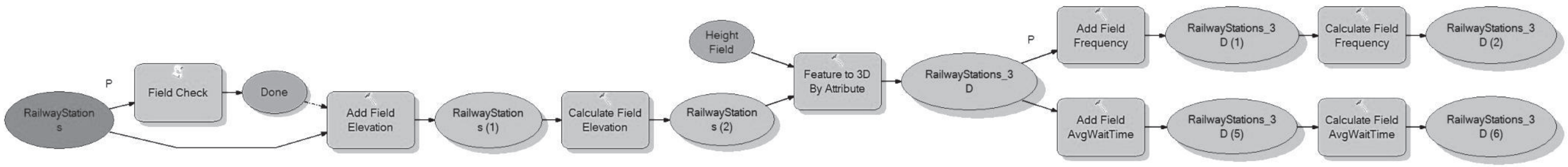
Cycling Connectors



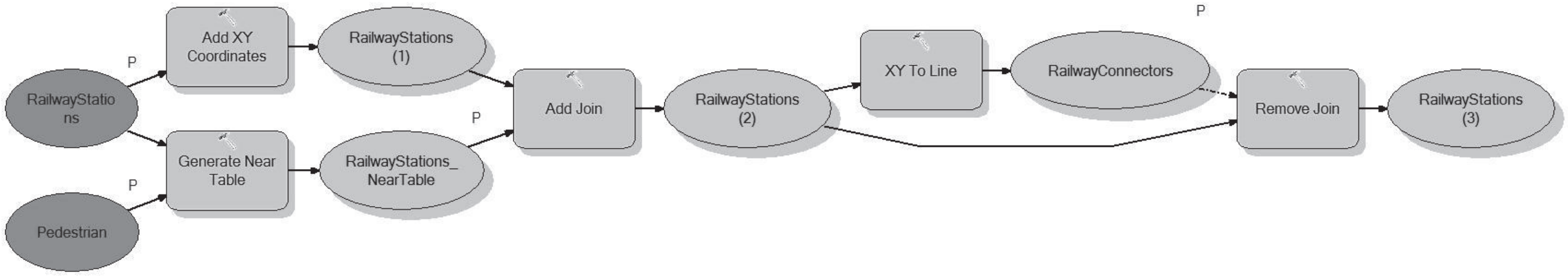

Railway_3D




RailwayStations_3D



Railway Connectors



# ANNEX 2: DETAILED DIRECTIONS OF THE OUTPUT ROUTES

Directions (Route 2)

| | | | | | | |
|---|---|---|---|---|---|---|
| [-] | **Route: Graphic Pick 1 - Graphic Pick 2** | | | 3592.7 m | 12 min | Map |
| | 1: | | Start at Graphic Pick 1 | | | Map |
| | 2: | | Go northwest on pedestrian 619 toward pedestrian 630/pedestrian 618 | 47.8 m | < 1 min | Map |
| | 3: | [+] | Continue on pedestrian 618 | 81.8 m | < 1 min | Map |
| | 4: | [+] | Turn left on pedestrian 34 | 110.6 m | 1 min | Map |
| | 5: | [+] | Make sharp right on Connector Line20 at Stevenfennestraat | | < 1 min | Map |
| | 6: | [+] | Make sharp left on BusLine20 | 3035.9 m | 4 min | Map |
| | 7: | [+] | Bear right on Connector Line20 at Kerk | | < 1 min | Map |
| | 8: | [+] | Make sharp right on pedestrian 332 | 62.1 m | < 1 min | Map |
| | 9: | [+] | Bear left on pedestrian 3246 | 78.1 m | < 1 min | Map |
| | 10: | [+] | Turn left on pedestrian 3245 | 106.7 m | 1 min | Map |
| | 11: | [+] | Bear left on pedestrian 3244 | 69.7 m | < 1 min | Map |
| | 12: | | Finish at Graphic Pick 2, on the right | | | Map |
| | | | Total time: 12 min<br>Total distance: 3592.7 m | | | |

