# Operational stability and reliability of urban bus routes in Zurich, Switzerland

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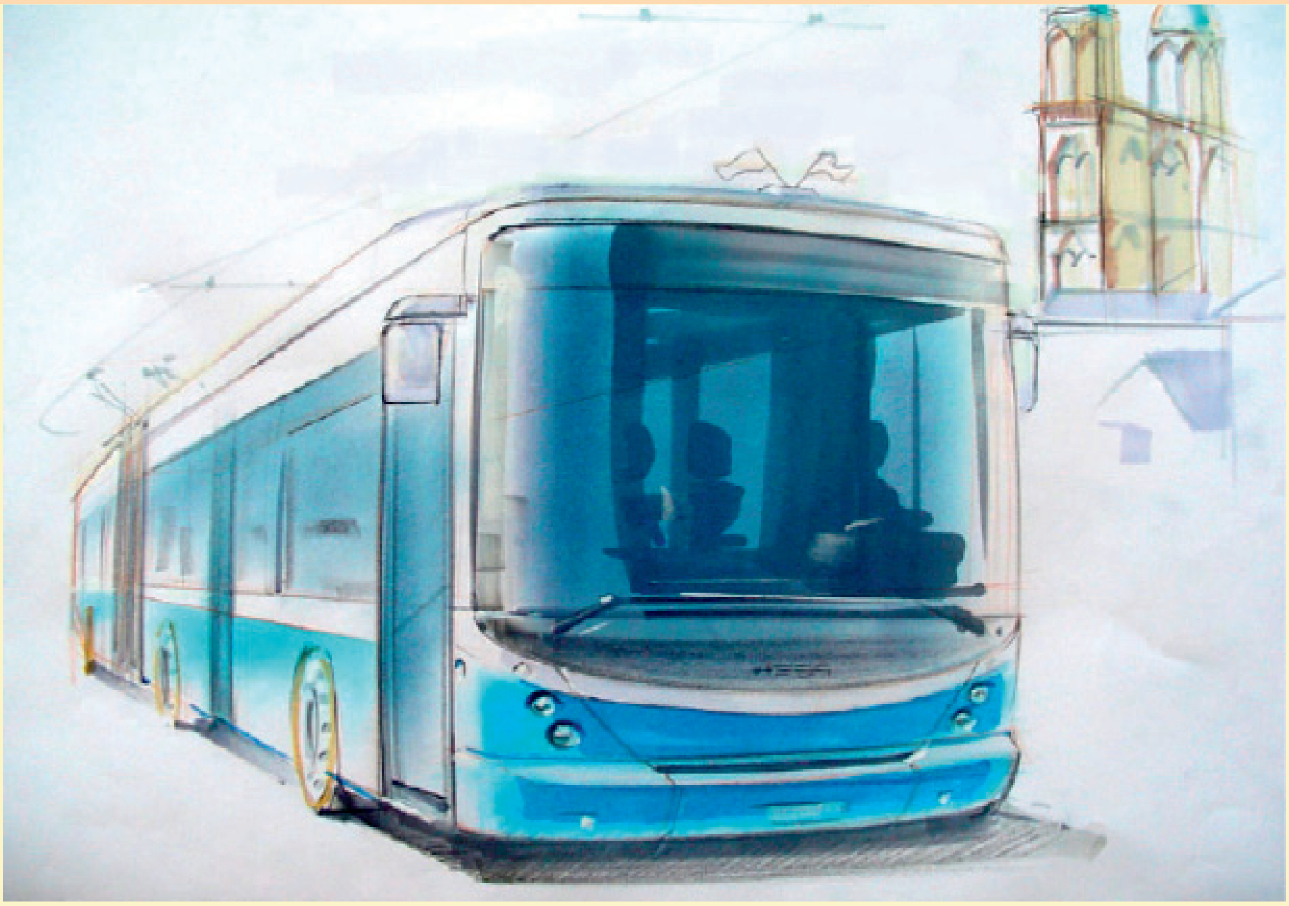

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Research project funded by the SBF in the framework of COST Action TU 0603
“Buses with High Levels of Service” (BHLS)

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## Abstract

Reliability and stability belong to the most determinant factors influencing mode choice for existing and potential public transport users. Service reliability impacts not only passengers but also operators. Unreliable services impose higher operating costs due to the additional resources required to deal with them, and reduce the revenue because of lost ridership.

This research project focuses on different elements of transport service reliability, in particular on the planning of the targeted level of service and on measuring the performance of service delivery. Performance analyses are based on the case study of trolley bus Line 31 in Zurich. Automatic vehicle location data are used for detailed analyses of operational performance. Based on evaluations of the deviation between the targeted and delivered level of service, causes of unreliability are identified and classified. General and particular measures to improve reliability are derived and discussed, which can be preventive or corrective in nature.

The present study was developed in the framework of COST Action TU0603 „Buses with High Level of Service (BHLS)", the goal of which is to increase the use of public transport and promote sustainable mobility by developing new, high quality bus services.

### Key words

Reliability; Public Transport; Zurich; Performance measures; AVL data.

### Preferred citation style

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# Abbreviations

| | |
|---|---|
| ADCS | Automatic Data Collection System |
| AFC | Automatic Fare Collection |
| APC | Automatic Passenger Counting |
| AVL | Automatic Vehicle Location |
| BHLS | Buses with High Level of Service |
| BI | Business Intelligence |
| BRT | Bus Rapid Transit |
| CBD | Central Business District |
| CBS | Conventional Bus Service |
| DAV | Dienstabteilung Verkehr (Zurich's Traffic Control Department) |
| DB | Data Base |
| DM | Data Mart |
| GIS | Geographic Information System |
| GPS | Global Positioning System |
| ITS | Intelligent Transportation System |
| LOS | Level of Service |
| MLS | Maximum Load Section |
| OTP | On-time Performance |
| QOS | Quality of Service |
| S-Bahn | Stadtbahn (refers to commuter focused, regional heavy rail services) |
| SER | State Secretariat for Education and Research of the Swiss Confederation |
| SQL | Structured Query Language |
| TAZ | Tiefbauamt Zürich (Zurich's Civil Engineering department) |
| TT | Travel Time |
| VBZ | Verkehrsbetriebe Zürich (Zurich's public transport operator) |
| ZVV | Zürcher Verkehrsverbund (Zurich's public transport authority) |

# Acknowledgements

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# 1 Introduction

## 1.1 Role and benefits of urban public transport

Urbanization and the demand for mobility have been constantly increasing around the world over the last decades. Public transport provides an efficient and sustainable way to meet increasing mobility needs, especially in urban areas.

Public transportation is typically provided on fixed routes and at regular time intervals according to published schedules. It is accessible to the general public, who shares the offered passenger transportation service. It mainly includes the use of buses, trams, trains, rapid transits and ferries. The basic function of public transportation is to collect and distribute passengers, from an origin station to a destination station.

Many benefits arise from using public transportation. Due to its ability to transfer large numbers of people and its comparably low consumption of required urban space, public transport reduces traffic congestion. Additionally it reduces energy consumption, dependence on oil and greenhouse gas emissions, and makes mobility more sustainable. Public transportation expands opportunities and transportation choices and provides an affordable mobility choice. It can additionally be one of the decisive factors for attracting investments, creating new jobs and ensuring economic growth. A high quality public transportation system can even contribute to the living standards and quality of life by reducing congestion, travel time and stress.

Switzerland and particularly Zurich are well known for their excellent public transport services. Decision makers in Zurich have recognized the importance and benefits of public transportation. They are constantly searching for ways to improve quality of service and current policies aim at increasing its modal split share. They take a pioneering role in several aspects of public transportation. Political and public support is a key element of success for public transport in Zurich.

## 1.2 Aim and scope of this project

The quality of service of public transportation influences the mode choice of travelers and their travel behavior. The overall quality of public transportation includes several criteria, such as customer care, comfort, information, etc. In general, a destination needs to be made between the quality of service targeted and delivered by the operator, and the quality of service perceived and required by the customer. Reliability and stability of provided transport services belong to the most significant quality criteria for existing and potential public transport users.

Service reliability not only affects passengers but also operators as unreliable services cause higher operating costs (due to additional resources required to deal with unreliable services) and reduces the revenue and patronage (due to decreasing numbers of customers).

Therefore, the benefits of public transportation can only be fully implemented if public transportation can increase its share in modal split. In places where people have a choice between modes, the shift in modal split from private to public transportation can only be achieved if the perceived quality of the service and most importantly the perceived level of service reliability are in line with the level of quality and reliability required by the customers. Thus, the attractiveness of public transport can be increased by reducing waiting time variability, mean waiting time and total travel time variability, which are the sources of trip disutility or unattractiveness[1].

For the mentioned reasons, reliability is in the focus both of operators, as well as potential and current public transport users. Unreliability can be defined as the deviation between the targeted (or planned) level of service and the delivered (or operational) level of service. Therefore it is essential to plan the targeted level of service effectively, to measure the deviation between the targeted and delivered level of service, to identify the sources of unreliability and their impact, and if possible to derive measures to improve reliability, based on adequate analyses and evaluations.

