Work Zone's Capacity Estimation and Investigation of Potential of Dynamic Merge Systems

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Abstract

Work zones are an essential part of roads maintenance. Despite all the efforts addressed to reduce work zone’s negative impacts on the road traffic performance and improve the road safety, there still exist work zone related congestions and traffic problems. This thesis aims to study and analyze highway reconstruction/maintenance activities, their impacts and existing ways of reducing these negative effects and investigating the role of Intelligent Transport Systems in improvement of the difficulties caused by work zones. The research of the factors influencing capacity resulted in three factors presented in each considered study. The factors are heavy vehicle percentage, weather conditions and police presence. An unusual approach presented by Weng & Meng (2011) distinguishes among the examined analytical models. Their Decision-Tree model, based on training a large data set, showed significantly lower values of errors of prediction of level-of-service. Three different dynamic late merge systems (DLMS) have been simulated and analyzed using the AIMSUN micro-simulation software. The simulation outcome shows promising results favoring the use of DLMS. Among the simulated systems is extra focus put on the ALINEA algorithm that shows potential to improve traffic flow in work zones. Conducted sensitivity analysis shows different behaving of the ALINEA algorithm due to change of regulator parameter and critical occupancy. In order to investigate performance of the ALINEA algorithm, an extensive research has to be conducted. The research should include various work zone configurations as well as different values of heavy vehicle percentage and the parameters within the algorithms code should be subjects to optimization.
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1 Introduction

Regular maintenance and reconstruction activities along motorways are essential to keep the roads in appropriate conditions. However, maintenance activities have numerous impacts on the performance of transportation facilities. Work zones, as the maintenance/reconstruction areas imply for, create road bottlenecks, i.e. elements limiting throughput and of course level-of-service of the road. The existence of a work zone with a poor throughput (poor implies for significantly lower than the flow rate along the road) lasting over large period of time, can negatively affect larger part of the road network and thus not only the section where the work zone is located. For both interested sides, system and user, it becomes crucial, that roadworks are well-managed. The main question, which the thesis deals about, is: How can the traffic conditions in roadworks be estimated and improved?

Work zone configuration can be a combination of: planned or unplanned (incidental), long-term (longer than 24 hours) or short-term and static or mobile activities. In this thesis only planned, long term, static work zones are considered due to the fact that, particularly this kind of work zone is often considered to have the most significant impacts in terms of level-of-service (LOS).

The study is divided into two general parts due to their dissimilar character. The first part consists of a literature review, various types of work zones, work zones’ traffic performance, description of different traffic performance compared to usual road conditions, general definition of capacity and influencing factors, analysis approaches, analytical models for estimation of capacity and finally, the adjustable Intelligent Transport Systems, with extra focus on the dynamic merge systems, systems that aim to optimize the merging act at the lane closure. In the second part is conducted an experiment examining dynamic merge systems, nowadays still unconventional ways to tackle the problem of insufficient capacity. The experiment contains simulation of three different dynamic merge systems using the AIMSUN micro-simulation software as well as analyses of the results.

1.1 Problem description

Work zones often require lane closures (Lentzakis, Papageorgiou, Spiliopoulou, Papamichail, & Wang, 2008). The lane closures results in reduced capacity (Benekohal, Kaja-Mohideen, & Chitturi, Evaluation of Construction Work Zone operational issues: Capacity, queue and delay, 2003), which causes disturbances in traffic performance and that consequently may result in increased delays, emissions and queues. The reduced traffic performance, respectively its consequences, can cause significant impacts to the society in the vicinity of the road and be very costly. Therefore there is a need for appropriate measure. Such solution to minimize the impacts can be realized by appropriate management of work zones, for example better planning and scheduling. Work zones have special characteristics differing from usual road traffic situations. This might be mainly because of a presence of unique elements and restrictions applied in work zones. Zheng, et al. (2010) conducted “Variable analysis of freeway work zone capacity prediction”, which summarizes the factors influencing
the traffic at work zones. However, in order to find the level of their influence, the factors need to be further thoroughly examined. As mentioned earlier, in order to minimize the social impacts and keep traffic under sustainable conditions, appropriate measures are needed. For such measures, though, it is vital to accurately estimate work zone’s capacity. Apparently, the more complex set of field data, which consist of the previously mentioned factors, that is available, the more accurate estimation can be expected. Although due to stochastic behavior of traffic streams (Transportation research board, 2000), ubiquitous loss of information can be assumed. The methods to estimate the traffic performance are in the report divided into two main groups; analytical and simulation based models.

Possible approach for minimizing the impact caused by presence of work zones can be application of Intelligent Transport Systems. In this thesis, this specifically mean Dynamic Merge Systems, in other words, systems disposing of real-time traffic data detection. Several configurations have been proposed on behalf of such systems (Barceló, 2010; Lentzakis et al., 2008; Wei et al., 2010). However, the systems are still not widely used, thus there is a lack of information about performance and reliability of the systems. Hence, their advantages and disadvantages need to be thoroughly evaluated.

1.2 Aim

The word, which all the tasks performed in the thesis have in common, is level-of-service. Level of service can be represented by parameters such as travel time, delay, number of stops or capacity or by a combination of variables. Actually, the capacity is often referred to as a crucial parameter whose importance prevails over the others. As explained in the problem description, it is absolutely vital for traffic analysts to have accurate estimation of the capacity in constrained traffic flow conditions. Capacity is affected, though, by numerous factors. The more factors that is observed and respected while estimating capacity, the more accurate estimation is possible to obtain.

Generally speaking this thesis aims to:

- Investigate which factors might influence the level–of–service in work zones
- Present and compare methods that have been used to estimate work zone’s level-of-service
- Investigate strategies that have been proposed to improve level-of-service in work zones, in particular dynamic merge strategies using traffic signal control
- Conduct a simulation study to estimate the potential of dynamic merge based on the ALINEA algorithm

The purpose of the first part of the thesis is to explain traffic flow theory in work zones and conduct a survey of the factors affecting the capacity, which might be taken into account when estimating capacity.
The aim of the second part of the thesis is to estimate and compare the potential of the dynamic merge systems. Three simulated dynamic merge strategies are based on previous studies. However, there is a lack of reports comparing dynamic merge systems. Merge-metering systems aim to optimize traffic during the merging act. Safety and traffic performance are typical evaluation factors for consultancy agencies.

1.3 Delimitations

The software (AIMSUN v7.0 (TSS-Transport Simulation Systems, 2011)) chosen for simulating the experiment is not originally developed for use of modeling work zones, hence does not directly allow modeling the essential elements of work zones. However, the ability of the software is considered to be sufficient for the scope of this study. The simulation is performed for only one configuration of parameters. According to Wennström’s examination (2010) of the software tool, Aimsun might be suitable tool to model work zone’s character. Also Lentzakis et al. (2008), the developer of the system applied in this thesis, used the same software tool to simulate it’s behaving in work zone. In practice, the merge metering systems consist of a large variety of devices and signs that affect the traffic. Although in this thesis dispose dynamic merge systems of only one controlling element and that is traffic lights placed 100 meters upstream the lane closure.

1.4 Methodology

Different methods for estimation of capacity consider different factors and use different approaches. Thus, after the survey of the factors, are the methods for estimating capacities and level-of-service in work zones presented and compared. Extra focus is on the accuracy of the methods and the employed approach. The traffic flow theory, which is placed in the beginning of the body of the thesis, uses description of traditional speed-flow diagram in order to provide to the reader understanding of the traffic flow behavior under different conditions (May, 1989). The work zone topology in this thesis is based on the methodology developed in a project of European union called ARROWS (National Technical University of Athens, 1998).

In the chapter “Evaluation of capacity estimation methods” is analytical models compared with each other based on value of mean square error exited during applying the models for the set of work zone data observed in USA.

Intelligent management of the work zones has been suggested to increase capacity and improve the level-of-service in work zones. In this thesis is such intelligent management considered as the application of ITS systems which use real-time traffic data detection. A literature review of the existing ITS systems will be conducted.

In the second part of the thesis a simulation experiment is performed on micro level because of the need for high level detail simulation. The implementation of the ITS systems requires including of several elements essential for Dynamic merge systems (DMS). Some examples of the elements are lane closure, traffic signs, traffic lights and detectors. While lane closure and traffic signs can be, to the certain extend, modeled on either micro- and macro-simulation
level. However, the feature making Dynamic merge systems “dynamic”, that means able to adapt its behavior based on traffic conditions, is ability to measure real-time traffic data. Such real-time measuring concept is realized through observing traffic conditions in the detectors and subsequent projection of the information via traffic lights. From aforedecribed is obvious that the system working with such feedback management, has to consider every single vehicle in order to provide functional merging system. Therefore is deployed microsimulation process to implement the DMS systems. The algorithm detecting traffic data, processing the information and providing it to the drivers is based on C++ language compatible with the Application Programming Interface (API) in Aimsun. In the evaluation part are considered several factors. This includes such as delay, travel time, number of stops, average queue and speed, where delay is considered the main factor. The assessment of the proposed systems is based on throughput maximization. The relative differences between systems are evaluated, as aforementioned through average delay. The algorithm of the ALINEA system is implemented via Application Programming Interface (API). The code is written in C++ programming language.

1.5 Outline

Chapters 2 and 3, which have rather more literature review character, describe the fundamental traffic flow theory and highlights divergences between non-constrained road and work zone conditions. This also includes definitions of the capacity, for both, road and work zone. Furthermore, factors affecting traffic flow and drivers behavior in work zone are examined based on existing literature, in order to find their importance. The literature review also consist of examinations of different work zone topologies, classifications and impacts on traffic and environment follows as well as capacity estimation methods (chapter 4).

The second part of the thesis, the part focusing on evaluation of the potential of ITS systems applied in the work zone (chapter 5), contains a brief, general description idea behind abbreviation ITS a research of existing dynamic merge systems in work zone and experiment based on micro-simulation.

In the end of the thesis (chapter 6.4) are discussed possible extensions and recommendations for further research in the subject.
2  Introduction to Work Zones and Work Zone 
Impacts

The objective of the following chapter is to provide a deeper insight into work zones and information about various road construction activities, more precisely along motorways, and to address different classifications of work zone impacts on the operation area. Firstly, work zone and different ways of work zone classification are introduced in this chapter of the report. It then continues with providing information about work zone layouts and work zone impacts in the second and the third parts, respectively. The chapter then ends by analyzing the road traffic performance at the work zone.

2.1  Definition of Work Zone

A work zone is defined as the part of a road facility which is influenced by works occurring on, near or above it (National Technical University of Athens, 1998). Work zone definition also includes the complete section of the road that includes different effective roadwork traffic controls and equipment which are explained in more details in following sections.

2.2  Classifications of Work Zones

Road construction activities vary from a simple short term repairing project to a long term reconstructing or renewing a part of an existing road.

Work zones can be categorized based on various features. Duration of the work, timing and the operation types are considered to be the major factors in order to develop a work zone management scheme in this study. The following four parts aim to name and shortly describe these various classifications in order to provide a deeper insight into developing a work zone management strategy.

2.2.1  Duration of the Work

Work zone duration is the length of time in which a work activity occupies a specific location. Duration of the road activity is an important factor to adjust the work zone configuration. Based on Michigan Department of Transportation (Work Zone Safety and Mobility Manual, 2010) road work duration can be divided into the following five categories:

- Long-term – work that occupies a location for several days or more
- Intermediate-term – work that occupies a location for at least one day, and up to several days
- Short-term – work that occupies a location for no more than 12 hours
- Short duration – work that occupies a location for up to one hour
- Mobile work – work that moves intermittently or continuously
2.2.2 Time Restrictions
Work zone activities can be categorized according to the time limitations. Constructing activities can be performed on weekends and during the day as well as week days and overnight. Traffic flow varies during different times of a day and days of a week. A common work zone management approach is to restrict the activity to off-peak hours and provide an entirely usable facility during the peak hours. This management approach can reduce the impacts to roadways. Noisy activities should be also restricted at night in urban areas.