Annex2- 1

Directions (Route 2)

| | | | | | | |
|---|---|---|---|---|---|---|
| [-] | **Route: Graphic Pick 1 - Graphic Pick 2** | | | 7871.9 m | 22 min | Map |
| | 1: | | Start at Graphic Pick 1 | | | Map |
| | 2: | | Go north on pedestrian 2467 toward pedestrian 125 | 116.2 m | 1 min | Map |
| | 3: | [+] | Continue on pedestrian 2466 | 2.7 m | < 1 min | Map |
| | 4: | [+] | Turn left on pedestrian 125 | 16.2 m | < 1 min | Map |
| | 5: | [+] | Make sharp right on Connector Line2 at Vanekerstraat | | < 1 min | Map |
| | 6: | [+] | Bear right on BusLine2 | 883.9 m | 1 min | Map |
| | 7: | | Turn right at Connector Line2 at Het Achtervoort to stay on BusLine2 | 1147 m | 2 min | Map |
| | 8: | | Turn left to stay on BusLine2 | 2466.8 m | 3 min | Map |
| | 9: | [+] | Bear right on Connector Line2 at MST Haaksbergerstr | | < 1 min | Map |
| | 10: | [+] | Make sharp right on Connector Line20 at MST Haaksbergerstr | | < 1 min | Map |
| | 11: | [+] | Make sharp right on BusLine20 | 2460 m | 3 min | Map |
| | 12: | [+] | Bear left on Connector Line20 at Borgbos | | < 1 min | Map |
| | 13: | [+] | Bear right on pedestrian 370 | 60.2 m | < 1 min | Map |
| | 14: | [+] | Turn left on pedestrian 2259 | 241.2 m | 3 min | Map |
| | 15: | [+] | Continue on pedestrian 2260 | 155.8 m | 2 min | Map |
| | 16: | [+] | Turn right on pedestrian 354 | 54.8 m | < 1 min | Map |
| | 17: | [+] | Make sharp left on pedestrian 363 | 28.5 m | < 1 min | Map |
| | 18: | [+] | Make sharp right on pedestrian 3170 | 238.7 m | 3 min | Map |
| | 19: | | Finish at Graphic Pick 2, on the left | | | Map |
| | | | Total time: 22 min<br>Total distance: 7871.9 m | | | |

Annex2- 2

Directions (Route 2)

| | | | | | |
|---|---|---|---|---|---|
| 1: | | Start at Location 1 | | | Map |
| 2: | | Go north on pedestrian 2467 toward pedestrian 125 | 116.2 m | 1 min | Map |
| 3: | [+] | Continue on pedestrian 2466 | 2.7 m | < 1 min | Map |
| 4: | [+] | Turn left on pedestrian 125 | 16.2 m | < 1 min | Map |
| 5: | [+] | Make sharp right on Connector Line2 at Vanekerstraat | | < 1 min | Map |
| 6: | [+] | Bear right on BusLine2 | 883.9 m | 1 min | Map |
| 7: | | Turn right at Connector Line2 at Het Achtervoort to stay on BusLine2 | 1147 m | 2 min | Map |
| 8: | | Turn left to stay on BusLine2 | 1859.6 m | 2 min | Map |
| 9: | | Bear right to stay on BusLine2 | 99.6 m | < 1 min | Map |
| 10: | [+] | Bear left on Connector Line2 at Enschede Central | | < 1 min | Map |
| 11: | [+] | Stay on Cycling connector at Enschede Central | | 1 min | Map |
| 12: | [+] | Go on Cycling87 Secondary | 99.6 m | < 1 min | Map |
| 13: | [+] | Turn right on Cycling80 Secondary | 321.8 m | < 1 min | Map |
| 14: | [+] | Bear left on Cycling107 Secondary | 20.3 m | < 1 min | Map |
| 15: | [+] | Turn right on Cycling81 Secondary | 30.8 m | < 1 min | Map |
| 16: | [+] | Continue on Cycling90 Secondary | 81.1 m | < 1 min | Map |
| 17: | [+] | Continue on Cycling109 Primary | 160.1 m | < 1 min | Map |
| 18: | [+] | Continue on Cycling110 Primary | 340.1 m | 1 min | Map |
| 19: | [+] | Bear right on Cycling112 Primary | 215.6 m | < 1 min | Map |
| 20: | [+] | Continue on Cycling113 Primary | 343.3 m | 1 min | Map |
| 21: | [+] | Continue on Cycling114 Primary | 248 m | < 1 min | Map |
| 22: | [+] | Continue on Cycling115 Primary | 190.1 m | < 1 min | Map |
| 23: | [+] | Continue on Cycling22 Primary | 110.8 m | < 1 min | Map |
| 24: | [+] | Continue on Cycling23 Primary | 629.3 m | 2 min | Map |
| 25: | [+] | Continue on Cycling24 Primary | 130.5 m | < 1 min | Map |
| 26: | [+] | Continue on Cycling216 Primary | 252.3 m | < 1 min | Map |
| 27: | [+] | Continue on Cycling217 Primary | 60.2 m | < 1 min | Map |
| 28: | [+] | Turn left on Cycling448 Secondary | 241.2 m | < 1 min | Map |
| 29: | [+] | Continue on Cycling449 Secondary | 155.8 m | < 1 min | Map |
| 30: | [+] | Turn right on Cycling687 Secondary | 46.8 m | < 1 min | Map |
| 31: | [+] | Bear right on Cycling572 Secondary | 238.7 m | < 1 min | Map |
| 32: | | Finish at Location 2, on the left | | | Map |
| | | Total time: 21 min<br>Total distance: 8041.6 m | | | |