The first objective of this study is therefore to describe the state of the art in public transport service planning procedure and to compare it to the current state of practice in planning conducted at Zurich's public transport operator, the VBZ. The subsequent objective is to analyze and evaluate the performance of delivered public transport service. The analysis will be based on a case study of trolley bus line 31 operated by the VBZ in Zurich. Before the performance can be measured effectively, reliability and performance measures for different aspects and perspectives of reliability (such as of passengers' or operators' perspective) have to be derived. Additionally, their suitability and applicability to the analyzed problems has to be evaluated. Several factors affect reliability and stability of transportation service in various ways and with different degrees of severity. Therefore, they are classified and categorized as this can facilitate the identification and assessment of possible approaches to deal with the factors influencing reliability and with their consequences.

Because reliability can be defined as the gap between the targeted and the delivered transportation service, the subsequent objective of the study is to compare the planning of transport service delivery with its actual delivery in the operation by means of the selected case study. Based on foregoing theoretical consideration the actual gap between planning and operation is

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[1] The causes and measurements of the difference between delivered and perceived quality of transportation service will not be in focus of this study.

analysed and the causes of unreliability derived. The quantitative impact of the single sources for unreliability is not part of this study.

Based on preceding analyses and strategies proposed in literature, strategies to increase reliability and stability of transportation service in general and for the analysed trolley bus line 31 in particular are proposed. Furthermore, the strategies proposed in the literature are analysed for feasibility and applicability in Zurich for the considered line or if they are already implemented.

The use of automatic vehicle location (AVL) and automatic person counting (APC) systems provides new sources of data for a detailed analysis of trolley bus operation performance. For this study only AVL data was available.

Some of the objectives planned at the beginning of the project had to be adapted due data availability, the practices already implemented at the operator's procedure or the missing systematical approaches used in practice.

The present study is embedded in the COST Action TU0603 „Buses with High Level of Service (BHLS)“. This COST action ultimately seeks to increase the use of public transport and promote sustainable mobility by developing new, high quality bus services comparable with rail modes that compete with car use within Europe. To its objectives belongs the goal to share and analyze current best practice in the field of BHLS and to facilitate exchange of knowledge about BHLS. This research study therefore contributes to that objective.

## 1.3 Report outline

The main structure of the report corresponds to the principal objectives of the study.

In Chapter 2 a general overview of road-bound urban public transport, its organization, basic elements, characteristics and operational processes is provided. As definitions often vary in this area, some basic terms related to operational reliability are defined, to provide a common basis for the entire report.

Chapter 3 gives an overview of public transport performance evaluation, specifically the different dimensions of transportation service reliability and stability, as well as their measures. Additionally, elements and factors influencing reliability are classified and categorized. Furthermore, the phenomenon of bus bunching and the technology of automatic data collection systems are introduced.

In Chapter 4 the public transport planning process is addressed. A generic planning process is proposed, based on the literature for the different levels of planning in public transport. The proposed generic planning process is subsequently compared to the public transport planning process practiced in Zurich, based on interviews with the VBZ.

Chapter 5 quantifies public transport service reliability in Zurich using off-line operational data, including AVL data. The results include operator-oriented measures such as detailed travel time, speed, punctuality and regularity analysis, together with reliability oriented performance measures. Additionally, the study includes an analysis of passenger-oriented measures of reliability focusing on different waiting time measures.

In Chapter 6, the planning of the service at the VBZ is compared to their actual service delivery. The idea is to identify potential gaps between planned and delivered transportation service either in planning or operation, and subsequently to identify potential for improving service reliability.

In Chapter 7, based on preceding analyses and strategies proposed in literature, strategies to increase reliability and stability of transportation service (in general and for the analysed trolley bus line 31 in particular) are proposed and reviewed qualitatively for their feasibility and applicability in Zurich.

Finally, Chapter 8 provides a summary and conclusions, as well as needs for further research.

# 2 Basic principles of urban public transport systems

## 2.1 Chapter overview

This chapter provides a general overview of road-bound urban public transport, its organization, basic elements, characteristics and operational processes. First, the specific context and boundaries of this work are specified, together with the hierarchic structure of planning and operations, as well as some basic definitions. These are useful because terms often vary in this area, and the same expression can be understood differently. Basic operating elements in public transport are described in the following section. The last section describes the operational processes taking place in the service delivery of urban bus lines.

## 2.2 Urban public transport as a system

### 2.2.1 Road-bound public transport

Urban public transport comprises all passenger services that are available for use by the general public in a town, city or metropolitan area. Surface urban public transport services are commonly provided by three types of modes: buses, trolleybuses and trams. In many cities with higher demand, these can be complemented by heavier rail-based modes (e.g. commuter trains, metro, monorail, etc.) and in some cases by other modes such as cable cars or boats. “Buses are by far the most widely used transit mode”, as stated by Vuchic (2007). Regardless of the size of a city, they are always present, either for high-capacity bus-based public transport systems such as Bus Rapid Transit (BRT), or as feeder services for rail based systems. The vehicles vary in capacity, from minibuses with about 15-25 spaces, to double articulated buses such as those operating in Line 31 in Zurich, with a capacity of about 200 spaces.

Buses can operate on almost all streets, providing services that cover a large range of quality, performance and operational costs. Trolleybuses are powered by electricity taken from two overhead wires suspended along the line, providing a lower degree of flexibility due to the need for energy supply infrastructure. Buses and trolleybuses are the public transport modes that most interact with other road users, such as private vehicles, bicycles and pedestrians. For this very reason, they are the most susceptible mode to the number and behaviour of other road users. This often leads to conflicts in road usage and a decrease in the quality of the service. In the context of this work, which is focused on bus routes in Zurich, only road-bound public transport modes will be contemplated with focus on buses and trolleybuses, and occasional inclusion of trams. Public transport services provided by heavy rail-based modes, as well as other existing modes in Zurich (funiculars and boats) are not included in this work.

### 2.2.2 Functional structure of public transport planning and its operation

The general structure of public transport systems consists of different, hierarchical levels, which deal with the planning and delivery of the service to the public. These are the strategic, tactical and operational levels, and are generally valid for any type of public transport system. They are depicted below:

Figure 1 Functional structure of public transport operations and planning

Source: adapted from Luethi (2009)

At the top of the hierarchy, the *strategic planning* level defines the plans and corresponding actions needed to reach the city's long-term public transportation goals. These objectives are defined in coordination with land use, mobility strategies, development forecasts, and related policies and standards, which define the vision of the city for the future.

Lawrie and Colston (2005) describe strategic planning as "a management tool (...) used to define an organization's vision, mission, core values, challenges, and opportunities; establish long- and short-range goals; guide business processes; and measure performance. It can assist an organization in creating its future rather than just reacting to it." Therefore, strategic planning deals with the transport service network design, although it can also define the types of service to be provided and the corresponding types of vehicle, their coverage and the required infrastructure.

*Tactical planning* in public transport uses the information provided by the strategic planning level as input to produce shorter-term, more limited objectives needed to deliver public transport services in the operational level. These include setting frequencies, designing timetables, and assigning resources (vehicles and drivers) to each route. The results of strategic and tactical planning provide the conditions for the delivery of the transport service in the *operational level*. This level deals with the implementation of the previous plans on a very short time scale, as well as with the supervision control of every day services, on a real-time basis. Additional tasks include reacting to emergencies, failures, interruptions and other unplanned events.

### 2.2.3 Definition of general terms

The following definitions aim to clarify the concepts that will be used throughout the following chapters. Some of them can be applied to other contexts, but in such cases they are defined to fit the framework of this study: road-based urban public transport.

**Availability** is a measure of the capability of a public transport system to be used by potential passengers, including such factors as the hours the system is in operation, route spacing, and accessibility to people with disabilities. TCQSM (2003).

**Capacity** can be used to describe many individual elements of a transportation system (e.g. public transport line, seating, standing, vehicle, etc.). In general, it refers to the ability of public transport facilities to move a certain amount of people and public transport vehicles in a given time frame. Normally expressed in passengers per hour-direction for a particular section.

**Effectiveness** in public transport is the degree to which the desired level of service is being provided to meet stated goals and objectives. For example, the percentage of a given service area population that is within the desired 400 meters to a bus or tram stop. TCQSM (2003).

**Efficiency** describes the extent to which time or effort is well used for the intended task or purpose. It also expresses the rate of success a specific process has either in recovering the expended resources (e.g. the extent to which energy has been recovered from the combustion of a given amount of fuel), or in achieving a given objective. Tomazinis (1975).

**Flexibility** can be understood in a number of ways, but for public transport systems it refers to the level to which the system can respond to uncertainty in order to sustain its planned service delivery.

**Level of Service (LOS)** can be understood in two ways. As the amount of public transport service provided (e.g. frequency, time-span of service, number of seats, etc.); or as a concept used to quantify quality of service based on a scale from A (highest quality) to F (lowest quality) according to the TCQSM (2003). In practice, different agencies and operators develop their own set of indicators according to their particular system and urban characteristics.

**On-time performance** corresponds to the proportion of the time that a public transport system adheres to its published schedule times within stated tolerances or thresholds. For example, a bus or tram arriving, passing or leaving a predetermined (time) point along its route or line within a time period that is no more than *x* minutes earlier and no more than *y* minutes later then the published schedule time. TCQSM (2003).