2.2.3 Work Zone/Road-Way Types of Interaction
This classification is about the different possible operational schemes of implementing work zones. According to the National Technical University of Athens (1998), there are six different classes considerable for on-roadway work zones and four more classes for off-roadway locations.

On-Roadway
- Lane narrowing - without lane closure
- Lane closure
- Diversion (detour) - diverting all or part of the stream to a diversion route.
- Contraflow (crossover) - diverting all or part of the stream to the opposite direction
- Alternate one-way traffic – only one lane will be remained open for both direction
- Road works at junction

Off-Roadway
- Road-works at shoulder or roadside
- Road-works at central reserve (median)
- Road-works at walkway or bikeway
- Road-works at tramway

2.2.4 Work Intensity
Work zone intensity shows the complexity of the operation and required management program. The intensity of the work can be defined based on three factors: time duration, length of the operation area and number of closing lanes. There are number of less important factors such as the road class, the location of the work zone and traffic volume which have their influence on the work zone intensity level. Six work intensity levels corresponding to different work types are defined as follow (Batson, et al., 2009).
- Lightest-Guardian repair/installation.
• Light-Pothole repair, bridge deck patching/inspection and maintenance barrier wall erection.

• Moderate-Resurfacing/asphalt removal, paving (light equipment activity), milling (light equipment activity).

• Heavy-Stripping/slide removal, paving heavy equipment activity), milling (heavy equipment activity).

• Very heavy-Pavement marking, final striping, concrete paving (heavy equipment activity), bridge widening (light equipment activity).

• Heaviest-Bridge repair, bridge widening (heavy equipment activity).

2.3 Work Zone Layouts

Work zones are defined as a segment of a road network which is affected by a construction, maintenance or renewing activity on or near it. The work zone expression is not limited to the area which is occupied by the constructive activity, but is more widespread (National Technical University of Athens, 1998). In order to have a more unified definition of work zones different subsections are defined, the sum of which result in a general work zone. These subsections are listed and explained as follows.

2.3.1 Advance Warning Area

The advance warning area provides the required time and distance for road user adaption which can be defined as a section of the road where the information about an upcoming work zone are given to the drivers by means of regular sequence of signs, lights and control devices. This area may consist of a single sign, lights on a vehicle or a series of signs and traffic controllers. The beginning element in the warning area is called the announcement and the ending point is the place that the first physical alternation of travelled way is encountered (National Technical University of Athens, 1998).

The placement distance of the warning signs is a critical issue which is varied in different road and traffic situations. As an example this area should considered to be longer along highways or other high speed road ways comparing to urban roads.

Since rural freeways are the objective road types in this study and they normally characterized by higher speeds, the first warning sign should be placed in substantially longer distance, from 1.5 to 2.25 times the speed limit in km/h (8 to 12 times the speed limit in mph). Since two or more advance warning signs are normally used for these conditions, the advance warning area should extend 450 m (1,500 ft) or more for open highway conditions (The State of Queensland (Department of Transport and Main Roads), 2012).

2.3.2 Transition Area

The second area is the segment between the advanced warning area and the start of actual road activity where the drivers are led to be placed in the open lane. This area moves with the work space in mobile operations. Transition area usually consists of either a one-step or a
two-step alternation. The first case is simple transition where the traffic is guided to the desired lane/part of the road and no narrowing is required (crossovers). The two-step transition occurs in situations where narrowing is required (lane reduction or lane closure) prior to the work area.

- Two required steps in the latter case are as follows:
  - The narrowing area
  - The stabilizing area which contains the idea of counterbalancing the flow after the narrowing (National Technical University of Athens, 1998)

2.3.3 The Work Activity Area

The work activity area is the actual area that the road activity is taking place. Traffic flow which was led to the right side of the road in transition area will travel parallel to the actual roadwork considering physical safety margins.

Longitudinal and lateral buffers are two other additional parts of a work zone which are placed immediately before and after the actual working area. The main objective of designing these distances are to provide higher safety and security for the workers.

2.3.4 Termination Area

The last part in a work zone area is referred to as the termination area where the traffic is returned back to the basic road condition.

The termination area shall be started from the downstream end of the work area to the last TTC (temporary traffic control) device such as an end roadwork signs (The State of Queensland (Department of Transport and Main Roads), 2012).
The mentioned parts of a work zone are presented in Figure 1.

### 2.4 Work Zone Impacts

Construction and maintenance activities along a road/stream result in significant impacts on different traffic conditions and characteristics of the road. Increased delay, queue appearance, fuel consumption and accident rate and capacity reduction of the underwork segment can be mentioned as examples. Some of these negative effects are occurred during the construction period, while others are possible to develop over time.
2.4.1 Safety Impacts
Work areas along a roadway have higher accident risk comparing with non-work sections. Problems such as sudden speed changes, inadequate distance between vehicles and consecutive acceleration and deceleration are substantial along work zones which are considered to influence the traffic safety in a negative way.

2.4.2 Mobility Impacts
Many highway projects have significant impacts on the road mobility. Congestion and delay are two critical issues which are important to be considered. Further capacity problems are also expected in high volume locations. Different roadway restrictions caused by work zones such as lane closure, lane narrowing, etc. will reduce the capacity of the road and relatively increase the delay, queuing and travel time. The level of mobility impacts of work zones vary regarding the duration and significance of the work.

2.4.3 External Costs
In addition to planning, designing, constructing, and reconstructing expenses, there is also number of non-monetized costs associated with the operation of highways. Road user cost consists of all additional expenses borne by motorists which are caused by the road activity. It can be referred to user delay costs, vehicle operating costs, crash costs, and emission costs as examples of the mentioned work zone impact (Sadasivam & Mallela, 2011). The expenses which influence the highway agency are referred to as operator/agency costs. The operator costs include e.g. initial constructional costs, costs caused by maintenance and rehabilitation activities.

2.4.4 Environmental Impacts
Construction and maintenance activities along roadway will cause issues such as noise, higher fuel consumption and consequently higher air pollution and emission which will negatively affect the environment.

2.5 Work Zone Traffic Performance Analysis

2.5.1 Mobility Analysis
The ability of moving road travelers through a road construction area with minimized delay and reduced overall costs, comparing to the no-work situation, is considered as work zone mobility. A mobility analysis has to be applied to all related projects in order to determine mobility impacts of the work zone. Volume-to-capacity ratio (V/C), level-of-service (LOS) and travel time delay are three key factors to be considered for a proposed work zone.

2.5.2 Safety Analysis
Work zone areas have higher congestion rate and accident risk for facility users and construction crews, due to unexpected roadway conditions. Driver perception and behavior such as speeding and driving at inadequate distances between vehicles occur along work zone areas which influence the traffic safety. According to National Technical University of Athens (1998), rear-end collisions contain more than half of the work zone areas’ accidents.
Sideswipe crashes, collision with fixed object and collision with road workers are three other possible work zone accidents which are of special importance. The inconsistency and inadequacy of work zone implementation can also be a major reason for driver confusion which leads to driving errors and accidents. Safety objectives such as informing, guiding, warning and traffic enforcement are defined in order to mitigate the work zone safety problems.

**Road user safety**

Work zone areas cause constant changes in roadway conditions which are unexpected for the user, occasionally lead to driver confusion and errors. Following actions help to promote safe and efficient movement for all road users through work zones (Transportation Information Center – LTAP, 2006)

- Give high-priority to traffic safety and temporary traffic control during every project from planning through design, construction, and maintenance.

- Provide clear, coherent and recognizable guidance to road users.

- Inspect traffic control elements routinely, both day and night, and make modifications when necessary.

- Increase roadside safety in the vicinity of temporary traffic control zones.

- Keep the public well informed.

The supported messages through traffic control devices, signs, and markings must be feasible, understandable and consistent. Motorists are of major importance to be considered during the safety measurements among all types of road users. Provided information should not be neither insufficient nor conflicting or too much, in order to prevent the drivers of being confused. Following elements are the key factors of work zone management plans for motorists.

**Speed Reduction**

Appropriate guidance and transitions to the work zone lower speed, from the highway (normal) speed has to be provided by the designers.

**Enhanced Enforcement**

In some cases the presence of physical measure reinforcement in work zones intends to reduce speed and moderate driver behavior (Massachusetts Department of Transportation - Highway Division, 2006). Aggressive traffic enforcement along approaches to and within the work zone can be an effecting strategy.

**Temporary Traffic Control Plans**

The use of various traffic control devices such as barriers, warning signs and markings and also the basic layout and configuration of the site are parts of traffic control plans.
Worker safety

One of the most hazardous carrier environments is highway construction areas. The risks which the workers are faced to have to be considered during the work zone management plan development. Speed limits and advisory signs have to be cooperated with physical measures in order to warn motorists of upcoming changes and protect the workers within the area. The following principles are of high importance regarding the road workers’ safety.

- Avoid exposure of workers to the traffic
- Make workers visible to the road users
- Provide physical protection
- Avoid excessive work hours
- Avoid exposure of workers to work vehicles

Work Zone Safety Measures

Road work zone safety measures can be classified as follows.

Traffic Control Devices

Traffic control devices aim at informing drivers to temporarily change their behaviors due to presence of a road construction/maintenance activity. Some of the most important signs/devices are listed below.

- Portable traffic lights - are in use as stop and go devices to make the traffic disturbance as little as possible.
- Road reflectors - are designed either in plastic or metallic types to be safely run over.
- Routing panels - illustrate the changes in the number of lanes or direction of traffic lanes by means of proper combinations of arrows.
- Traffic markings - two types are commonly used: painted markings and self-adhesive tape. This type of safety devices are often used at long term work zones.
- Traffic signs - include both conventional and high intensity signs. These signs can be used together with lights. Yellow background is recommended for this type of signs.
- Variable message signs - give the driver real time messages using an on-line connection to a central unit.

Closure and Guiding Equipment

This type of work zone traffic equipment creates a visual and physical separation of opposite-way lanes and guide and channelize the traffic (National Technical University of Athens, 1998).
- **Guiding barrier** - are commonly plastic walls which are filled with sand, water or other possible materials with two different colors. Guiding barriers are used to separate two opposite directions in highways.

- **Guiding humps** - guiding humps are used primarily in order to separate traffic in opposite directions in combination with guiding beacons.

- **Guiding traffic closure** - are used in case of a road closure in order to diverse the traffic to another existing road (detour).

- **Mobile trailers** - are equipped vehicles used to warn and/or channelizing the traffic.

- **Traffic closures** - are horizontal rails carry a vertical signs at the approximate eye level of drivers which are used in order to control the traffic by restricting or closing a part of the carriageway.

- **Traffic cones** - are three dimensional shapes which are recommended to be used in short term activities.

**Information and Warning**

This group includes equipment used to inform the drivers about the presence of a work zone as and its effects on their route/lane choice and speed.

- **Flashing arrow** - consists of a group of lamps shaping an arrow signal sign which is used as an advanced or closure warning sign.

- **Additional lightning** - in a single color, is used individually or in combination with other traffic equipment as a warning device.

- **Speed reducer bumps** - are placed prior to the entrance of the work zone, mostly in urban areas, in order to reduce the vehicles’ speed.

- **Warning tape** - is a guidance element to emphasize the construction area.

**Protective Equipment**

This traffic equipment tries to prevent the entrance of vehicles or pedestrians inside the work area and reduce accidents involving vehicles running off the roadway.

- **Crash barrier** - is used as either a closure or a protection device at the construction zones. Crash barriers work as vehicle energy absorbing devices in case of a head on collision or redirecting device in case of a side collision.