Annex2- 3

Directions (Route 2)

| | | | | | |
|---|---|---|---|---|---|
| [-] | | **Route: Graphic Pick 2 - Graphic Pick 3** | 5119.7 m | 15 min | Map |
| 1: | | Start at Graphic Pick 2 | | | Map |
| 2: | | Go north on pedestrian 1934 toward pedestrian 154 | 111.8 m | 1 min | Map |
| 3: | [+] | Turn right on pedestrian 154 | 60.2 m | < 1 min | Map |
| 4: | [+] | Turn left on pedestrian 3282 | 4.3 m | < 1 min | Map |
| 5: | [+] | Bear left on pedestrian 3339 | 63.1 m | < 1 min | Map |
| 6: | [+] | Turn right on Train from ENSCHEDE to ENSCHEDE-DE ESCHMARKE | 4235.3 m | 4 min | Map |
| 7: | [+] | Turn left on pedestrian 3338 | 331.4 m | 4 min | Map |
| 8: | [+] | Turn left on pedestrian 3137 | 313.5 m | 4 min | Map |
| 9: | | Finish at Graphic Pick 3, on the left | | | Map |
| | | Total time: 15 min<br>Total distance: 5119.7 m | | | |

Annex2- 4

Directions (Route 2)

| | | | | | | |
|---|---|---|---|---|---|---|
| [-] | **Route: Location 1 - Location 2** | | | 5119.7 m | 10 min | Map |
| | 1: | | Start at Location 1 | | | Map |
| | 2: | | Go north on pedestrian 1934 toward pedestrian 154 | 111.8 m | 1 min | Map |
| | 3: | [+] | Turn right on pedestrian 154 | 60.2 m | < 1 min | Map |
| | 4: | [+] | Turn left on pedestrian 3282 | 4.3 m | < 1 min | Map |
| | 5: | [+] | Bear left on pedestrian 3339 | 63.1 m | < 1 min | Map |
| | 6: | [+] | Turn right on Train from ENSCHEDE to ENSCHEDE-DE ESCHMARKE | 4235.3 m | 4 min | Map |
| | 7: | [+] | Stay on Cycling connector at ENSCHEDE-DE ESCHMARKE | | 1 min | Map |
| | 8: | [+] | Go on Cycling690 Secondary | 331.4 m | < 1 min | Map |
| | 9: | [+] | Go on Cycling550 Primary | 313.5 m | < 1 min | Map |
| | 10: | | Finish at Location 2, on the left | | | Map |
| | | | Total time: 10 min<br>Total distance: 5119.7 m | | | |

Annex2- 5

Directions (Route 2)