**Performance measure** refers to a qualitative or quantitative measure (or indicator) of how well an activity, task or function is being performed. In transportation systems, it is usually computed by relating a measure of service output (or use) to a measure of service input (or cost). TCQSM (2003).

**Performance measurement system** refers to the set of measures, data collection procedures, evaluation methods, goals, and reporting methods used to monitor an operator's effectiveness, efficiency, service quality, and goal achievement for the purposes of improving decision-making and meeting objectives. TCQSM (2003).

**Quality of service (QOS)** is the overall measured or perceived quality of transportation service from the users' or passengers' point of view, rather than from the operating agency's point of view. It is defined for public transport systems, route segments and stops by *level of service*, according to the TCQSM (2003). In a more detailed level, quality can be described in four classes, these are expected, targeted, delivered and perceived quality.[2]

**Reliability** refers to the extent to which public transport service is provided to the user as promised by the operating company. It affects waiting time, consistency of passenger arrivals from day to day, total trip time, and loading levels. TCQSM (2003). A more extensive discussion on reliability in the context of public transport can be found in section 3.2.

**Regularity** refers to the evenness of headways between successive public transport vehicles. It is particularly important for high frequency services (below 10 minutes). It influences on time performance, vehicle loading levels and passenger comfort.

**Right-of-way (ROW)** refers to the degree of separation of public transport vehicles from other road users. See section 2.3.4.

**Robustness** is the ability of a public transport system of being able to withstand variations, disruptions or changes in operational conditions. Additional buffer (or slack) time to absorb delays contributes to more robust schedules, however, excessive buffer time leads to lower operational speeds and higher operational costs. Redundant infrastructure also contributes to increasing the robustness of a system, providing ways to reorient vehicles if disruptions occur.

**Stability** refers to the ability of a public transport system to compensate for delays and return to its desired operational state. A stable timetable will include some buffer time to compensate for small disruptions and delays. A timetable can be stable without being very robust. This is the case when the distribution of the buffer time throughout the schedule is not optimal and is concentrated in the layover times. Initial delays are propagated before they are absorbed at the end of the run.

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[2] A structure for classifying public transport service quality can be found in page 60 of Kittelson, Urbitran, et. al. (2003).

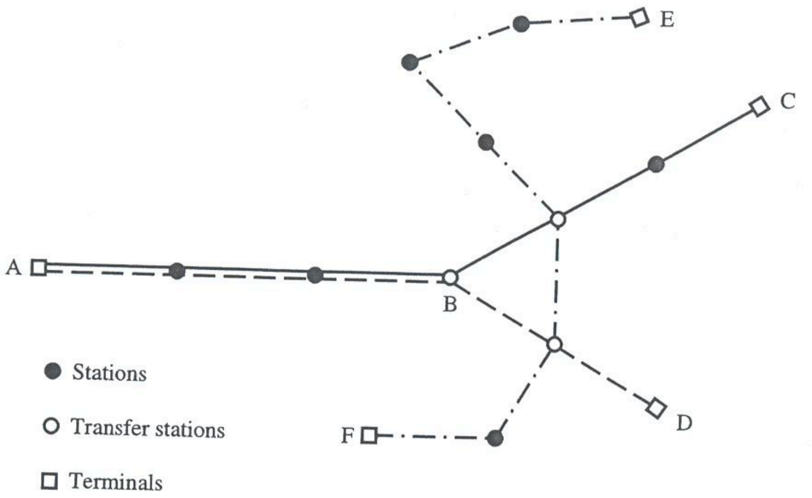
## 2.3 Basic operating elements

### 2.3.1 Line, Route, Network

Most public transport services are provided by vehicles (buses, trams, trains, etc.) that travel along predetermined lines, following given schedules. Therefore, the basic component of a public transport system is a *Line*. The elements of a public transport Line are described below:

Referring to Vuchic (2005), a public transport *Line* is "the infrastructure and service provided on a fixed alignment by vehicles or trains operating on a predetermined schedule". The infrastructure elements can vary from very simple designations of a stop along a street, to a grade separated, fully segregated and controlled right-of-way (ROW) with designed stations providing a number of services and amenities to passengers. A public transport *Route* is often used as a synonym for Line, and usually refers to road-bound public transport, with often-overlapping lines. A public transport *Network* is a set of Lines connecting with or crossing each other and (ideally) coordinated to achieve efficient operation and provision of integrated services in a given area. The idea is to improve the convenience of passengers and the efficiency in operations. Figure 2 illustrates these concepts.

Figure 2 Public transport line, network and station concepts



Source: Vuchic (2005)

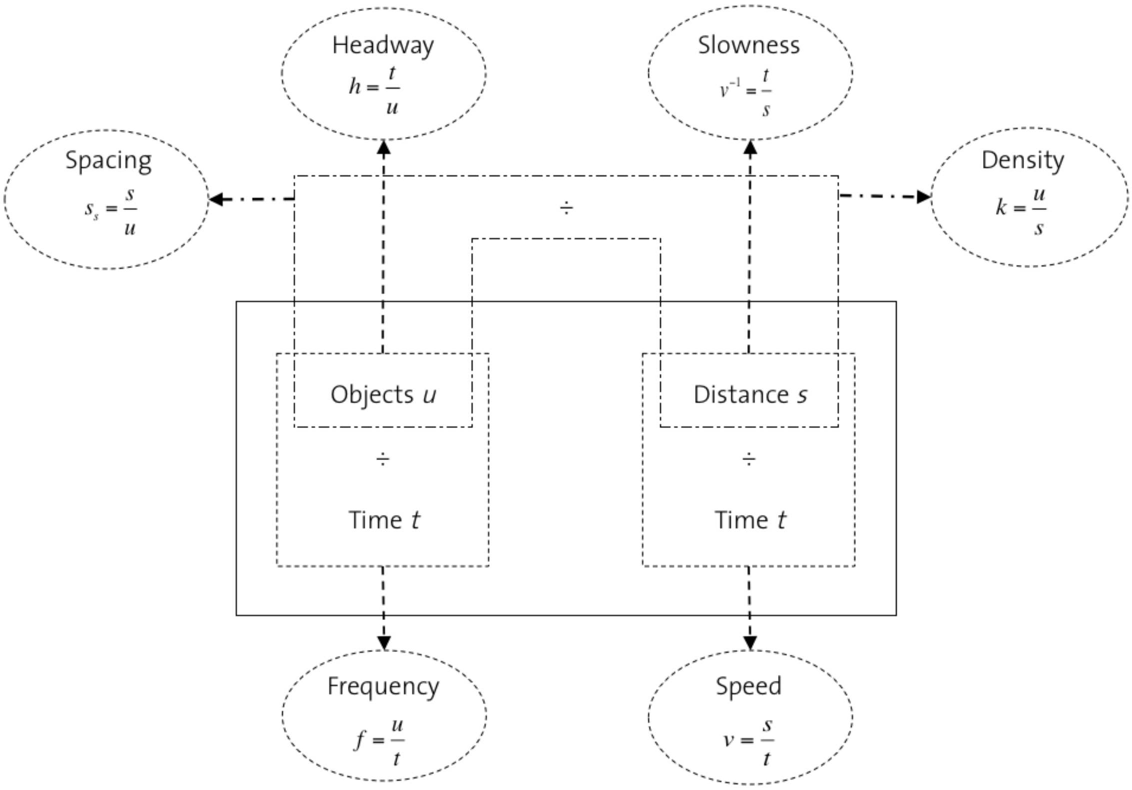
In the previous figure, if the distance between stations corresponds to 1 km, the values of the network are: Line lengths: (AC, AD and EF), 6, 5 and 7 km correspondingly. Network length: AC+BD+EF= 15 km. Total Line length: AC+AD+EF=18 km.

A public transport *Stop* is a location along a Line where public transport vehicles halt and passengers can board or alight. It can be equipped with signs, static and dynamic information, a place to sit and shelter from the weather. A _Station_ is a more developed structure with facilities for passenger boarding / alighting, waiting and transfer. In this work the terms *stop* and *station* will be used interchangeably. Different types of stops and stations are depicted in Figure 2.

### 2.3.2 Headway and frequency

Vuchic (2005) defines the basic process of transportation as "the movement of objects *u* over a distance *s* during an interval of time *t*". As described in Vuchic (1981), different relations between these three elements constitute the majority of operating elements of transportation systems. The figure below shows some of these relations.

Figure 3 Basic operating elements of public transport systems



Source: adapted from Vuchic (2005)

In public transport operations, the most common elements are headway (*h*), frequency (*f*), time (*t*) and speed (*v*). _Headway_ is the interval of time between two consecutive public transport vehicles passing the same fixed point on a Line (on the same direction). Headway is normally expressed in minutes. Users are interested in short headways to minimize their waiting time at stops, but because more vehicles with less capacity result in higher operating costs (specially in places where the cost of labour is high), headways are normally set as an agreement between user travel time and convenience, and the operational cost. As Vuchic emphasises, uniform headways are desirable as they provide the most stable operation and are most attractive for passengers as they are simple, reliable and minimize waiting times. It is also desirable to use clock headways (the same departure minute every hour at a stop) as passengers can therefore memorize the timetable with ease.