- **Safety barrier** - is a steel or concrete element used to prevent vehicles from breaking in to the work area. It is not fixed on the road and must be tested by crash test.
2.5.1 Work Zone Delay and Road User Cost Analysis

As it is mentioned earlier in this report, road user cost can be defined as all types of additional expenses the motorist and the community have to afford in abnormal traffic conditions. Within the context of this specific study these expenses refer to user delay cost, vehicle operational costs (VOC), crash costs and emission costs. Additional travel time required to pass a segment of a road due to road activities comparing to a non-work condition can be expressed as delay cost and is an important component of work zone cost analysis. This additional time consists of the vehicle deceleration delay, speed reduction delay, queuing delay at the work zone and acceleration delay. The corresponding costs of these additional travel delays can be computed individually sum of which determines the total user cost at work zones.

\[ C_{wz} = C_d + C_{sr} + C_q + C_a \]

\( C_{di} \): Deceleration cost,
\( C_{sr} \): Reduced speed cost,
\( C_q \): Queue corresponding cost,
\( C_a \): Acceleration cost.

Above mentioned costs can be computed using related delays which are explained in the following section.

Traffic Delay

Decreased capacity and vehicle speed at work areas, compared to other sections of the road, result in disruption and delay in traffic flow. When the traffic flow rate exceeds the capacity, congestion occurs, which results in queuing and delay. This delay includes the vehicle deceleration delay (approaching area), speed reduction delay (through the work area), queuing delay at the work zone and acceleration delay (after exiting the construction area).

Work zone delay is an important component of work zone traffic performance impacts and the basis for computing the work zone related user costs. Different layouts of work zones have various impacts on the traffic measures such as speed and flow rate. As an example, a crossover work zone provides a safer area for workers but it affects the traffic in both direction of the road while partial lane closure affects the traffic only on one side of the road. All work zones related delays are listed and shortly described in the following parts.

Delay due to Deceleration

In order to simplify the computation of the deceleration related delay, the vehicle deceleration before a work zone is assumed to be uniform. In normal (no-work) condition, the travel time of a vehicle over a section of length \( S \) at the freeway speed limit, \( V_f \) is as follow (Jiang, 2001):
\[ T_f = \frac{S}{V_f} \]

Where:

- \( S \): Road section length (km),
- \( V_f \): Freeway speed (km/h),
- \( T_f \): Freeway travel time (h).

With a work zone, the approaching travel time (affected by deceleration) of the vehicle with a uniform deceleration over the same section to reduce its speed to the work zone speed is computed as below (Jiang, 2001):

\[ T_d = \frac{2S}{V_f + V_z} \]

Where:

- \( S \): Road section length (km),
- \( V_f \): Freeway speed (km/h),
- \( V_z \): Work zone speed (km/h),
- \( T_d \): Approaching travel time due to deceleration (h).

The delay due to deceleration before entering the work area then can be calculated as follow (Jiang, 2001):

\[ D_d = T_d - T_f = \frac{2S}{V_f + V_z} - \frac{S}{V_f} \]

Where:

- \( D_d \): Deceleration delay (h),
- \( T_d \): Approaching travel time due to deceleration (h),
- \( T_f \): Freeway travel time (h),
- \( V_z \): Work zone speed (km/h),
- \( S \): Road section length (km),
- \( V_f \): Freeway speed (km/h).
**Delay due to Reduced Speed**

The difference between the required time to pass a work zone at the reduced speed and the same the time needed to pass the same length of the road in normal condition is defined as the work zone delay due to reduced speed (Jiang, 2001).

\[ D_{sr} = L \times (\frac{1}{V_z} - \frac{1}{V_f}) \]

Where;

- \( D_{sr} \): Speed reduction delay (h),
- \( L \): Work zone length (km),
- \( V_z \): Work zone speed (km/h),
- \( V_f \): Freeway speed (km/h).

**Delay due to Queue formation**

The average delay time during uncongested traffic that an arrival passenger car spends before entering the work zone is computed as follow:

\[ D_w = \frac{F_a}{F_c \times (F_c - F_a)} \]

Where;

- \( D_w \): Uncongested traffic delay time (h),
- \( F_a \): Average arrival rate of vehicles (veh/h),
- \( F_c \): The service rate of the system at work zone capacity (veh/h).

The delay due to vehicle queues during the congested traffic, which occurs when the traffic flow exceeds the segment capacity, is obtained using the following equation.

\[ D_{qi} = \frac{Q_{i-1}^2}{2(F_d - F_{qi})} \]

Where;

- \( D_{qi} \): Congested traffic delay time (veh-h),
- \( Q_{i-1} \): Vehicle queue length at time \( t \) between hour \( i-1 \) and hour \( I \) (veh),
- \( F_d \): Vehicle queue discharge rate (veh/h),
- \( F_{qi} \): Vehicle queue formation rate (veh/h),
$F_{ai}$: Hourly volume of arrival vehicles at hour $i$ (veh/h).

**Delay due to Acceleration after Exiting**

Vehicles accelerate to their original speed after exiting the work zone and this acceleration produces an extra delay in the network. The required distance and time to change speed from work zone speed to freeway can be estimated (Jiang, 2001).

$$S = \frac{V_f^2 - V_z^2}{2a}$$

$$T_{a1} = \frac{V_f - V_z}{a}$$

In case of having no work zone the time needed for a vehicle to travel the same distance is:

$$T_{a2} = \frac{S}{V_f} = \frac{V_f^2 - V_z^2}{2aV_f}$$

Finally, the delay caused by acceleration to the original speed after exiting the work zone is:

$$D_a = T_{a1} - T_{a2} = \frac{V_f - V_z}{A} - \frac{V_f^2 - V_z^2}{2AV_f}$$

$$= \frac{(V_f - V_z)^2}{2AV_f}$$

Where:

$V_z$: Work zone speed (km/h),

$V_f$: Freeway speed (km/h),

$A$: Average acceleration (km/h$^2$),

$S$: Required distance for acceleration (km),

$T_{a1}$: Required time for acceleration (h),

$T_{a2}$: Required time when no work zone exists (h),

$D_a$: Acceleration delay (h).

**Total Delay at Work Zone**

The total traffic delay at a work zone is the sum of all the above discussed delays. This value is computed as follows under the uncongested and congested traffic conditions, respectively.

Traffic delay at the work zone under uncongested traffic condition:

$$D_i = F_{ai} \times (D_a + D_{sr} + D_w + D)$$
Traffic delay at the work zone under congested traffic condition:

\[ D_i = F_{a_i} \cdot (D_d + D_{sr} + D_a) + D_{q_i} \]

- \( D_i \): Total delay (veh-h)
- \( F_{a_i} \): Average arrival rate of vehicles (veh),
- \( D_d \): Delay due to deceleration (h),
- \( D_{sr} \): Delay due to speed reduction (h),
- \( D_a \): Delay due to acceleration (h),
- \( D_w \): Delay due to queue formation in uncongested traffic condition (h),
- \( D_{q_i} \): Delay due to queue formation in congested traffic condition (h).
3 Traffic flow theory

In this thesis capacity is considered as a typical representative of level-of-service of roads. The task of this chapter is to provide the reader information about traffic flow in freeways, and work zones and highlight important relations.

Capacity is defined in each moment by three variables - flow, density and speed. These variables and relations between them are illustrated in traditional fundamental diagram. In case of observing traffic from macroscopic point of view, when the results are obtained through system characteristics and not individual, mean speed is referred to instead of individual's speed. Distinction between single approaches of observing traffic is described in the section 5.1.2.

The important traffic parameters definitions are as follows:

- Flow (V) = Number of vehicle passing a certain point during a given time period, in vehicles per hour (veh/h);
- Speed (S) = The rate at which vehicles travel (km/h);
- Density (D) = Number of vehicles occupying a certain space (veh/km);
- Occupancy (O) = Percent of time a point on the road is occupied by vehicles. This definition is going to be useful later on in chapter 6, which deals about the conducted experiment.

The formula between flow, speed and density is:

\[ V = D \cdot S. \]

3.1 Congestion

Congestion occurs on freeways when demand exceeds the capacity. Fundamental diagram in Figure 2 helps to understand at what traffic stage congestion occurs and what are the circumstances of such case.
3.1.1 Fundamental diagram

Figure 2: Fundamental diagram (Transportation research board, 2000)

Figure 2 shows the relationship between two independent variables, speed and flow rate. The third variable is recovered by means of relationship $V = D \cdot S$. Important state points are closely described in the following text:

**Completely free flowing traffic**

Vehicles that are not affected by traffic ahead, travel at a maximum speed of $S_f$ (average free flow speed). At free flow speed, flow rate and density are close to zero.

**Saturated traffic**

For highly saturated roads, as well as for free flow traffic, average speed and the flow rate are close to zero. Vehicles tend to travel in one platoon and traffic collapses at maximum density of $D_j$ (jam density)

**Capacity traffic**

When the maximum flow rate $V_m$ is reached, the capacity of the road is reached as well. The maximum flow rate of $V_m$ has associated capacity speed of $S_o$ and capacity density of $D_c$. From
the diagram it is apparent, that the capacity speed \( S_o \) is lower than the maximum (free flow) speed \( S_f \).

Free flow state occurs during light traffic conditions. Conversely, when traffic conditions are heavy and density reaches its maximum (critical density - \( D_o \)), freeway reaches its maximum flow. At this stage the speed is reduced to \( S_o \). When the density exceeds the value of critical density, the flow consequently decreases. Traffic becomes oversaturated. The flow reducing continues until the jam density, when it is zero and traffic collapses. Below the jam density is flow considered stable, or uncongested. If the flow is stable, that means density is in between critical and jam value, the capacity of the road is reduced. In order to optimize capacity value is therefore important to keep density as close as possible to critical, but rather below as beyond.

3.1.1 Phenomenon called Capacity Drop

Figure 3 shows a more realistic relation of speed and flow than idealized Figure 2 (Maze, Schrock, & Kamyab, 2000). The curve is not continuous but divided into two parts. This is caused by phenomena called capacity drop. The upper part presents uncongested traffic state, while the lower one presents traffic conditions during congestion. When the traffic reaches the maximum flow rate, flow characteristics become labile and their behavior is difficult to predict. If the critical density is exceeded, rapid reduction in flow is experienced. This is called capacity drop. Capacity drop is a well-known phenomenon, however, there is a lack of observations of the phenomena from field data.
3.2 Capacity and its definitions

Freeway capacity definition

- "The maximum sustainable flow rate at which vehicles or persons reasonably can be expected to traverse a point or uniform segment of a lane or roadway during a specified time period under given roadway, geometric, traffic, environmental, and control conditions" (Transportation research board, 2000)

In the case of common freeways, researchers use merely different definition for capacity than the one presented in the Highway capacity manual. In case of work zones, however, the sources dealing about work zone capacity do not use a unique definition to estimate work zone capacity (Benekohal, Ramezani, & Avrenli, 2010). Follows several examples of work zone capacity definition:

Work zone capacity definitions

- “The discharge flow when there is a continuous flow of traffic.” (Benekohal, Kaja-Mohideen, & Chitturi, 2004)
- “The traffic flow rate just before a sharp speed drop followed by a sustained period of low vehicle speeds and fluctuating traffic flow rate.” (Jiang, 2001)
- “The mean queue discharge flow rate from the bottleneck that was located at the end of the transition area.” (Al-Kaisy & Hall, 2003)
- “95th percentile value of all 5-min within-a-queue” flow rate (Dixon & Hummer, 1996).
- “The average volume of the ten highest volumes immediately before and after queuing conditions” (Maze, Schrock, & Kamyab, 2000).

Work zone capacity has the same meaning as freeway capacity however the situation is considerably more complex. Above mentioned examples of capacity definitions demonstrate the difference in the complexity.