| | | | | | | |
|---|---|---|---|---|---|---|
| [-] | **Route: Location 1 - Location 2** | | | 5173.7 m | 9 min | Map |
| | 1: | | Start at Location 1 | | | Map |
| | 2: | | Go east on Cycling374 Secondary toward Cycling80 Secondary | 12 m | < 1 min | Map |
| | 3: | [+] | Continue on Cycling375 Secondary | 87.1 m | < 1 min | Map |
| | 4: | [+] | Turn left on Cycling80 Secondary | 126.9 m | < 1 min | Map |
| | 5: | [+] | Continue on Cycling639 Secondary | 4.3 m | < 1 min | Map |
| | 6: | [+] | Bear left on Cycling691 Secondary | 63.1 m | < 1 min | Map |
| | 7: | [+] | Stay on Cycling connector at ENSCHEDE | | 1 min | Map |
| | 8: | [+] | Go on Train from ENSCHEDE to ENSCHEDE-DE ESCHMARKE | 4235.3 m | 4 min | Map |
| | 9: | [+] | Stay on Cycling connector at ENSCHEDE-DE ESCHMARKE | | 1 min | Map |
| | 10: | [+] | Go on Cycling690 Secondary | 331.4 m | < 1 min | Map |
| | 11: | [+] | Go on Cycling550 Primary | 313.5 m | < 1 min | Map |
| | 12: | | Finish at Location 2, on the left | | | Map |
| | | | Total time: 9 min<br>Total distance: 5173.7 m | | | |

Annex2- 6

Directions (Route 2)

| | | | | | | |
|---|---|---|---|---|---|---|
| [-] | **Route: Graphic Pick 1 - Graphic Pick 2** | | | 8748.6 m | 19 min | Map |
| | 1: | | Start at Graphic Pick 1 | | | Map |
| | 2: | | Go southwest on pedestrian 1460 toward pedestrian 97 | 53.8 m | < 1 min | Map |
| | 3: | [+] | Turn left on pedestrian 97 | 35.9 m | < 1 min | Map |
| | 4: | [+] | Turn left on Connector Line1 at Jupiterstraat | | < 1 min | Map |
| | 5: | [+] | Turn right on BusLine1 | 3817.3 m | 5 min | Map |
| | 6: | [+] | Make sharp right on Connector Line1 at Enschede Central | | < 1 min | Map |
| | 7: | [+] | Make sharp left on pedestrian 154 | 99.6 m | 1 min | Map |
| | 8: | [+] | Turn left on pedestrian 3282 | 4.3 m | < 1 min | Map |
| | 9: | [+] | Bear left on pedestrian 3339 | 63.1 m | < 1 min | Map |
| | 10: | [+] | Turn right on Train from ENSCHEDE to ENSCHEDE-DE ESCHMARKE | 4235.3 m | 4 min | Map |
| | 11: | [+] | Turn left on pedestrian 3338 | 331.4 m | 4 min | Map |
| | 12: | [+] | Turn left on pedestrian 3137 | 107.8 m | 1 min | Map |
| | 13: | | Finish at Graphic Pick 2, on the left | | | Map |
| | | | Total time: 19 min<br>Total distance: 8748.6 m | | | |

Annex2- 7

Directions (Route 2)

| | | | | | | |
|---|---|---|---|---|---|---|
| [-] | **Route: Location 1 - Location 2** | | | 8748.6 m | 16 min | Map |
| | 1: | | Start at Location 1 | | | Map |
| | 2: | | Go southwest on pedestrian 1460 toward pedestrian 97 | 53.8 m | < 1 min | Map |
| | 3: | [+] | Turn left on pedestrian 97 | 35.9 m | < 1 min | Map |
| | 4: | [+] | Turn left on Connector Line1 at Jupiterstraat | | < 1 min | Map |
| | 5: | [+] | Turn right on BusLine1 | 3817.3 m | 5 min | Map |
| | 6: | [+] | Make sharp right on Connector Line1 at Enschede Central | | < 1 min | Map |
| | 7: | [+] | Make sharp left on pedestrian 154 | 99.6 m | 1 min | Map |
| | 8: | [+] | Turn left on pedestrian 3282 | 4.3 m | < 1 min | Map |
| | 9: | [+] | Bear left on pedestrian 3339 | 63.1 m | < 1 min | Map |
| | 10: | [+] | Turn right on Train from ENSCHEDE to ENSCHEDE-DE ESCHMARKE | 4235.3 m | 4 min | Map |
| | 11: | [+] | Stay on Cycling connector at ENSCHEDE-DE ESCHMARKE | | 1 min | Map |
| | 12: | [+] | Go on Cycling690 Secondary | 331.4 m | < 1 min | Map |
| | 13: | [+] | Go on Cycling550 Primary | 107.8 m | < 1 min | Map |
| | 14: | | Finish at Location 2, on the left | | | Map |
| | | | Total time: 16 min<br>Total distance: 8748.6 m | | | |

Annex2- 8