While headway is defined as the time between consecutive vehicles (*t/u*), *frequency* describes the inverse relation, or the number of public transport vehicles passing a point on a Line in one direction for a period of one hour (*u/t)*. The terms headway and frequency are often confused, not only by the users, but also by operators. To provide a clarifying example, for a 10-minute headway, the frequency would be six vehicle departures per hour.

### 2.3.3 Schedules

In the context of public transport, a timetable or schedule is a listing of the times at which public transport services arrive or depart from a specific stop or station. It is normally available to the public in the form of a leaflet, poster, dynamic display, or electronically. In Switzerland all public transport services run according to a schedule, regardless of their frequency. However, this is not the case in other countries, where operators might simply state that a service runs e.g. "every 3-5 minutes". This situation is common in high frequency services like metro systems and some urban bus services.

Timetable design is a component of public transport planning. Consistent with section 2.2.2, timetables are set using the input provided by the network and route design, and serve as an input to schedule vehicles to a set of trips (or blocks) and schedule crews (or rosters). A more detailed description of the operational planning process and timetable design can be found in chapter 4.3.

### 2.3.4 Rights-of-way (ROW)

Right of way basically refers to a strip of land that is provided for transportation purposes. In our context, corresponds to the area on which a public transport line operates. Among the different characteristics of ROW, the most important for public transport operations and performance is level of segregation that public transport vehicles have from other vehicles, road users and pedestrians. According to Vuchic (2007), there are three basic ROW categories distinguished by the degree of their separation from other traffic, however, it is possible for a line to have a segment-wise mix of ROW categories.

**Category C** corresponds to roads with mixed traffic. Public transport may have preferential treatment, such as reserved lanes separated by lines or special signals or travel mixed with other traffic, such as in the photo below.

Picture 1 ROW Category C: public transport in mixed traffic (Zurich, own picture)

**Category B** includes ROW types that are "longitudinally physically separated by curbs, barriers, grade separation and the like from other traffic, but with grade crossings for vehicles and pedestrians" Vuchic (2007). This category is frequently used for Trams and sometimes buses such as the one depicted below, in Zurich.

Picture 2 ROW Category B: partial separation (Zurich, own picture)

**Category A** involves a fully controlled ROW without grade crossings or any legal access by other vehicles or persons Vuchic (2005). See picture below

Picture 3 ROW Category A: fully separated way (Glattalbahn viaduct, Zurich)

Source: originally uploaded to Flickr by KARLCH

Some features of modes with different ROW categories can be seen below.

Table 1 Characteristics of modes with different ROW categories

| | ROW Category | | |
|---|---|---|---|
| **Features** | **C** | **B** | **A** |
| System performance: capacity, speed, reliability, safety | Moderate | High | Very high |
| Investment Cost | Low | High | Very high |
| Level of Service (LOS) | Moderate | High | Very high |
| Image / identification | Moderate | Good | Very strong |
| Passenger attraction | Moderate | High | Very high |
| Potential impact on urban form | Weak | Strong | Very strong |
| Full automation possibility | None | None | Full |

Source: Vuchic (2007)

## 2.4 Operational processes in urban bus lines

Until now, the basic operating elements in public transport have been studied. These elements interact with each other under an operational framework to provide the actual service to the users. This framework is based on a series of operational processes. The analysis of the different operational processes of an urban bus line involves describing the sequences of events taking place and their temporal dependencies. Different process hierarchies are developed in the following sections, based on a schematic process. These help describe the sequences of events occurring within the operation of an urban bus line.

In the initial part, the general processes or urban bus lines are first approached and described in broad terms. Two general activities have been proposed: STOP and DRIVE. For each higher-lever activity, a first hierarchy of processes (Level 1) is complemented by a more detailed process description (Level 2). Subsequently, the factors influencing the different sub-processes are defined.

A distinction can be made between factors influencing the *frequency* of occurrence for individual sub-processes in an urban bus line, and factors determining the *duration* of the sub-processes (distribution of process times). Especially critical are factors that affect both the frequency of occurrence and the duration of a process.

### 2.4.1 Process delivery of urban public transport bus services

Conventionally operated urban bus lines run between two established terminal (end) stops along fixed lines according to planned schedules. The number of stops between terminal stops (i.e. where passengers can board and alight the vehicle) depends on the length of the line, the urban density and the type of service provided, among others. Between stops, vehicles drive along sections of road that can be either shared with conventional car traffic, other public transport vehicles, or be segregated and for exclusive use for the buses (e.g. Bus Rapid Transit lines, or BRT).

Sections between stops can vary significantly in terms of length and other characteristics, such as street geometry, and degree of separation from other traffic and pedestrians (ROW). In urban areas the distance between stops is considerably shorter than in rural areas. In the city of Zurich, the average distance between stops is 378 m, according to Cantaluppi (2010).

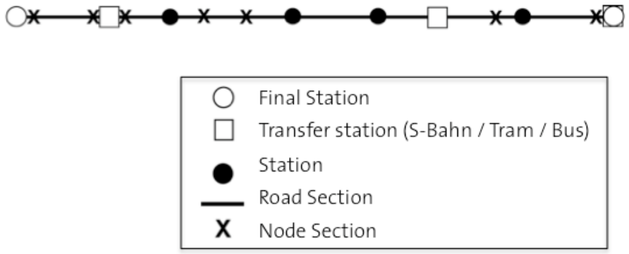
Stops that need to be considered differently are transfer stations. These can be located at a terminal stop, as well as in other points along the line. Transfer stations guarantee the connection of passenger to other modes/vehicles, such as S-Bahns, trams or other buses. In Zurich, schedules are designed to optimize the connections between lines at different points throughout the network, for each individual bus- and tramline. Bus lines serving several transfer stations tend to be critical, as they must (normally) guarantee a number of scheduled connections.

Additionally, high numbers of passengers normally converge in such stations (large number of passengers boarding / alighting), heavily influencing dwell times.

A section between two stops can be classified in one of the following two categories: road section or node section. Actual road crossings, as well as the road space destined for vehicles to wait before crossing the intersections, belong to the node section. The number of node sections between two stops varies depending on the location. Due to the large influence that node sections have on the stability of a bus line, they are considered separately from conventional road sections along the line.

Nodes (road intersections) can be regulated using traffic light signals, which can be equipped with bus priority systems. Other types of nodes are not directly controlled. The influence of a node (without bus preference measures) on the travel time of a bus can be very large, depending on the precedence rules and the allowed turning movements. A schematic representation of the elements of a public transport line is depicted below.

Figure 4 Schematic representation of the main elements in an urban bus line



Source: adapted from Weidmann, Buchmüller et al. (2008)

### 2.4.2 Sub- process description – Level 1

Based on the previously depicted process chain, the individual parameters for the different elements of the process are defined in the following Table.

Table 2 Process analysis of a fixed-route bus line

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Higher-level activity (Level 0)* | **Stop** | | | | | **Drive** | | | |
| *Location along line* | Dispatch stop | Transfer stop with planned connection | Transfer stop without planned connection | Other stop | Final stop | Before stop | After stop | Free road section | Node-section |
| *Common-activity process (Level 1)* | Stop process for all stations | | | | | Stop approach process | Stop departure process | Drive process | |
| | + | + | + | | + | | | | + |
| *Location-specific processes (Level 1)* | New course designation | Connection protection | Spontaneous connection | | Turning process | | | | Waiting process for node access |

Source: adapted fromWeidmann, Buchmüller et al. (2008)

The Table above shows the results for the process analysis of the first level, or Level 1. The different elements of the process chain (types of stops, the approach and departure manoeuvres from the stops, the free road section drive and node section drive) are described in terms of their processes.

At every station a common stop process takes place. In transfer stations with protected connections, additional waiting times will occasionally occur while waiting for a delayed connection. At transfer stations without scheduled connections, especially those serving many lines (e.g. Bucheggplatz in Zurich) spontaneous connections may take place, which results in unplanned waiting times. In an optimal case, the connection time overlaps with the stop process duration. In extreme cases, this event can extend the dwell time in several minutes.

Turning movements take place at end stations. These vary from very easy to complicated, depending on the station design. At the end station, or terminal, the vehicle is prepared to begin the following course, although the vehicle normally does this automatically.

Between stations, the driving process takes place along road sections. It is dependent on the physical limitations of the vehicle and its interaction with the other drivers and actors in the road (e.g. pedestrians, cyclists). In a worst-case scenario (very high volumes of traffic), the traffic flow can be dramatically reduced or temporarily come to a complete halt.

The level of priority and segregation of public transport vehicles has a large impact on the driving process along node sections. Similar to the free road sections, high traffic volumes can cause longer waiting times.

### 2.4.3 Sub-process definition – Level 2

A more detailed look at the processes described in Level 1 results in the definition of its composing sub-processes (Level 2). From the refined description it is possible to deduce the relations taking place between processes. The sub-processes in Level 2 are listed in Table 3 and described in the following section.