It is evident that some of these definitions are based on the mean traffic flow rate whereas the others are based on the maximum observed values. Some definitions give queue discharge rate while the others estimate maximum flow that can be processed before and after flow breakdown. In general are all the definitions more or less similar. They direct to the same point. That is to find maximal amount of vehicles able to go through work zone without experiencing traffic collapse. Due to a lack of proves it is not possible to conclude whether one work zone capacity is better than another. Further Research on the subject might clarify proper way of defining the capacity at work zones.
3.2.1 Work zone capacity influential factors

Evaluation of impact of single variables on capacity is an important part for an accurate estimation of traffic performance at work zone. Some variables are assumed to have a significant impact, but they might be difficult to observe. On the other hand, some variables have small negligible impact. Therefore they are not included in capacity estimation procedure. The following text summaries the most important variables divided into several groups according to their character. The number of the factors may be indefinite. According to Zheng, et al. (2010), variables can be categorized in the following way:

**Work zone infrastructural property**

To this group belong factors related with physical dispositions of the road, and the work zone. In general are factors static at the work zone. Their adjustment is often very costly as they are often solid parts of the infrastructure. The factors are *Hard shoulder occupation, Lane width, Lateral distance, Location of closed lanes, Pavement conditions, Number of available/closed lanes, Road gradient, Road curve radius* and *Work zone length*.

**Work zone operations**

Work zone operations factors are dependent on time of the day, week, year, phase of the work zone, configuration of the work zone or placement of the work zone. Hence, the factors change depending on the phase of the work.

The factors are *Work day, Work zone durations, Work phase, Work time, Work zone intensity, Work zone location, Work zone layout* and *Work zone transition/buffer length*.

**Traffic mitigation measures**

The factors in this group are measures introduced by management of the work zone in order to improve both safety and traffic performance. The measures constrain drivers at work zones to avoid accidents and/or let management of work zones to control the traffic.

The factors are *Lane merging discipline, Additional lightning, Presence of traffic signs, Presence of signal control, Separation measures* and *Temporary speed limit*.

**Driving behavior influence**

The factors are related to the traffic stream behavior. The factors can be divided into two groups. First group includes factors with psychological effect on drivers and the second group includes physical abilities of the traffic in the work zone.

The factors are *Share of heavy vehicles, Driving behavior, Driver population* and *Sight deprivation*. 
External factors

Apart from the Darkness factor, the factors in this group are of stochastic nature and prediction is often difficult.

The factors are Darkness factor, Incident occurrence, Road conditions and Weather conditions.

3.2.2 Statistically significant factors

According to the results of statistical tests presented in Zheng’s study (2010) 12 of total 31 aforementioned factors are recognized as significant. However, in existing analytical models in chapter 4.2.1 is usually taken in the account considerably less factors than 12. An exception is the Decision-tree model (Weng & Meng, 2011) described in the chapter 4.2.1, which considers 16 statistically significant factors. Venugopal & Tarko (2011) presented Investigation of factors affecting capacity at freeway work zones. Their study resulted in recognizing parameters that cause a reduced capacity. The total number of investigated parameters was seven.

Three factors are presented in all three studies:

- Heavy vehicle percentage
- Weather conditions
- Police presence

The six following factors are presented in two studies:

- Lane width
- Ramp distance
- Temporary speed limit
- Work zone length
- Number of lanes
- Work intensity

The number of factors in the reports varies considerably. For the complex evaluation of significant factors is necessary to conduct more, thorough studies.
4 Work zone capacity estimation methods

Various methodologies and transportation software tools are utilized to determine the impacts of different alternatives on the transportation network. These approaches in this thesis are divided into two major groups, Analytical Models and Simulation Models. Short descriptions of basic concepts and differences of these methods, within the context of work zone analysis and based on FHWA Traffic Analysis Toolbox VIII (Hardy & Wunderlich, 2008), are provided in the following parts.

4.1 Highway Capacity estimation methods

For estimating the capacity of the highway there are information available from previously performed studies. Related existing researches have typically studied the results of interpretive empirical studies or related those results to known theoretical models. All these researches made significant progress in investigating highway capacity and traffic characteristics (Xiao-bao & Ning, 2007). Two widely used highway capacity estimation methods are the Highway Capacity Manual method using speed-density relationship (Transportation research board, 2000), and the statistical method using observed traffic volume distribution (Chang & Kim, 2000). The HCM method detects 15 minutes base traffic data (speed, volume, density), searches speed-volume-density relationship and finally determines the highway capacity. The statistical method detects peak hour 1 minute base volume and average speed, transfers 1 minute base data to 15 minute base. (Zunhwan, Jumsan, & Sungmo, 2005).

Highway Capacity Estimation Based on HCM

The capacity defined by HCM is stated in section 3.2. The HCM capacity for different road types can be estimated using the following equation.

\[
Cap = Base \ Cap \times N \times f_{HV} \times PHF \times f_p \times f_G
\]

Where,

\(Cap\) : Capacity in terms of vehicles per hour.

\(Base \ Cap\) : Base capacity in terms of passenger cars per hour per lane.

\(N\) : Number of through lanes.

\(f_{HV}\) : Heavy vehicle adjustment factor.

\(PHF\) : Peak-hour factor (the ratio of the peak 15-minute flow rate to the average hourly flow rate).

\(f_p\) : Driver population adjustment factor.
Level-of-Service depends on different factors:

- Average Highway Speed of all vehicles
- Average time percentage that vehicles spend in platoons behind slow vehicles
- Driver comfort and convenience
- Operating cost
- Traffic interruptions

HCM (Transportation research board, 2000) uses volume to capacity ratio (v/c) to distinguish between various levels of service. This value can be between 0 and 1. Six levels of service is defined by HCM using the travel speed and v/c (level A to level F).


This study represents a quantitative method to estimate capacity. It executes the peak hour base volume and average speed (for one minutes) and transfers these one minute values into 15 minutes base values. It then finds the time head way distribution using the average volume and finally defines the highway capacity. For more information about the details of this method one can refer to Chang and Kim (2000).

### 4.2 Work Zone Capacity Estimation Methods

#### 4.2.1 Analytical Models

The subchapter 4.2.1 represents a summary of some of the existing analytical models and their ability, limitations and requirements to model work zone capacity impacts. Analytical models usually consider limited number of factors, because mathematical formulation becomes too comprehensive along with increasing number of interacting variables. Two analytical methods of work zone capacity estimation are fully-described while number of other existing methods are listed and explained in a more general approach. More information about each of the methods can be obtained using the sources which are stated along the report.

*HCM (2000) - Highway capacity manual*

The Transportation research board (Highway capacity manual, 2000) recommends a value of 1600 passenger car per hour per lane (pcphpl) as the short term freeway-work zone’s base capacity and it states that this value will change by changing the adjustments according to a specific work zone. Based on HCM, the work intensity can increase or decrease the base value up to 10 percent. It also considers the heavy vehicle presence as an effecting factor of capacity reduction. The last value which is considered to have impact on the freeway capacity by HCM is the presence of ramps. The provided equation by HCM for estimating the work zone capacity is as follow:

\[
C_a = (1,600 + I - R) * F_{HV} * N
\]
\( C_a \): Adjusted mainline capacity (pch – passenger cars per hour)

\( I \): Adjustment factor for intensity, type and location of the work zone (from -10% up to +10% of the base capacity)

\( R \): Ramp presence adjustment factors

\( F_{HV} \): Heavy vehicles adjustment factors

\( N \): Number of open lanes through a short term work zone

It also provides the values for long term work zone capacity. The average capacity for a two-to-one lane closure with the presence of a crossover is around 1550 passenger car per hour per lane (pcphpl) based on the HCM (Highway capacity manual, 2000) and the same value can increase up to 1750 in the case that no crossover is present. For a three-to-two lane closure these ranges will be between 1780 and 2060 pcphpl (HCM 2000, Chapter 22, freeway facilities).

Weng and Meng (2011) introduced another approach, which aims to develop a decision tree-based model considering 16 effective factors to estimate work zone capacity. It employs F-test splitting criterion and a post-pruning approach.

Factors such as Heavy vehicle percentage, Work zone grade, intensity and length, number of open and closed lanes, weather condition, lane width and driver composition are examples of factors which are considered in this study.

The freeway work zone capacity, denoted by \( y \), can be expressed as a function of the 16 variables.

\[ Y = f(x_1, x_2, \ldots, x_{16}) \]

This model consists of three general steps:

- Applying tree growing on training data.
- Using tree pruning checking data to prune the grown decision tree.
- Rule extracting

In this model is the target variable recursively partitioned so that the data in descendant nodes are always more pure than the data in the parent node. During the procedure splits the data based on tested significance of each split. The model uses the F-test splitting criterion. For each node \( t \), the best split among all possible splits is chosen, gradually from the top one, with respect to variable \( X \). The best split here refers to the split with the smallest \( p \)-value of the F-test. Since the equations and the model description are out of the scope of this thesis for more information about the methodology see Weng & Meng (2011). Generally, the comparison of this model's results with HCM 2010 shows that the tree based model provides a more accurate estimation of work zone capacity (Weng & Meng, 2011). The comparison is based on USA field data.
Benekohal et al. (2004) present a model that establishes a relationship between capacities and operational speed, in a step-by-step methodology, to estimate work zone capacity for a two-to-one lane closure configuration. This model considers capacity at operating speed \( U_0 \) and heavy-vehicle adjustment and platooning factors as the most important parameters affecting the base capacity.

Sarasua et al. (2006), conducted an investigation to determine the capacity of short-term freeway work zones in South Carolina using equations derived from Transportation research board (Highway capacity manual, 2000). Speed, traffic volume, and queue length were collected at 22 sites over one year. The model estimates the capacity of two-to-one, three-to-two and three-to-one lane closure work zone configurations. The model adjusts the HCM (Highway capacity manual, 2000) methodology. The base capacity depends on lane closure configuration and passenger car value equivalent. Heavy vehicle adjustment factor, number of lanes open through the work zone and adjustment factor for type, intensity, length and location of the work activity were found to have impact on the capacity in this study.

Al-Kaisy and Hall (2003) examined capacities at six long-term work zone sites in Canada. They have found that all those sites had lower base capacity than HCM (Highway capacity manual, 2000). They developed a multiplicative capacity model using the Microsoft Excel optimization tool. They estimated the capacity at work zones considering the base capacity of the road. Seven factors which are considered in their method are adjustment factors for heavy vehicles, driver population, work activity, side of lane closure, rain, light condition and non-additive interactive effects.

Kim et al. (2001) developed a multiple regression model for capacity estimation at work zones considering the following influencing factors: Number and location of closed lanes, the proportion of heavy vehicles grade of work zone and the lateral distance.

Dixon et al. (1996) performed a capacity study at North Carolina work zones since they assumed that the HCM 1994 capacity values were applicable only to Texas. They investigated and collected data at 24 short-term freeway work zones during one year, 1994 to 1995. They found higher values for North Carolina work zone capacities than the HCM (Highway capacity manual, 2000) by at least 10 percent (Kianfar, Edara, & Sun, 2012).

**Evaluation of analytical models**

According to the conducted literature review in this study, which considers not all but most in use methods, the effects of the following factors on work zone capacity have been partially studied in those different methods.

- Number of open lanes and number of closed lanes
- Heavy vehicle percentage
- Speed limit
- Position of closed lanes
• Weather conditions
• Driver population
• Work intensity
• Lateral Clearance
• Type of work zone (short term or long term)
• Lighting conditions
• Lateral distance of work activity area

Some of these factors are in common among studied literature such as heavy vehicle percentage, number of close and open lanes and work intensity. In contrast, there are factors such as weather and light conditions which were taken in to consideration in few of these researches such as Al-Kaisy and Hall (2003).

It can be also stated that, except the tree-based model, none of the several analytical models reflect the effects of all above-mentioned parameters on capacity.

Weng & Meng (2011) conducted a comparison of the analytical models described in this chapter. The decision tree model uses 18 sets of data in order to evaluate its accuracy. The decision-tree model was also compared with HCM (Highway capacity manual, 2000) capacity estimation methodology. Mean square error was significantly lower for decision-tree model. HCM methodology showed a tendency to consistently underestimate the capacity (Weng & Meng, 2011).