Table 3 Sub-process definition of an urban bus line

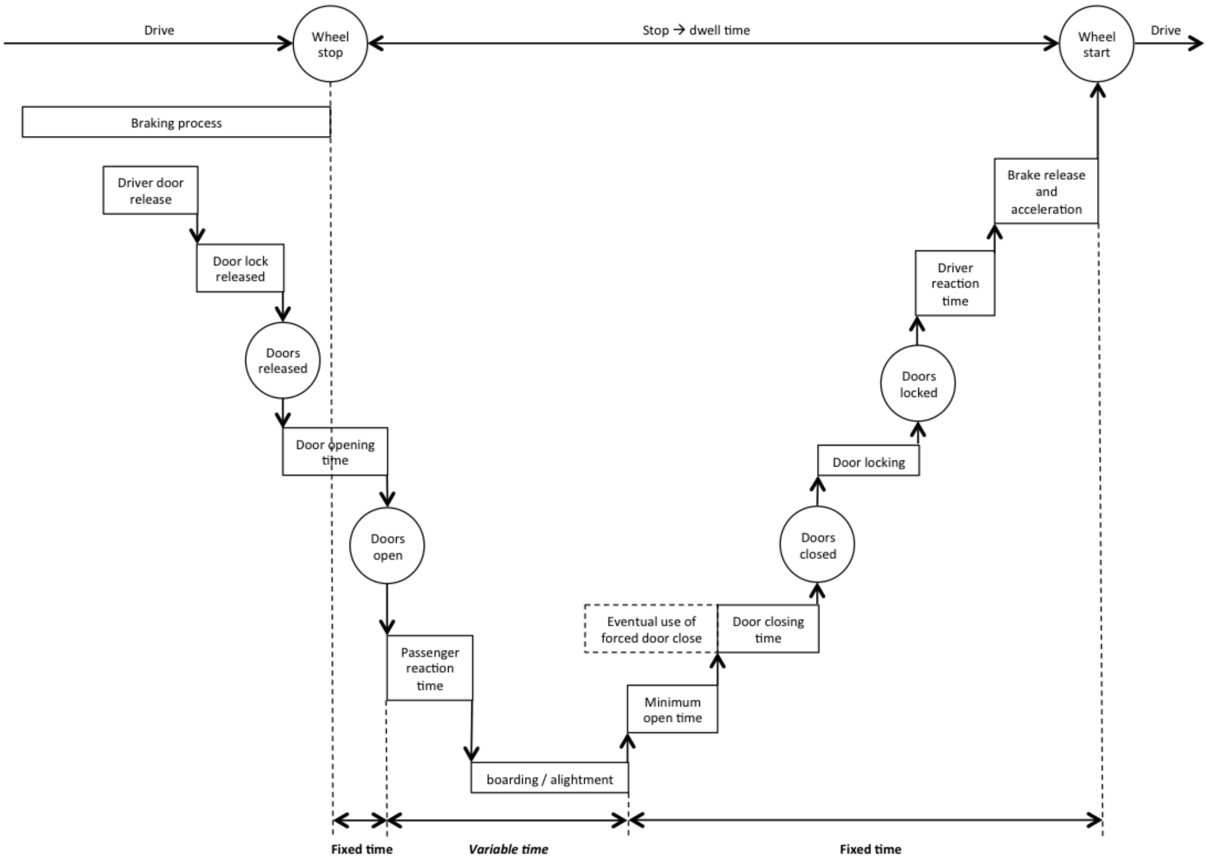
| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Higher-level Activity (Level 0)* | **STOP** | | | | | **DRIVE** | | | |
| Location along line | **Dispatch Stop** | **Transfer stop (with planned connection)** | **Transfer stop (without planned connection)** | **Other Stop** | **Final Stop (terminal)** | **Before stop** | **After stop** | **Free road section** | **Node section** |
| *Common process (Level 1)* | **Stop process for all stations** | | | | | **Stop approach process** | **Stop departure process** | **Drive process** | |
| *Sub-processes (Level 2)* | - Door control process<br>- "Kneeling" of the vehicle<br>- Passenger boarding and alighting<br>- Boarding and alighting of handicapped passengers<br>- Passenger information<br>- Waiting until scheduled departure time (when required) | | | | | - Check stop request<br>- Stopping manoeuvre, or<br>- Drive through | - Wait for „Running" passengers<br>- Communication with traffic lights<br>- Departure from station | - Driving process<br>- Impeded driving along street (Road works, temporary traffic light)<br>- Impeded driving due to traffic (congestion, queuing traffic)<br>- Impeded driving due to slow traffic (Pedestrian crossings, bicycles)<br>- Passenger information<br>- Communication with control centre | |
| *Location-specific processes (Level 1)* | **New course designation** | **Connection protection** | **Spontaneous connection** | | **Turning process** | | | | **Waiting process in node section** |
| *Location-specific Sub-processes (Level 2)* | - Technical preparation for new course (automatic) | - Waiting for connections<br>- Communication with control centre | - Waiting and transporting of passengers from spontaneous connection | | - Turning manoeuvre<br>- Driver pause<br>- Communication with control centre<br>- Vehicle check<br>- Vehicle cleaning | | | | - Waiting time (e.g. for a traffic light)<br>- Communication with control centre |

Source: Weidmann, Buchmüller et al. (2008)

### *Stop process for all stations*

This process is basically composed of a fixed part and a variable part. The fixed part corresponds to the time required to release the vehicle's doors when stopping, and secure them before departing. The variable part is the time required for the boarding and alighting of passengers. The figure below illustrates this process.

Figure 5 Schematic representation of the dwell process of an urban bus line



Source: adapted from Weidmann, Buchmüller et al. (2008)

The variable part of the process is determined by three factors. First, the number of passengers alighting and boarding the bus; second, the distribution of the doors in the vehicle (number and location of the doors, passenger distribution in the vehicle and at the stop); and third, the accessibility conditions at the stop (vehicle door width, differences in boarding levels, people density at the stop, etc.)

People with reduced mobility need to be taken into account. This includes persons in wheelchair, but also the elderly, and passengers with baby buggies, bulky luggage, etc. The share of such passengers is relatively low, but the additional time required can extend the total stopping time significantly (kneeling of the vehicle, obstruction to other passengers due to the additional space required at the door, etc.). These events may lead to dwell times much larger than the average.

The process described in Figure 5 also applies at transfer stops and/or terminal stops. Additional for these stops might be the time required by the driver to prepare for the following course, the scheduled and spontaneous connections, and the turning manoeuvre.

### *Transfer protection*

Scheduled connections between bus lines, or with an S-Bahn line, take place at transfer stations. These connections are guaranteed mostly for rural lines; however they must be taken into consideration for urban bus lines as well. During peak hours they are not as relevant, but in the evening or during the weekend, when frequencies are lower, they gain relevance for the users. The time destined to wait for a connection is determined by the delay distribution of the connecting line, as well as by the existing guidelines regarding the maximum waiting time allowed for a connecting line. The first criterion cannot be influenced because it is external to the line in consideration. In contrast, the maximum waiting time for a transfer between lines (or if required for individual courses) can be defined in consideration of the guidelines and the current operating situation.

### *Spontaneous connections*

Often, few or no connections are scheduled within the timetable at transfer stations serving several lines with high frequencies (e.g. Bucheggplatz in Zurich). However, in daily operations it happens that vehicles shortly wait for passengers arriving from other lines, so they can benefit from the spontaneous connection.

### *Turning manoeuvre*

For the turning manoeuvre (which may take place either before or after the stopping process, depending on station design) there is a distinction between the actual process of turning the vehicle, and some additional operational procedures (minimum break time for the driver, short vehicle inspection, minor cleaning activities, etc.). Moreover, a compensation (or buffer) time is required, which is derived from the time required to turn around, and from the route headway. The actual turning process is inevitable unless the line involves a loop (e.g. around the block); all other processes can be shortened or delayed, depending on the operational conditions. However, the turning process is highly dependent on the type of vehicle (length, articulation, and single or bidirectional in the case of trams), and the particular topology of the turning site.

### Station approach process

This process depends to a large extent on the stop layout. In the simplest case, the vehicle stops on the right side of the street (curbside), or in a bus bay along the road. For larger stations (especially at transfer stations) the bus normally deviates from the street traffic and drives into the station area and the assigned stopping location.

For stops that require a stopping wish by the passengers (stop on demand), this event is reviewed as the vehicle approaches the stop. Those passengers wishing to exit the vehicle at a stop report this wish to the driver by pressing the exit button inside the bus. Passengers wishing to enter the vehicle at a stop inform the bus driver with their presence at the stop (or in some cities, with a hand signal). When no stop is requested for the next stop, and no persons are waiting for the bus, the bus can drive through.

### Station departure process

The station departure procedure involves the process between the actual driving away from the stop until the complete integration of the vehicle with the flowing traffic. After driving away from the stop, the driver focuses on the moving traffic and waits for a slot among the coming vehicles (in most cases). When the bus driver finds the slot, or another driver yields, the bus can merge into the driving lane and proceed to the next stop.

At stations with coordinated traffic lights and bus preferential measures, the bus announces the willingness to drive away and after a determined time receives the clearance to drive away.

In some cases, it is also possible that the bus driver stops the vehicle after a few meters to wait and allow entrance of passengers hurrying to get the bus.