In addition, other factors such as flagger presence or ITS presence can also have effects on work zone capacity, which have not been perfectly investigated.

In summary, there were many studies that derived work zone capacities from field data. The primary focus of most studies is to develop a model that can finely estimate work zone capacities without requiring the actual flows to be collected. Each study assumes a certain definition of capacity. As examples, Sarasua et al. (2006) and Benekohal et al. (2004) proposed different speed-flow relationships for work zones. Benekohal et al. (2004) only considers the percentage of heavy vehicles and platooning factor as the main effective factors for capacity drop and uses the capacity at operational speed to estimate the capacity at work zone. The model developed by Sarasua et al. (2006) does not provide a satisfactory evaluation of the effect of work intensity, weather condition and length on capacity, due to the lack of sufficient data (Sarasua, Chowdhury, Davis, & Ogle, 2006). In comparison, Al-Kaisy and Hall (2003) considers more factors such as rain, side of lane closure and light factors. Although the more influencing factors are considered the more complex are the data gathering and the equations, the results will be more accurate and reliable according to the real situation.
4.2.2 Simulation based models

There are different computer modeling software which can be used to model work zones and simulate their traffic performances. In the following part different simulation methods and their ability to model work zones are briefly described, based on FHWA Traffic Analysis Toolbox Volume VIII (Hardy & Wunderlich, 2008).

Traffic Signal Optimization Tools

FHWA Traffic Analysis Toolbox VIII indicates this category as suitable methods to develop signal timing plans for isolated signal intersections, signalized arterial corridors, and signal networks. Many of these optimization tools are able to perform capacity calculations, cycle length determinations, splits optimizations, and coordination plans. Regarding the specific study case, work zones, traffic signal optimization tools are useful for planning temporary traffic signals or analyzing signal plans in an existing signalized arterial roadway. The single focus of these tools, mostly limited to traffic signals, can be considered as their usage limitation. Passer IV-96, Synchro and TRANSYT-7F are examples of these optimization tools.

Macroscopic Simulation Models

Macroscopic simulation models are based on the deterministic relationships of the flow, speed, and density of the traffic stream in which the simulation is done on a section-by-section basis rather than tracking every single vehicle. These models require less computer power than microscopic models and are not able to provide as detailed transportation improvement analysis as the microscopic models can. Macroscopic models have also the ability to model large geographic networks which can be important while studying work zones with higher geographical impacts such as having a full closure. These models are fast to set up and run since they do not simulate individual vehicle characteristics. The simple representation of traffic movement can be mentioned as their usage limitation.

Mesoscopic Simulation Models

FHWA Traffic Analysis Toolbox VIII (Hardy & Wunderlich, 2008) defines the Mesoscopic simulation models as the newest generation of traffic simulation modeling tools. These tools evolved from a need for an intermediate level of analysis. Mesoscopic simulation models provide more detailed view of the network than macroscopic simulation models. Although they have the ability to model the relative flow of vehicles on a network link, they do not represent individual lanes on the link and provide less fidelity than microsimulation models which will be discussed later.

They are able to model and analyze large geographic areas and corridors as well as diversion routes and signalized intersections. However they do have numbers of weaknesses such as their limitation to model detailed operational strategies such as complex signal control and the complexity of the model and higher data requirements for accurate results. Commonly used mesoscopic simulation tools for work zone analysis include the family of DYNASMART and
DYNAMIT models as well as newly introduced hybrid/multi-scale models including Cube’s Avenue and Caliper’s, TransModeler (Hardy & Wunderlich, 2008).

**Microscopic Simulation Models**

Microscopic simulation models are based on car-following, lane-changing, gap acceptance etc. theories for individual vehicles. Computer time and storage requirements for microscopic models are large, usually limiting the network size and the numbers of simulation runs that can be completed. The limitation of this type is the substantial amount of roadway geometry, traffic control, and traffic pattern data they require. This limitation cause transportation agencies to use microscopic models in combination with travel demand models to better understand the impact of roadway geometry modifications on level-of-service and carrying capacity. These models are useful to evaluate scenarios which are beyond the limitations of other model types including heavily congested conditions, complex geometric configurations, and system-level impacts of proposed transportation improvements. AIMSUN, CORSIM and VISSIM (Barceló, 2010) are examples of microscopic models (Hardy & Wunderlich, 2008).

**Limitations/requirements**

Different previously described simulation methods have their limitations and requirements in order to be applied to a case study and in order to give have efficient and accurate results. This section aims to list these requirements and criteria in order to build the appropriate background to choose the best suitable methodology among different approaches.

Traffic Signal Optimization Tools, described previously in this chapter are mainly computer based models. With respect to work zones, these models are useful in developing a temporary signal plan for a signal control or analyzing an existing signalized artery. As mentioned before these models are mostly limited to traffic signals which can be considered as their usage limitation.

Macroscopic Models have limited detail in modeling the real world traffic conditions and do not have the ability to analyze transportation improvements in as much details as mesoscopic and microscopic models. Furthermore, input of macroscopic models is speed-density graph. Hence, capacity has to be known as well and that is a problem in case of work zones.

Mesoscopic simulation is the latest generation of simulation models which strikes a balance between the macroscopic and microscopic models. Mesoscopic models provide higher accuracy than macroscopic models, but less accuracy than microscopic models in real-world traffic behavior simulating. They have the ability to analyze larger geographic areas within more reasonable time, than microscopic analysis, and providing more detailed data than macroscopic models. Mesoscopic simulation models have a number of weaknesses. One is their limited ability to model detailed operational strategies such as complex signal control. Another weakness is the overall model complexity and data requirements necessary for accurate results.

Microscopic simulation models are useful for simulation of the base and work zone condition in complex work zone scenarios. A limitation of microscopic simulation models is the lack in
ability to model large geographic areas. The reason is the difficulty of calibrating large networks which require substantial data and resources and consequently longer required run time.
5 ITS in work zones

The purpose of this chapter is to give an overview of ITS systems in work zones. However, in the beginning it is appropriate to first clarify the general idea behind ITS.

5.1.1 ITS in general

The abbreviation ITS stands for Intelligent Transport Systems. As the name suggests, such systems are supposed to provide information between system and users in order to make the transportation process more effective. ITS involve the use of information technologies in order to collect information about the traffic on the road, process it and take appropriate actions. ITS technology can, for example, be employed for monitoring and management of the traffic, managing of incidents, increase safety or managing of work zones. There are several levels of ITS. However, often a combination of the purposes is in focus where single levels may cooperate with each other. Below follows a brief description of the different levels.

Global ITS

Global ITS works along the roads and do not require any special equipment in the cars. These systems usually use sensors along the roads to collect traffic data, which initiates either adjustments of road parameters (for example maximum speed) or are distributed to the users in form of corresponding information through displays placed along the roads.

Built-in ITS

Built-in ITS can either work as stand-alone-systems or cooperate with the Global ITS. An example of stand-alone-system is ABS, which can be helpful in case of losing control over the vehicle. Cooperative Built-in ITS can be for example well-known GPS. GPS can provide information about location of the.

Before and during the journey

The driver can also use one of the most common agents to obtain information about the intended journey. Traditional media like internet, telephone service, television or radio also play a non-negligible role in ITS technology.

There is no uniform definition or categorization of ITS. Hence it may differ from source to source. For example the U.S. Department of Transportation (2009) distinguishes main research fields within ITS in following manner:

- Vehicle to Vehicle (V2V)
- Vehicle to Infrastructure (V2I)
- Infrastructure to Vehicle (I2V)
- Real-time data capture and management
5.1.2 ITS at Work zones

In case of the use of ITS in work zones is emphasis put on both making a more effective transportation process and support work zone management. Often safety and mobility are in the main focus.

Examples of the devices collecting data and providing information in work zones are sensors, detectors, counters, cameras, traffic signals or variable message signs. Through the devices the system either control the traffic, that means the system takes appropriate action, or provides information about traffic conditions to the drivers and letting them to take the action. The provided information can be for example information about alternate route, estimated delay or notification of queues.

Set of devices cooperating together is often the case of managing work zone through ITS technology. Such systems may be focused on enforcing drivers to respect certain speed limit, avoid queueing, optimize queue discharging or to perform dynamic late merge in merge areas.

In this are in focus Dynamic merge systems. The systems maximizing throughput of work zones through optimizing the merging act.

Dynamic Lane Merge Systems (DLMS)

Dynamic merge systems are not widely used. These systems are supposed to optimize the act of lane changing in the merging area. In order to do that is often necessary not only to constrain the vehicles in the closed lane but also vehicles in the open lane. When traffic demand is less than capacity of the road, DLMS are not activated.

McCoy & Pesti (2004) distinguishes two basic approaches of dynamic merge, Early merge and Late merge.

Early merge

One approach is called the Early merge, which is designed to encourage drivers to merge into the open lane sooner than in the Late merge. Figure 4 is provided for better understanding of the differences between the Late and Early merge. If the traffic flow is low, it is preferable to use the Early merge because the drivers look for acceptable gaps along a longer section. Thus the speed can be kept higher and safety is also better. However, if the density of the traffic flow is close to capacity of the road, it is beneficial to perform to apply the Late merge instead, since the traffic is too dense for drivers to look for acceptable gaps to change the lane. The Early merge is further divided into two approaches, Static and Dynamic. Both, Static and Dynamic Early merge provides the drivers message about merging to the open lane. This sign is provided in advance. For the Static Early merge is the sign placed in constant distance to the merge point while for the Dynamic Early Merge the distance depends on the actual queue length. Therefore the Dynamic early merge requires placing of several signs in interval in contrary to just one sign in case of the static option. According to (McCoy & Pesti, 2004) the merging act is smoother for The Dynamic Early Merge.
Late merge

As the Early Merge encourages the drivers to change the lane in advance before approaching the merge point, the Late Merge works in an opposite way. The traffic density is higher, acceptable gaps occur with lower frequency and forced merging would cause traffic disturbances. From these reasons is better to let the system take care of the merging act. The simplest solution of the Late Merge is that drivers in the closed lane look for acceptable gaps, when approaching the merge point. The zip rule can also be applied. That means, if the closed lanes are queued, the cars are passing evenly for each lane. For example, assume 2-to-1 lane work zone configuration one car passes in the open lane, then one car in the closed lane etc. This system requires a certain level of solidarity from driver’s side. A more common control of the merging act than the two previous ones is to use traffic lights. The lights, similarly as in intersections, provide alternate red and green signal.

While for the Early merge non-saturated traffic is assumed, the Late Merge often operates in the congested conditions, when the work zone becomes a bottleneck. In that case it is vital to optimize the traffic in the best possible way, otherwise the traffic may collapse. Hence, from the traffic performance point of view, properly working Late Merge system is more important than the Early Merge. Study conducted by McCoy & Pesti (2004) shows significantly higher capacity values and better safety in the Late Merge than in the Early Merge. However, the evaluation is valid only for peak traffic hours. Otherwise it is beneficial to employ the Early Merge strategy (McCoy & Pesti, 2004).

As envisioned in the previous text, the work zones, where DLMS are applied, are equipped with a set of signs notifying the drivers about further process and also intend to evoke appropriate behaving. Properly set marking may have positive effect on the traffic

Figure 4: The upper part is dedicated to The Early Merge (a), density is low and drivers preferably change the lane before approaching to the merge point. The Late Merge (b) situation in lower part assumes higher density and merging closer to the merge point then the Early merge. The example is developed by Pennsylvania Department of Transportation (Kang & Chang, 2006)
performance and safety. Hence the configuration of the signs needs to be the subject of researches in order to optimize its effect.