### Driving along road section

The driving process along the line is a result of the physical characteristics of the vehicle bound to street layout, maximum speed allowed, planned service schedule and the current traffic situation. Obstructions caused by road works, congestion, pedestrian crosses, etc., need to be taken into account.

### Waiting process in node section

The management of the traffic flow at the node itself influences the waiting process along node sections. Depending on the priority scheme of the node, the existing turning movements, and the presence of a traffic signal with or without bus priority, the driving process can be optimized in the node area and the variability of the travel time reduced.

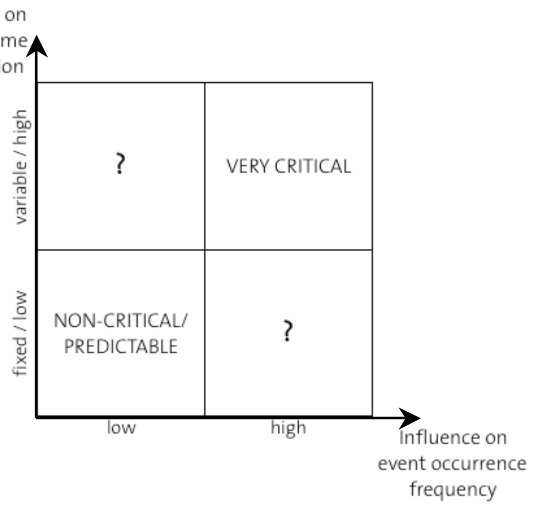
### 2.4.4 Recurrence and duration of processes

The timetable stability of a bus service is a result of the interactions and events that occur during the described processes and sub-processes of an urban bus line. At the same time, the following characteristics of the individual processes play an important role:

- Individual processes within a bus line take place with varied frequency, depending on the time and day of the week. For example, some stops along a line will only be served when passengers express their wish to exit the vehicle, or when people are waiting for the bus at the stop. In the case no passenger wishes to enter/exit the vehicle, and the scheduled departure time has been reached, the bus can drive through. On the other hand, other processes take place constantly. The length of a given line does not change during the valid period of a published schedule. Therefore, the ***frequency*** of individual processes influences the entire (higher-level) process duration.
- The ***duration*** of individual processes varies considerably in most cases. So, for example, the time required for passengers to board/alight the vehicle depends (among others) on the number of passengers wishing to enter and exit the bus. If among these passengers there are passengers with reduced mobility, the duration of this process is normally longer.

A graphic relationship between duration (delay) and frequency of occurrence of events, and their influence on the operational stability of bus lines is depicted below. Question marks indicate uncertainty regarding the impact of an event under the given conditions.

Figure 6 Process duration and frequency, and their influence on operational stability



Source: adapted from Weidmann, Buchmüller et al. (2008)

Table 4 describes the parameters influencing the frequency and duration of the stopping processes. Table 5 includes the parameters that influence the frequency and duration of a process by type of station and the location-specific activities taking place at these stations.

Table 4 Parameters influencing the stopping process

| | **Parameters influencing STOP process** | |
|---|---|---|
| | **Frequency** | **Duration** |
| Passenger exchange (see Figure 5) | - Number of stops with passengers boarding/alighting the vehicle | - Number of passengers<br>- Vehicle access layout<br>- Design of the bus stop<br>- Passenger distribution at the doors<br>- Vehicle's occupancy rate<br>- Share of passengers with reduced mobility<br>- Use of Kneeling feature |
| Fixed share of stop time (see Figure 5) | - Number of stops with passengers boarding/alighting the vehicle | - Door opening/closing process<br>- Minimum door opening time<br>- Reaction times of driver/passengers<br>- Time reserve in schedule |
| | - Breakdown susceptibility of the vehicle | - Kind of vehicle breakdown |

Source: adapted from Weidmann, Buchmüller et al. (2008)

Table 5 Parameters influencing frequency and process duration by station type

| **Location specific process** | **Parameters influencing process frequency and/or duration** | |
|---|---|---|
| | **Frequency** | **Duration** |
| New course designation | - Line length | - Course entering in on-board system |
| Connection protection | - Number of protected connections<br>- Number of scheduled transfers<br>- Delay frequency of connecting lines | - Delay distribution of connecting courses |
| | - Scheduled transfer time<br>- Maximum waiting time for connections | |
| Spontaneous connection | - Number of transfer stops with non-scheduled connection courses<br>- Frequency of connecting lines | - Number and temporal distribution of transfer passengers from connecting lines |
| | - Behaviour of driver<br>- Guidelines regarding waiting of spontaneous connections | |
| Turning process | - Line length | - Turning manoeuvre<br>- Minimum rest time<br>- Reserve in schedule |

Source: adapted from Weidmann, Buchmüller et al. (2008)

The table below describes the parameters that influence frequency and duration in the driving process.

Table 6 Parameters influencing the frequency and duration of the driving process

| | **Parameters influencing DRIVE process** | |
|---|---|---|
| | **Frequency** | **Duration** |
| Stop approach process | - Number of stops (Predetermined stop plus request stops with stop request) | - Type of stop<br>- Stop access length<br>- Interference by other buses, private vehicles or passengers |
| Stop departure process | - Number of stops (Predetermined stop plus request stops with stop request) | - Type of stop<br>- Waiting for running passengers<br>- Traffic flow<br>- Precedence rules<br>- Traffic light communication |
| Drive process | - Length of the road section | - Layout of the road section<br>- Allowed speed<br>- Street condition<br>- Weather conditions<br>- Vehicle type and condition<br>- Driver's behaviour<br>- Current timetable deviation<br>- Traffic flow<br>- Obstructions along the street (Road works etc.)<br>- Existing bus lanes<br>- Need to communicate with control centre |
| Waiting process in node section | - Number of nodes/intersections | - Node/intersection type<br>- Node regulation (Regelung)<br>- Node control (Steuerung)<br>- Existing turning conditions<br>- Traffic flow<br>- Type of bus priority measure |

Source: adapted from Weidmann, Buchmüller et al. (2008)

### *Critical factors influencing operational stability*

Some factors are critical for the operational stability of a bus line, because they influence both the frequency of occurrence and the distribution (duration) of process times. Based on the influencing factors previously mentioned, the following critical elements are considered:

- Number of passengers and share of them with mobility restrictions in lines with high stop density and short headways.
- Number of connecting lines susceptible to delays.
- Short turning times in long lines.
- Number of road intersections along the line frequently reaching their capacity due to high vehicle traffic.
- Share of the line running along frequently congested road sections with no preference treatment for public transport vehicles.

### 2.4.5 Measurement parameters for process quantification

The quantification of the main factors influencing schedule stability can be done using operational measurements collected automatically by the vehicle and the control centre, or by other measurements (mostly manual observations). The measures to be determined correspond to:

- Frequency of process incidence (Level 1 and 2)
- Statistical distribution of the process times for the relevant process parameters in Levels 1 and 2 (mean, median, standard deviation, statistical distribution). See chapter 3.4.2 for a discussion on reliability metrics in public transport.

The following Table includes the relevant metrics for quantifying the main factors influencing operational stability. They were proposed by Weidmann, Buchmüller et al. (2008).

Table 7 Metrics and quantification of process elements

| *Higher-level Activity (Level 0)* | **STOP** | | | | | **DRIVE** | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Location along line* | **Dispatch Stop** | **Transfer stop (with planned connection)** | **Transfer stop (without planned connection)** | **Other Stop** | **Final Stop (terminal)** | **Before Stop** | **After Stop** | **Free road section** | **Node section** |
| *Common process (Level 1)* | **Stop process for all stations – Quantification metrics** | | | | | **Stop approach process** | **Stop departure process** | **Drive process** | |
| *Sub-process Metrics (Level 2)* | - Arrival time (actual and planned)<br>- Vehicle process times (Door control, etc.)<br>- Number of „kneeling" procedures<br>- Number of passengers boarding<br>- Share of boarding passengers with mobility limitations<br>- Number of passengers alighting<br>- Share of alighting passengers with mobility limitations<br>- Frequency of information requests by passengers<br>- Departure time (actual and planned)<br>- Number of different types of vehicle breakdowns | | | | | - Access drive process (Time-point-data)<br>- Number of Drive-through events | - Drive away process (Time-point-data)<br>- Number of "runners" taken<br>- Time process of traffic light | - Drive process (Time-point-data) | |
| *Location-specific processes (Level 1)* | **New course designation** | **Connection protection** | **Spontaneous connection** | | **Turning process** | | | | **Waiting process in node section** |
| *Location specific Sub-process Metrics (Level 2)* | - Vehicle process times | - Arrival time of connecting course (actual). Distribution | - Arrival time of other courses (actual). Distribution | | - Time required for turning manoeuvre | | | | - Waiting time at node access |

Source: Weidmann, Buchmüller et al. (2008)

## 2.5 Summary

This chapter reviewed the basic principles of urban public transport systems, focusing on the elements and operational processes involved in the provision of service. Focusing on road-bound modes, a functional structure for planning and operations was formulated, which is consistent with following chapters of this work. Subsequently, definitions relevant to this work followed, mostly involving terminology on service quality and reliability.

The basic operating elements of public transport were identified to be the network and its components, the headway and frequency of service, the schedules, and the level of segregation of public transport from other modes.