5.1.3 Benefits related with using ITS in work zones

Establishing of work zones often imply negative traffic flow impacts. That motivates the use of the previously described work zone’s ITS. The purpose of this chapter is to gather experiences from previous studies, present the key impacts and discuss the overall benefit of using ITS for work zone management. The list of the benefits below is observed at sites which were evaluated before and after introducing ITS, so it becomes easier to observe the difference.

Observed traffic benefits in applied ITS

- Significant traffic diversion rates, lower demand reduction and lower congestion was observed thank to appropriate messages displayed during congested conditions, and enhanced ability to manage incidents at sites in Texas and District of Columbia (Luttrell, et al., 2008).
- Incident clear time reduced from 45 minutes in past to 25 minutes (Scriba, 2004)
- The observed traffic flow showed improved ability to react to stopped and slow traffic in Arkansas (Luttrell, et al., 2008).
- Provided delay information at strategic locations in Arkansas reduced delay, because drivers may choose alternative road (United States Department of Transportation - ITS, 2002).
- Aggressive maneuvers were reduced after introducing a dynamic merge system in Michigan. Forced merges were 7 times less frequent, and dangerous merges were 3 times less frequent (Luttrell, et al., 2008).
- According to a conducted survey, drivers perceived improved work zone safety (Luttrell, et al., 2008).
- ITS helped to mitigate traffic backups in Illinois (United States Department of Transportation - ITS, 2002)
- ITS helps to reduce operation costs by not requiring full-time commitment of agency staff, however, no quantified evaluation is referred. (United States Department of Transportation - Federal Highway Administration, 2012; United States Department of Transportation - ITS, 2002; Scriba, 2004)

Conclusion

The number of cars is constantly increasing, while the number of kilometers of roads is also increasing but with respect to the increase rate of cars the increase rate of road kilometers is negligible. That results in higher frequency of work zones, hence higher number of potential
bottlenecks. Evaluation and development of work zone’s management becomes important and indispensable for optimized traffic in work zones. Dynamic message signs help to reduce congestion and improve incidence clearing. Introducing of dynamic merge systems improves behavior of traffic flow and safety. It might also reduce operational costs of Work zones.

In order to evaluate the total benefit of using ITS in work zones, the total cost needs to be examined. The most significant parts of the total cost are capital costs, long-term operational costs and project cost. Project cost is relative to the used ITS system. It is also appropriate to mention that the collected data for the evaluation are limited and quantification of the data is poor, hence it cannot be conclusively claimed whether mitigation of impacts caused by introducing work zone outweigh its cost.
6 Examination of Dynamic Late Merge Systems (DLMS)

Introduction

In this chapter three merging control systems for managing lane closure work zones are simulated and evaluated. Two of the systems, called Fixed and Continuous, use fixed timing for the traffic lights, while one switches between three fixed times due to traffic flow approaching the work zone (Wei et al., 2010). The third one, called ALINEA, is based on the ALINEA algorithm (Lentzakis et al., 2008). The employed strategies are designed for late merge. Thus they are assumed for the use under dense traffic conditions. Divergences between the late merge and the early merge approach are described in subsection 0.

Real-time traffic data detection concept

The idea behind feedback systems is their ability to adapt their behavior according to the prevailing traffic conditions. The measurements are detected, processed and finally the appropriate action is executed. This way the system can react to different traffic conditions in order to manage to improve traffic performance.

6.1 Simulation setup

Each scenario was run with 10 replications in order to improve average statistics of the conducted simulation and to get more reliable results and to be able to conduct statistical calculations. The behavior models, which are used in the simulation, are conducted with AIMSUN v7.0 (TSS-Transport Simulation Systems, 2011). The simulation approaches are inspired on previous studies. In order to replicate driver’s behavior described in the studies (Wei et al., 2010; Lentzakis et al., 2008) shortened reaction times were introduced. The reason for truncating them is to replicate movements of the vehicles passing through the traffic lights described in the studies. In particular, two driving maneuvers were in focus to generate. First maneuver described Wei et al. (2010) in the system called Continuous. There green and red signal alternate every 1 second, the author mentions that every green phase lets one car pass. The second maneuver refers to the ALINEA system and its property of dispatching every green time (4s) between two and three cars. After adjusting driver reaction time and driver reaction time at lights, and stop parameters, values of 0.5 and 0.7 seconds were found to provide the aforementioned movements. The rest of the calibration process is based on implicit calibration of Aimsun.

Utilized parameter values

- Driver reaction time = 0.5s
- Driver reaction time at stop = 0.7s
- Driver reaction time at lights = 0.7s
- Queuing up speed = 1 m/s
- Queue leaving speed = 4 m/s
- Lane width = 3.5m
- Acceleration = 1 m/s²
- Deceleration = 4 m/s²
- Speed acceptance = 1.1

**Work zone layout and configuration**

The work zone’s layout presented in Figure 5 is considered to demonstrate the potential of three proposed dynamic merge strategies. The traffic in two arriving lanes is merged in to one open lane. Merge area is of 20m length and occupancy detectors are placed right before the merge area. Traffic lights are placed one hundred meters upstream the occupancy detectors in order to provide independent signal for each lane. The length of the road before the traffic lights has been set to 2500 meters.

![Figure 5: Sketch of the work zone's physical configuration used in the simulation](image)

**Assigned flow**

The flow assigned in the simulation is showed in Figure 6. However, the values in the figure are average. Actual values in a particular period may differ because the used arrival demand scenario is stochastic. The flow values were adjusted so all the evaluated systems experience congestion and all vehicles are dispatched.

In the first 15 minutes the average flow is 1250 veh/h. During the next 15 minutes the average value becomes 2125 veh/h and the following peak has a value of 3000 veh/h. After 15 minutes peak flow the flow is decreasing with the same steepness as was used for the increasing. Thus 15 minutes after peak flow has demand flow of 2125 veh/h and during the last 15 minutes is the flow 1250 veh/h. The duration of the simulation is 90 minutes. The time is long enough to assure that all cars are dispatched.
The assigned flow is equally distributed into the lanes and assured that the equal flow will approach the lights. This is realized through physical separation of the lanes (see Figure 7).

6.2 Simulated scenarios

In total four scenarios are simulated while one dispose of no metering control (static) and three others are dynamic. The static system is called the No control and the dynamic systems are called the Fixed, the Continuous and the ALINEA.

6.2.1 Static late merge

This scenario is simulation without any control algorithm. It was carried out to evaluate differences between static and dynamic merging in the work zone.

6.2.2 Dynamic late merge

ALINEA metering system

The ALINEA was originally developed as a ramp-metering control system. In contrast to the original purpose of the ALINEA algorithm, in this thesis it is used to control all the vehicles on the mainline. Ramp-metering controls only vehicles approaching from local ramps. Unlike algorithms considering only flow as traffic conditions measure is the ALINEA more reliable,
because it also uses occupancy and critical occupancy vary less than capacity. The capacity flow may differ under various conditions (Lorenz & Elefteriadou, 2001).

The ALINEA algorithm was implemented into the simulation through the AIMSUN Application Programming Interface (API). The interface with external codes allows AIMSUN to use wider range of possibilities to develop various traffic situations, which the Graphical User Interface (GUI) is not able to provide. The external code is programmed in the C++ programming language (see the Appendix A).

Control algorithm

The algorithm receives real-time measurements of occupancy from detectors placed upstream of the merging area every 30 seconds. This information is processed in the same simulation step as the measurement is taken. The output of the calculation process is the estimated flow rate which will pass through the traffic lights in the next detection period. The equation below expresses the calculation of the flow.

\[ Q(k) = Q(k - 1) + K_r [O_{cr} - O(k - 1)] \]

Where:

- \( k=1,2,\ldots \) is the discrete time index;
- \( Q(k) \) is the controlled entering flow (veh/h) to be implemented during the next period \( k \);
- \( O(k-1) \) is the last measured occupancy (%) averaged over all lanes;
- \( K_r > 0 \) is a regulator parameter;
- \( O_{cr} \) is the set (ordered) value for the occupancy which may be set equal to occupancy for maximum exit flow.

The feedback algorithm guarantees that in case of congestion in the merge area, the arriving flow is reduced so the queued cars can be discharged. The parameters \( K_r \) and \( O_{cr} \) largely influence the behavior of the algorithm. The goal is to secure smooth traffic flow in the work zone, but at the same time, to maximize throughput.

The calculated output flow is distributed through traffic lights providing independent signal to each approaching lane. Hence, the flow has to be translated to the cycle time consisting of green and red signal. The algorithm considers the red as variable and the green as constant. The flow is transformed to cycle time for each lane by the following equation:

\[ Q = \left( T \cdot \frac{M}{C} \right) \cdot 3600 \rightarrow C = 3600 \cdot T \cdot \frac{M}{Q} \]

Where
• $7 < C > 15$ is the interval of possible cycle times in seconds; The cycle time consists of a constant green (4 s) and a variable red; The value is always round up, so the output is integer value;

• $M$ is number of arriving lanes; in this case is $M = 2$;

• $Q$ is the flow in time $K$ calculated in the previous equation;

• $T$ is assumed number of cars passing in one cycle time; in this case is $T = 2$.

The above equation provides the cycle time for one lane. All arriving lanes get the same cycle time. The flow approaching the lanes is equally distributed, that justifies the equal distribution of the cycle time between the lanes. The upper bound cycle time defines $Q_{\text{min}}$, which correspond to 960 veh/h, if there is assumption of two cars passing the lights each green signal period. The lower bound ($Q_{\text{max}}$), then, represents flow of 2057 veh/h and has provided 15 seconds cycle length. The green time provided to the lanes is separated in time by three seconds as illustrated in Figure 8. Thus the minimum cycle time is 7 seconds. The offset assures smoother flowing through the merge area. The reader can notice that there are assumed two cars passing each cycle time. However, when the cycle time is of the lowest value (7s) there might be three passing vehicles. This happens because the red signal (3s) is not long enough to make the cars approaching the lights to stop. What happens instead is that the green signal turns in, while the approaching vehicles still have some speed. Hence, the vehicles need shorter time to pass the lights. Thus the estimated flow within the algorithm's equations and the real flow may differ. However, this inaccuracy does not affect the function of the algorithm.

![Figure 8: Illustration of the offset between the lanes; green and red line imply for green and red signals, respectively;](image)

Note that the cycle time value does not have to be multiplication of the feedback control interval (30s). This produces a synchronization issue. The problem is solved by holding the last calculated flow for the next period until the previously applied cycle time does not meet its multiplication. However, this solution generates an error. Every time the feedback control detects occupancy values and calculates the new flow, the system waits before it applies the new value of flow until the currently applied cycle time is passed. The above described issue results in various times when single cycles are applied.
Figure 9 shows the timeline of the ALINEA algorithm. The feedback control detects occupancy exactly every 30 seconds in order to set an appropriate cycle time. When the new cycle time value is calculated, the cycle time is not changed directly. The value of the new cycle time is held until the current cycle time reaches its end and then it is applied. This causes the previously mentioned synchronization problem. In practice, the cycle time can be applied for longer or shorter times than 30 seconds. The Figure 9 contains a range of durations from 28 to 36 seconds. The synchronization problem is considered negligible with respect to the function of the merge-metering strategy.

Figure 10: Delay time of various configurations of the ALINEA; X-axis – regulator parameter; Y-axis – delay time

presents various configurations of the system and their values of average delay. The delay is in Aimsun computed as the measured travel time compared to travel time under free-flow conditions. Two parameters vary in the graph, regulator parameter \(K_r\) and critical occupancy \(O_{cr}\). The range of the tested parameters is 50-150 in case of regulator parameter and 30-50% in case of critical occupancy. The lowest value of average delay is achieved with the configuration of critical occupancy value of 40% and regulator parameter value of 75.