In the final part of the chapter, the operational processes involved in service delivery were described for a generic bus line in the form of a schematic process. Different levels were identified and described. The recurrence and duration of a process were identified as elements that have a large impact on the potential for increasing delay in a line. The chapter closed with a few metrics that quantify each of the previously described process elements.

# 3 Performance and reliability

## 3.1 Chapter overview

A large body of literature exists on the topic of public transport performance evaluation. For the purpose of this work, the topics discussed will be those related to the operational stability of urban bus lines and the reliability of the service provided to the passengers, i.e., the operational and service reliability. Subsequently, the different elements and factors influencing reliability are classified and categorized. Then, a selection of metrics derived from the literature for describing reliability measures is presented.

The phenomenon of bus bunching, or package building among public transport vehicles (a common consequence of unreliable service) is explained and discussed to a certain detail in the following section. Those parameters influencing operational stability are shortly discussed.

In the final part of this chapter, the reader will find a short summary of technologies currently used to capture data automatically. These include vehicle location, passenger counting and fare collection systems. A short discussion on their uses, benefits and challenges closes the section.

## 3.2 Definition and relevance of performance

Performance of a public transport system refers to how well the system achieves its intended goals and objectives. Measuring performance is very important because it provides information on how well the service is being provided, and when it is not, it helps in diagnosing problems and finding solutions.

In the past, estimating performance measures in public transport was difficult and expensive due to the lack of comprehensive performance data. However, these limitations have slowly been overcome by advances in technology, which allow the use of automatically collected data, and thus provide large amounts of high quality data for this purpose.

The focus of public transport performance measures has traditionally been on attributes of service supply such as capacity, speed, passenger loads, frequency, regularity and reliability. However, a number of studies have also looked at performance measures from the demand side. For example Kopp, Moriarty et al. (2006) focused on the measuring the attractiveness of travel by public transport; Ceder, Le Net et al. (2009) worked on connectivity measures; and the unpublished work by Nökel and Bundschuh (2006) developed reliability indicators for transfers from the passenger's perspective. Work by Kittelson, Urbitran et al. (2003) defines eight performance measure categories for public transport:

- Availability: when and where service is provided
- Service delivery: including reliability, customer service, passenger loading
- Safety and security: likelihood of an accident (safety), or victim of crime (security)
- Maintenance and construction: effectiveness of maintenance programs
- Economic: performance from a business perspective
- Community: impact of public transport on individuals and the community
- Capacity: ability of facilities to move vehicles and people
- Travel time: of trip from *a* to *b* with public transport and compared with other modes

This work focuses on the performance metrics of service delivery from the supply side, specifically on reliability and travel time metrics. Demand side issues such as passenger waiting times are discussed to a lesser extent. Consequently, the scope of this work excludes other forms of performance measures.

### 3.2.1 The multiple dimensions of reliability

Reliability is a term that can be defined differently, depending on the context or discipline in which it is being treated. It is used in engineering, statistics, data management, measurement, and information technology, among many others. Synonyms of the word "reliability" are: dependability, accuracy, constancy, fidelity and security.

Public transport users experience reliability mostly through punctuality, with the associated additional waiting time at the stop; and trough travel times, as reliability provides and idea on their consistency and variability, though it does not explain why they vary. From another perspective, a public transport operator will focus on a number of system features to characterize reliability, such as schedule adherence, headway regularity, and percentage of trips completed on time, among others.

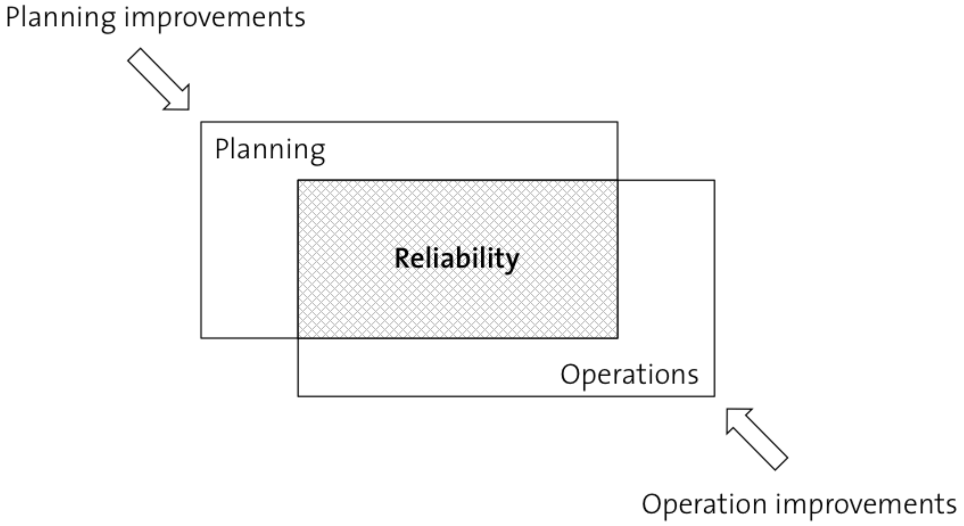
A strict definition of reliability is defined by Vuchic (2005) as: "one minus the probability of failure". However, in public transport systems failure is complex and hard to define. It can relate to different elements (infrastructure, vehicles, communications, technology, processes, etc.) and be of different types. Reliability is usually measured by its consequences: number of persons affected, lost time, time between breakdowns, recovery time, etc. Another characteristic of reliability is that it takes place over a period of time, not at a point in time (e.g. a day, a month, a year, a season). As previously mentioned, this work deals mostly with travel time, service reliability and passenger waiting time, with the associated performance metrics.

*Travel time reliability* can be defined as the consistency or dependability in travel times, measured from day to day for the same trip. Travellers on well-known routes learn to adapt to the possible unexpected events and adjust their travel time budget[3] accordingly. Their travel time will vary from day-to-day for the same trip for unreliable services regardless of the mode.

Public transport *service reliability* can be understood in different ways, as summarized by El-Geneidy, Horning et al. (2008). It can be understood as the “variability in performance measured over time”, Turnquist and Blume (1980); as the “variability of service attributes and its effects on traveller behaviour and on transport agency performance”, Abkowitz (1978); or mostly as “schedule adherence and keeping schedule related delays (on-time performance, run time variation, headway delay and headway delay variation) to a minimum”, Levinson (1991) and Turnquist (1981). Reliability issues of public transport services are often attributed to the dynamic nature of the operating environment Abkowitz and Engelstein (1983). According to Levinson (1991), to provide a reliable service means “keeping buses on schedule, maintaining uniform headways and minimizing the variance of maximum passenger loads”.

In the framework of this work, a conceptual model for defining reliability will be used, based on van Oort and van Nes (2008). In it, reliability is qualitatively defined as the overlap of planned and delivered services. In other words, more reliable services are those that are delivered to a larger extent according to the service planned by a public transport agency. See Figure 7 below.

Figure 7 Conceptual model for service reliability improvement in public transport



Source: van Oort and van Nes (2008)

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[3] The travel time budget of a person is defined as the expected travel time, plus the additional (buffer) time a person would add, in order to absorb the variability in travel time.

Performance metrics are calculated in section 5.3 using operational data from a bus line in Zurich. These metrics are then used to quantify the level of reliability of bus operations, in a way consistent with the multiple definitions of travel time and service reliability defined earlier in this section.

### 3.2.2 Operational stability and reliability

In general, operational stability refers to capable and reliable processes and equipment. In the public transport industry, this translates into high levels of reliability for both scheduled and frequency based services (but also vehicles, supporting systems, and processes). In places where scheduled services are predominant, such as Switzerland, schedule adherence is normally the indicator used by transport agencies to measure operational stability. However, the use of this metric implies that schedules are already ideal (realistic and achievable); therefore it can be misleading where sub-optimal schedules are in use.

In places where very frequent services are predominant –normally those with headways equal to or below 10 minutes, according to Kimpel, Strathman et al. (2000)– the focus tends to change towards regularity. The main reason is the assumption that users of frequent services ignore the timetable and arrive randomly at the station, though a number of studies exist where this restriction is relaxed. See for example Bowman and Turnquist (1981), or Luethi, Weidmann et al. (2006) where it was found that some passengers in Zurich consult the timetables and do not arrive randomly, even with a 5 minute frequency. An even spacing between vehicles then becomes the main priority, in order to distribute passengers evenly on the vehicles and avoid overloading that may lead to the accumulation of delays which in turn results in package building, or “bus bunching” (see section 3.5).

### 3.2.3 Importance of reliability in public transport

The characteristics of a public transport system (frequency, travel time, etc.) and the level of reliability of public transport services influence the mode choice of travellers. The value placed on reliability by these, relative to other service attributes, will determine the level to which their travel choices are influenced. Attitudinal surveys have shown reliability to be among the most important public transport service attributes for all travellers under certain conditions, e.g. the works by Abkowitz (1978), Turnquist (1981), and Vuchic et al (1994). In the first study, reliability was considered more important than average travel time and costs for both work and non-work trips. Moreover, unreliable services lead to higher operating costs, as well as decreased ridership by unsatisfied users.