Therefore the comparison part is conducted with this particular configuration.
The power of the ALINEA merge-metering algorithm is an ability to flexibly react to congestion occurred in merge area. If the occupancy of the detector placed in merge area reaches the critical value, the traffic flow released to the merge area in the next period is reduced, so the congested traffic in the merge area can be discharged and generated shockwave is eliminated. The process of occurred congestion and consequent reaction is illustrated in Figure 11, Figure 12 and Figure 13. The purpose of describing characteristics of the three following configurations is to show different patterns of behaving of the system caused by adjusting regulator parameter ($K_r$) and critical occupancy ($O_{cr}$). In the chosen configurations was observed significant differences, which might clarify their different values of the average delay presented in the figure above.

In the Figure 11 is the applied configuration of $K_r=50$ and $O_{cr}=30\%$. From the figure it is apparent that the detected occupancy never exceeds the critical value of detected occupancy throughout the whole simulation, while the flow is fluctuating between 1000 veh/h and 1800 veh/h. The fact that the critical occupancy is, in this case, never exceeded, implies for a too low value of $K_r$. The addition of flow every 30 seconds is insufficiently big to reduce the cycle time by at least 1 second and consequently increase the flow rate. The configuration does not use the full potential of the metering strategy. The advantage of this configuration might be in non-collapsing traffic in the merge area and related safety issues. Nevertheless, safety is not subject to evaluation in this thesis.
The configuration applied in Figure 12 experiences congestion in the merge area. The occupancy of 80% is exceeded seven times during the simulation. The high values of occupancy are detected from the 27\textsuperscript{th} minute to the 85\textsuperscript{th}. The increase of $K_r$ to 150 caused too steep additions of flow, so the system is not able to avoid the congestion. Flow, in this case, fluctuates between 1000 veh/h and 3000 veh/h. The both values are boundaries of the system. Thus this configuration is able to provide higher values of flow than the previous.
The configuration presented in Figure 13 uses $Ocr=40\%$ and $Kr=75$. The regulator parameter is decreased, while occupancy is increased. The detector detects 100% occupancy five times during the simulation. The configuration of $Ocr=40\%$ and $Kr=75$ is the best performing configuration among the tested ones included in Figure 10. That is the reason why this configuration was chosen to be compared with two other metering strategies and no control scheme as well.
Wei et al. (2010) presented a fixed cycle merge metering system based on three fixed cycle lengths depending on traffic flow. The cycle lengths are 30 s, 60 s and 120 s. The cycle consists of red and green signal times. Both signals have always equal duration. The systems are called Fixed 30, Fixed 60 and Fixed 120 with respect to the applied length of the cycle time. Despite the fact that the Fixed Cycle Merge Metering is one system, the single cycle lengths are presented in the evaluation part as single systems. The purpose of presenting the systems separately is to find volume thresholds for switching from one cycle length to another. In this way the range of traffic flow for each cycle length is defined. The detailed time line of the system is illustrated in Figure 14.
Wei et al. (2010) presented also a strategy called Continuous merge metering. The cycle consists of red and green signals and each signal lasts one second. Thus the system is based on alternating the signals in order to let one car passing during each cycle time. The continuous merge metering resembles ramp metering strategy in approach. Here the vehicles in each lane have alternating, continuously displayed, green and red signals for one second each. Continuous merge metering is assumed to use real-time traffic data measurements only to activate the system. Once the system is running, the signal configuration does not change. It only deactivates itself when it is beneficial not to use the control strategy. The detailed time line of the system is illustrated in Figure 15.

Figure 14: Fixed cycle metering: Illustration of the offset between the lanes; green and red line imply for green and red signals, respectively;

**Continuous merge metering**

Figure 15: Continuous metering: Illustration of the offset between the lanes; green and red line imply for green and red signals, respectively.
6.3 Simulation results and conclusion

The comparison of the scenarios, the ALINEA, the Fixed metering, the Continuous and the No-control approach, described in previous subchapter is illustrated in Figure 16 and Figure 17. The figures show delay per vehicle and mean queue lengths, respectively.

![Figure 16: Delay curves of the merging systems](image1)

![Figure 17: Queuing lengths of the merging systems](image2)
From the figures above it is apparent that there is proportionality between delay and mean queue length of the single systems. According to the graphs, the Continuous represents the worst performance and the No-control has slightly better results approach. Vehicles of both systems experience the peak of delay and mean queue length (approximately 260 s/km and 300 veh) at the 75th minute and the 65th minute, respectively. The ALINEA manages to have the peaks of delay and mean queue length (109,67 s/km and 124,74 veh) at the 50th minute and the 55th minute, respectively. The Fixed system performs best among the tested systems. Its performance is positively correlated with decreasing cycle time. 30 seconds cycle experiences both peaks of delay and queues (27,22 s/km and 29,02 veh) at the 50th minute. Furthermore, the 30 seconds cycle time has better results than the cycle times of 60 and 120 seconds during the whole simulation length. The shorter cycle length produces shorter queue lengths and drivers experience shorter delay.

The following paragraphs summarize the reasons for the differences in performance of the metering methods.

According to Figure 16 and Figure 17 the Continuous merge metering system performs even worse than the No-control metering. The reason for this is that the one second offset creates insufficient distance between vehicles in the adjacent lanes to avoid congestion in the merge area. As the cars get congested, the shockwaves start forming in both places, the merge area and at the lights. The shock wave created in the merge area, soon reaches the traffic lights and the two queues becomes one. The Continuous metering does not tackle the problems with the congestion, moreover the lights upstream the merge area are causing additional delay.

ALINEA show significantly better results than the Continuous system and the No-control approach. According to the observations, there were two main reasons found, which might have the positive effect on performance. Probably the most crucial measure is the ability of the ALINEA system to sufficiently offset the vehicles in the parallel lanes, while both lanes are being served. During one cycle are always two or three vehicles dispatched in each lane, while each lane has offset of three seconds to the previous one. This measure postpones occurrence of congestion and consecutive shockwaves into higher values of traffic flow. In case of the continuous approach, where lanes have offset of one second, the cars in the merge area do not have sufficient distance and therefore get congested. Furthermore, if the ALINEA experiences congestion, the system is able to suppress the shockwave. This is realized through adjusting the cycle length. When the occupancy detected in the merge area reaches the critical value, the cycle length is enlarged, thus the red signal is longer and the congestion in the merge area is getting room for discharging (see Figure 12 and Figure 13). After the occupancy value is recovered below the critical value, the cycle length starts to get shorter, thus the flow rate arriving to the merge area increases.

Regarding the evaluation of the Fixed cycle lengths metering systems Figure 16 and Figure 17 show that the shorter the cycle time is, the better is the performance. However, the question is whether the results are realistic. The Fixed metering profits mostly from ability to separate the vehicles in both lanes into two halves of the cycle time, so congestion never occurs in the merge area. In the Aimsun model used for the simulation the lanes upstream the traffic lights
are physically separated, as shows Figure 7. This was mainly introduced to provide equal flows to each lane, since the signals between the lanes are equally distributed. However, further examination of the drivers’ behavior is recommended. In case that the cars would be unequally distributed between the lanes, the system, due to the equal signal distribution, might lose the high performance. The question is how the drivers would tackle the problem. Of course, the equal flow cannot be expected for the ALINEA as well. However, since the ALINEA serves all the lanes at the same time\(^1\), there are expected queues at each lane. Thus the driver’s behavior would eliminate unequal queue lengths automatically. Moreover, in case of restricted lane changing and random flow distribution among the lanes proposed Lentzakis, et al. (2008) an advanced strategy of adjusting the signals. The inequality in the queue lengths is to be tackled by additional detecting queues upstream the lights and corresponding distribution of red signal among the lanes.

| Table 1: Merge strategies results; Delay time is computed by Aimsun as the travel time compared to travel time in free-flow conditions. |
|---|---|---|---|---|---|---|
| Delay Time | sec/km | ALINEA | Fixed 120 | Fixed 60 | Fixed 30 | Contin | No control |
| Harmonic Speed | km/h | 55.71 | 40.75 | 30.96 | 14.07 | 134.78 | 128.03 |
| Mean Queue Length | vehs | 34.31 | 28.61 | 20.38 | 8.17 | 108.03 | 103.03 |
| Stop Time | sec/km | 32.45 | 27.81 | 19.92 | 9.87 | 104.30 | 99.36 |
| Total Travel Time | h | 221.74 | 191.88 | 174.54 | 124.29 | 365.29 | 353.53 |

Table 1 shows the delay, speed, queue length, stop time and travel time of the network for different merging methods. As it can be seen, the method using the Fixed metering produces the best results compared with the other simulated methods. 30 seconds cycle time performs best of the Fixed metering strategies. Although due to previously described unrealistic conditions regarding the Fixed metering and the poor performance of the Continuous metering is focus put on comparing the ALINEA algorithm with and the No-control strategy. The ALINEA results in approximately 44% reduction compared to the No-control’s delay time and almost 183% reduction of harmonic speed. Relative differences of mean queue length, speed and stop time are of 33, 136 and 33%, respectively. Finally, the total travel time for the ALINEA system is 63% of the No-control’s total travel time. However promising the results seem to be, a statistical analysis needs to be conducted in order to provide an appropriate conclusion.

The continuous metering performs even worse than the No-control approach. Relative result of delay time of the Continuous metering is approximately 105% with respect to the No-control’s results. Similar pattern between the results is observed with the rest of the variables included in Table 1.

\(^1\) The statement is not entirely true since there is introduced offset between the lanes. Although from this point of view is the offset negligible.
Statistical interpretation of the results

In order to evaluate the results from a statistical point of view a comparison was conducted between systems, the ALINEA and the No-control. T-test was conducted for testing whether the differences between the two systems are statistically significant or not.

T-test statistics for two independent samples is defined by following formula:

\[
t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{S_{x_1}^2}{n_1} + \frac{S_{x_2}^2}{n_2}}}
\]

Here \(S_{x_1,x_2}\) is the pooled standard deviation, 1 = ALINEA, 2 = No-control. \(\bar{X}_{1,2}\) is the mean value of corresponding variable, \(n\) is the number of samples (\(n\) is for both systems equal to 10) and \(t\) is the standard error of the difference between the systems.

Table 2: Statistical results of significance or non-significance of variables of two best preforming systems – ALINEA and No control

<table>
<thead>
<tr>
<th></th>
<th>Average value</th>
<th>Standard deviation</th>
<th>Statistical significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ALINEA</td>
<td>No-control</td>
<td>ALINEA</td>
</tr>
<tr>
<td>Delay time</td>
<td>55,71</td>
<td>128,03</td>
<td>22,91</td>
</tr>
<tr>
<td>Harmonic speed</td>
<td>30,11</td>
<td>18,76</td>
<td>12,75</td>
</tr>
<tr>
<td>Stop time</td>
<td>32,45</td>
<td>99,36</td>
<td>17,38</td>
</tr>
</tbody>
</table>

The performed statistical analysis (see Table 2) shows significant differences between the ALINEA system and the No-control systems in all the tested parameters. Significance level for all the tests is 0,5.

Another way to interpret performance might be to estimate capacity according to one of the presented definitions in the subchapter 3.2. One minute averages of flow values (passing the bottleneck) used for measuring the capacity are collected in 30 seconds samples (Cassidy & Rudjanakanoknad, 2005). Capacity values of the simulated systems, estimated according to the definition of capacity stated by (Jiang, 2001) are presented in Table 3. Jiang’s definition is in this thesis interpreted as average of maximal flow values after the bottleneck. The value is taken just before a sharp decrease. Hence, the highest value does not necessarily mean best performance of the system, but stability has to be considered as well. The ALINEA has the highest value of capacity (2600 veh/h), followed by The Fixed metering 120, 30 and 60, with values of 2554, 2550 and 2548 veh/h, respectively. The rest of the results correspond to the performance proportionality in Table 1. The continuous metering has a capacity value of 1944

58
veh/h and the No-control approach 1980 veh/h. The obtained values are relatively high with respect to the recommended capacity value.

Table 3: Capacity of the simulated systems according to Jiang’s definition (2001)

<table>
<thead>
<tr>
<th>System</th>
<th>Capacity (veh/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No control</td>
<td>1980</td>
</tr>
<tr>
<td>Continuous</td>
<td>1944</td>
</tr>
<tr>
<td>Fixed 60</td>
<td>2548</td>
</tr>
<tr>
<td>Fixed 30</td>
<td>2550</td>
</tr>
<tr>
<td>Fixed 120</td>
<td>2554</td>
</tr>
<tr>
<td>ALINEA</td>
<td>2560</td>
</tr>
</tbody>
</table>

6.4 Discussion of the simulation results

Accurate estimation of level-of-service is a prerequisite for applying systems like Dynamic merge systems (DMS). Nowadays DMS are commonly used only in USA. Several traffic and safety performance improvements were noticed by its use (Luttrell, et al., 2008; Scriba, 2004; United States Department of Transportation - Federal Highway Administration, 2008). However costs for introducing such systems are not sufficiently quantified yet.

Simulation of three different approaches of dynamic merge system was conducted. All the systems have in common that they use traffic lights in the merge area. All the systems were simulated for a work zone configuration with 1 open and 1 closed lane. The author’s was to show the potential of the ALINEA algorithm based on its ability to flexibly react to various traffic conditions. The other systems which have predefined fixed cycle times have considerably simpler character than the ALINEA. This is the reason why the ALINEA has given more space in this report. From the performed sensitivity analysis of the ALINEA system, where variables were regulator parameter and critical occupancy, is the best performing combination of critical occupancy of 40% and regulator parameter 75.

Lentzakis et al. (2008) also evaluated the best performing the ALINEA configuration the one where congestion does not occur at all. The sensitivity analysis conducted in this thesis shows that the congestion occurred in the merge area, does not have necessarily have negative impact of overall performance of the system. The configuration of 30% critical occupancy and 150 regulator parameter performs than the configuration of critical occupancy 30% and regulator parameter 50, even though the second configuration avoids occupancy values higher than 29%. It can be drawn that the second configuration does not utilize the whole potential of the algorithm. However, the lower values of congestion might have probably positive effect on potential safety issues related with high-dense and collapsing traffic.
Furthermore was all DMS compared with respect to factors such as delay, harmonic speed, mean queue length, stop time and total travel time. The Fixed metering shows the best results among the tested approaches, however, due to favoring conditions, caused by lane changing restrictions and physically separated lanes, the Fixed metering’s results are not considered valid for the evaluation. Excluding the Fixed metering, the ALINEA shows better performance in all parameters than the Continuous metering and the No-control approach. The ALINEA was further compared with the No-control approach in order to determine whether the differences between the results are statistically significant. Three parameters were included, delay, harmonic speed and stop time, where all of them were recognized as statistically significant.

The capacity evaluation conducted based on Jiang's definition (2001), showed the highest capacity for the ALINEA system. The second, third and fourth highest value of capacity belongs to the Fixed metering. Capacity, as it is interpreted by the Jiang's definition (2001) may not be appropriate indicator for evaluation of the performance of the systems. The definition considers capacity as the highest value just before a sharp decrease. This directly implies for the congestion, which follows after the capacity value is taken. Thus at the moment, when the capacity value is recorded, the system is beyond “the point of stability”. In other words, the followed congestion inevitable has to occur and that is certainly not desired.
7 Discussion and conclusion

This thesis studies work zones along highways and the consequences and impacts they have on the traffic flow. It investigates the possibilities of implementation of three different merging schemes and their potential to improve the traffic condition at work zones.

These road reconstruction/maintenance activities can be categorized as short-term, long-term, stationary or mobile work. They can also be dividable based on the work intensity, time restriction and the interaction between the road and the work zone. Lane closure is one of the common work zone classes which causes traffic disturbance along the road that consequently results in queues, delays, and emissions. When flow rate exceeds the capacity of the increased road in a particular segment, congestion occurs, which results in longer travel time, delays and road user cost. Hence capacity reduction at work zones turns out to be an important factor to be studied in order to improve the road traffic performance. Categorization of capacity influential factors is defined in this thesis according to Zheng, et al. (2010). A literature review of analytical models of capacity estimation (Weng & Meng, 2011; Benekohal, Kaja-Mohideen, & Chitturi, 2004; Kim, Lovell, & Paracha, 2001; Dixon & Hummer, 1996; Transportation research board, 2000; Sarasua, Chowdhury, Davis, & Ogle, 2006) agree on that there are eleven factors which have been considered the most in work zone capacity models. Heavy vehicle percentage, number of open and closed lanes and work intensity can be mentioned as the most significant factors affecting the capacity which are considered in most of the reviewed models. Factors such as weather condition, light supply, driver behavior, lateral clearance and lateral distance can be referred to as parameters with the lowest given attention. Reviewing the previously performed researches illustrates that implementation of Intelligent Systems at these specific road construction conditions is also another factor with no high attention (Zheng et al., 2010; Weng & Meng, 2011; Venugopal & Tarko, 2011).

Work zones have generally complicated character. It can be demonstrated either by various definitions mentioned in subchapter 3.2 or by the number of variables affecting traffic performance. The experienced lack of field data from work zones results in impossibility to accurately estimate level-of-service. In an ideal case it would work zone management available fundamental diagram of the work zone, from which would be possible to accurately estimate capacity of the work zone and avoid collapsing of the traffic due to capacity drop. Lack of data can to the certain extend be compensated by the use of an appropriate estimation method. As Weng & Meng (2011) demonstrated by their unusual approach of the analytical model, certain information might be valid for certain type of work zone. However, analytical models are not able to consider as many physical parameters as simulation methods. Especially microsimulation software seems to be appropriate tool to model work zones. The current Aimsun version does not implicitly offer to model work zone, but it can be to the certain level imitated.

Conclusively, if a certain level of accuracy is reached while estimating level-of-service, the discussion of how to improve it may take place. The use of ITS in work zones is rather limited nowadays. However, it can be assumed that it will become even more important as new
control strategies develop and number of cars increases. Among the tested approaches of so-called dynamic merge systems, ALINEA showed potential to increase level-of-service for work zones. The ALINEA is one of the more sophisticated dynamic merge systems and its configuration consists of several parameters. For those parameters, extensive sensitive analysis has to be conducted in order to utilize the system as much as possible. The ALINEA was originally developed for ramp metering and for such purpose was proposed an optimization of the algorithm using another genetic algorithm (Chu, Yang, & Recker, 2003). The study considers four parameters, including the update cycle of the metering rate, a regulator constant, the detector location and the desired occupancy of the downstream detector station. The situation in work zones is similar. The significant differences in the results of the various configurations of the ALINEA evaluated in this thesis, shows a need for optimization.

**Recommended further research**

- The field data collected in work zones mostly comes from USA. Further studies in the subject require sufficient collection of data from European conditions. This includes the information about various types of highways and work zones with different number of lanes.

- In order to avoid collapsing of traffic a detailed study is needed to determine the cause of capacity drop and its consequences on work zone’s traffic performance.

- The adjustment values used in the analytical models for single variables are usually directly taken from the HCM for basic freeway sections. There is a need to collect field data to determine if these values are applicable for work zones and furthermore under European conditions.

- The number of factors considered so far, might not be the most efficient and the best possible selection. Finding more significant factors might increase estimation accuracy.

- Using ITS technologies may affect work zone capacity. Effect of using ITS technologies on speed-flow curve and capacity needs to be studied more thoroughly. This includes a detailed analysis of benefits and costs of using ITS technologies in work zones.
Bibliography


Appendix A

The ALINEA algorithm source code

#include "AKIProxie.h"
#include "CIProxie.h"
#include "ANGConProxie.h"
#include "AAPI.h"
#include <stdio.h>
#include <math.h>

// Variables declaration
char astring[128];
double O_last=0;
int Flow = 0;
int OldFlow = 0;
double Flow_rate_last = 0;
double NewCycleTime = 0;
double NewFlow = 1500; // Initial value of flow in the equations of ALINEA algorithm
int check = 0;
double OldCycleTime = 0;
double Offset1 = 0;
double Offset2 = 3;
double green = 4; // Duration of the green phase. (Constant during the whole simulation)
double YellowTime = 0; // Duration of the yellow phase.
double cycle_duration = 0;
double Density_last = 0;
double Speed_last = 0;
int ApproachingLanes = 2;
int NumberOfCars = 2; // Number of cars passing the lights during a green cycle.
int OpenLanes = 1;
int IdDetector = 559;
int VehType = 0;
int RegPar = 100;
int Ocr = 40;
int MinFlow = 1500;
int MaxFlow = 2400;
int aidarc1 = 343;
int time_interval = 30;

int AAPILoad()
{
    AKIPrintString("LOAD");
    return 0;
}

int AAPIInit()
{
    AKIPrintString("\tInit");
    ANGConnEnableVehiclesInBatch(true);
    return 0;
}

int AAPIManage(double time, double timeSta, double timTrans, double acl)
{
    AKIPrintString("\tManage");
}
int AAPIPostManage(double time, double timeSta, double timTrans, double acicle) {

    O_last = AKIDetGetTimeOccupiedAggregatedById(IdDetector, VehType); // Last detected Occupancy
    Density_last = AKIDetGetDensityAggregatedById(595, VehType); // Last detected Density
    Speed_last = AKIDetGetSpeedAggregatedById(595, VehType); // Last detected Speed
    Flow_rate_last = Density_last * Speed_last; // Last computed Flow Rate

    if (fmod(time, AKIDetGetIntervalDetection()) == 0) { // The condition assuring that the process of computing cycle times happens only every 30 seconds.
        NewFlow = Flow_rate_last + RegPar*(Ocr - O_last); // The basic ALINEA algorithm’s equation.
        if (NewFlow < MinFlow) { // Setting bounds for the Approaching Flow.
            NewFlow = MinFlow;
        }
    }

    OldCycleTime = NewCycleTime;
    NewCycleTime = 3600*NumberOfCars*ApproachingLanes/NewFlow;
    NewCycleTime = ceil(NewCycleTime); // Rounding up the value.

    if (NewCycleTime < 7) { // Setting bounds for the cycle time.
        NewCycleTime = 7; // 7 seconds is minimum value of the cycle time of a lane because of necessity for the 3 seconds offset between the lanes.
    }

    if (time < 70) { // In the first 70 seconds is cycle time set to 10 seconds. This Condition is introduced because the cars are not able to reach the merge area earlier, thus the algorithm would set the longest possible cycle time. Consequently, the first cars that approached the merge area might be blocked for no reason.

        NewCycleTime = 10;
    }

    check = 1; // Auxiliary variable assuring that the process of computing cycle times happened.
}

AKIPrintString("\tPostManage");

cycle_duration = cycle_duration + acicle; // Time for which is the last computed cycle time applied.

    if (fmod(cycle_duration, OldCycleTime) == 0) { // Condition assuring that the applying of cycle times happens only when the duration of the last applied cycle
// time is multiplication of the cycle time. (See the synchronization issue described
// in ALINEA algorithm description.)

if (check == 1) {// Condition assuring that the following rows do not
apply already applied cycle time before.

    ECIChangeParametersGreenMeteringById(432, timeSta, green, green, green,
                NewCycleTime, Offset1, YellowTime);

    ECIChangeParametersGreenMeteringById(431, timeSta, green, green, green,
                NewCycleTime, Offset2, YellowTime);

    check = 0;

    cycle_duration = 0;

    return 0;

} // End if

int AAPIFinish()
{
    AKIPrintString("\tFinish");
    return 0;
}

int AAPIUnLoad()
{
    AKIPrintString("UNLOAD");
    return 0;
}

int AAPIPreRouteChoiceCalculation(double time, double timeSta)
{
    AKIPrintString("\tPreRouteChoice Calculation");
    return 0;
}