### *Importance for passengers*

Improvements in reliability have the potential to enhance the mobility of public transport users and induce car users to switch mode. Therefore, by reducing waiting time variability, total travel time variability and mean passenger waiting time (all sources of trip disutility, or unattractiveness) the attractiveness of public transport increases. Moreover, reliability influences departure time decision for the trips travellers intend to take. Often, these decisions are made with the objective of reaching a destination at a specific time. This is particularly relevant for work trips, where lateness is generally considered to have very high disutility values. When deciding on departure time, a traveller will seek to minimize his or her travel time related disutility. A trade off takes place between mean travel time components and travel time variability components. Because total travel time (and its variability) must be considered by each traveller when deciding when to depart (by any mode), total travel time variability will directly influence the time of arrival at the destination.

Variability in travel times thus means that extra time must be planned for, as travellers have to leave earlier, adding a buffer to their planned travel time (travel time budget) to account for possible delays, or, in other words, absorb the unreliability of their travel time. The additional time a traveller must add to his or her travel time can be considered as a cost for the person traveling. This extra time is at least as costly as regular travel time, and according to Bowman and Turnquist (1981) is more sensitive to schedule reliability than service frequency.

### *Importance for operators*

The discussion above shows how reliability influences travel behaviour. However, reliability is not only an issue for the traveller, it is also of utmost importance for public transport operators, who must devote part of their resources to deal with the consequences of unreliability. The lack of reliable services can have a significant impact on an operator's costs and may also affect system ridership and consequently revenue. An increase in reliability allows the operator to optimize the use of resources. By reducing the amount of recovery time built into schedules, operators can increase the availability of drivers and vehicles. Reduction in vehicle breakdowns and better schedule adherence allows the operator to reduce the number of spare vehicles and drivers kept on stand-by. Improving headway regularity will reduce the probability of bus bunching, lowering the mean passenger waiting times and improving the efficiency in vehicle capacity utilization.

By taking advantage of the increased availability of vehicles and drivers, an operator can translate the improved reliability into other kinds of benefits (either cost savings with the same service, or improvements in service with the same amount of resources). In summary, as pointed out by Kimpel, Strathman et al. (2000), public transport service reliability is "an important measure of service quality and directly affects both passenger demand and level of service".

## 3.3 Description and classification of elements influencing service reliability

The reliability of urban bus services is influenced by a number of factors. Not only unpredictable events[4] (such as major incidents), but also inherent properties[5] of the involved entities (such as the length of the route) and system states[6] (such as a state characterized by a certain passenger volume at the considered stop) affect reliability with different degrees of severity.

Public transport users perceive some of the influencing factors intuitively (e.g. the influence of signalized intersections, or the variability of passenger loads due to holidays or public events). Passengers modify their travel behaviour to anticipate some of the factors (e.g. customers starting their trip earlier during peak hours). Unpredictable factors such as weather conditions can have a significant impact on the system's reliability, but are perceived by most travellers in a different way than, for example, technical perturbations. Furthermore, various factors can mutually influence each other. These interactions intensify or reduce the impact of single factors on reliability. Due to the large number of influencing factors and their interactions, it is considerably complex to isolate single sources of unreliability and to quantify the impact of each single factor on reliability. It is essential to classify and to categorize factors influencing service reliability as this can facilitate the identification and assessment of possible approaches to deal with the factors influencing reliability and (to a certain extent) with their consequences.

### 3.3.1 Literature review on the factors affecting reliability

Several authors have already made an approach to derive and classify the factors influencing reliability of urban bus systems. Immers and Jansen (2005) classified the causes of variations in demand and supply of public transportation. The considered dimensions were:

- Everyday occurrences / exceptional conditions
- Expected / unexpected situations.

Based on these two main categories, the authors proposed a two-dimensional matrix, in which they mainly categorized delay causing events.

Ap. Sorratini, Liu et al. (2008) classified reliability influencing factors by just one dimension in the following groups:

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[4] An event is defined as something that occurs in a certain place during a particular interval of time. Events do not necessarily happen suddenly or are of unpredictable nature.

[5] A property (of the system, subsystem or single entity) is defined as an essential or distinctive attribute or quality of the considered entity or object.

[6] States are defined as the present condition of a system or an entity. They can be influenced by events and express the manifestation of the properties.

- Traffic characteristics
- Route characteristics
- Passenger characteristics
- Bus operational characteristics.

Strathman and Hopper (1993) considered in their study the “factors contributing to poor on-time performance” and their classification. They made a distinction between internal and external factors, discussed the issue of “controllability”, and pointed out the lack of full control on a technical system, referring to the bus system as a “stochastic system”. This is consistent with work by Levinson (1991), in which traffic (or exogenous) factors such as traffic signals, curb parking, variable traffic conditions, unexpected occurrences, weather, and emergencies contrast to public transport system (or endogenous) factors. These endogenous factors are classified in fleet maintenance practices, route structure, stop spacing, passenger arrival rate, ridership variation and trends, scheduling practices, and driver selection, behaviour, training and supervision.

In the work by Cham (2006) a slightly different approach was followed and the most significant causes of service reliability problems were categorized as follows:

- Schedule deviations at terminals
- Passenger loads
- Running times
- Environmental factors
- Operator behaviour

Abkowitz and Engelstein (1983) did not explicitly make a classification of the different influencing factors, but rather estimated empirical models of mean running time and running time deviation of bus routes. The influencing factors of running time deviations that they included in their models were trip distance, people boarding and alighting, and signalized intersections.

Several other studies on public transportation system reliability and its influencing factors exist. Some of the studies conducted in the field of individual transportation reliability (private vehicles) are also of interest for this study, because part of the influencing factors in individual and in public transportation are congruent, such as incidents, weather conditions, etc. (see for example Lomax, Schrank et al. (2003)).

### 3.3.2 Classification and categorization of factors influencing reliability

In all of the previously mentioned studies, up to two dimensions in categorizing and classifying factors that influence reliability (in most studies only one dimension) were considered. In this study, an attempt is made to propose several classification categories. This approach enables a simplified categorization of unreliability sources, and based on the categorization, it facilitates the identification and assessment of approaches that aim at improving reliability. Some of the categories applied in the previously mentioned studies are adopted and partly adjusted for the present study.

The first classification dimension of the influencing factors has already been presented in the introductory part of this chapter: *states, properties and events*. Furthermore, the following categories have been derived in order to classify the influencing elements by different *dimensions*. The defined categories are:

- Expectability
- Regularity
- Composition of travel time
- Involved entity
- Level of potential influence
- Quantification
- Source of variability (only applicable to the events).

In the following, the single dimensions and their subcategories will be introduced and described. The first dimension, *expectability,* relates in particularly to events. It is essential to anticipate events and their impact on public transport service at the planning level, in case they can be expected. Even though there are just two subcategories: expectable and not expectable, the level of expectability may vary between different factors: some events are more expectable than others.

Some events and states take place with certain *regularity*, others only in exceptional cases. A classification of regularity, particularly in combination with the dimension of expectability, may provide hints on how effectively events or certain states can be influenced. Therefore factors are distinguished based on their regular or exceptional occurrences. Furthermore, different factors can influence the various components of *travel time* in a different way. According to van Oort and van Nes (2008) travel time can be divided into:

- Driving time
- Stopping time[7]
- Dwell time
- Turning time.

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[7] The time during which the bus is not driving, but is stopped, e.g. waiting in front of a traffic light.

An additional dimension for classification is the *involved entity*. The defined entities are based on work by Cham (2006) and extended by two additional entities “stop” and “environment”. It must be noted that more than one entity can be involved with a particular factor simultaneously. The defined entities include:

- Traffic
- Route
- Passenger
- Stop
- Bus operation
- Environment

In association with the discussion held in Strathman and Hopper (1993) on the *controllability* of the system, this dimension in included in the categorization of factors. In the present study, the different levels on which the factors can be controlled (and influenced) are the:

- Strategic level
- Tactical level
- Operational level.

The meaning of these levels is discussed in chapter 4.3.

Finally, it is important to identify if a factor can be *quantified* or not. This is essential if quantitative models are to be developed for measuring and predicting the impact of single factors on service reliability.

Furthermore, and particularly in the case of stochastic events which can display a considerable variability, the factors are classified according to their *source of variability*. For the dimension of variability, only events are classified. Following questions are to be considered when defining the source of variability:

- Is an event varying in terms of its **duration**?
- Is the source of variability the **point in time** of the occurrence of the event?
- Does the event always occur in the same **location** or does location change?

Table 8 includes the main list of factors influencing reliability as well as their classification and categorization. In some cases, only combinations of several dimensions provide the required information. For some dimensions it is not always possible to make a binary decision if the factor belongs to the considered class or not, therefore in such cases the category “partially” is derived.

Table 8 Categorization and classification of delay influencing elements

| | | Expect-ability | | Regularity | | Composition of travel time | | | | Involved entity | | | | | | Level of potential influence | | | | Quanti-fication | | Source of variability (for events only) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Yes | No | Regular occurrences | Exceptional conditions | Driving | Dwell | Stopping | Turning | Traffic | Route | Passenger | Stop | Bus operation | Environment | Strategy | Tactical | Operation | Not influenceable | Yes | No | Duration | Point of time | Location |
| **States** | Traffic composition (mix of passenger cars, trucks, bikes etc.) | p | | ✓ | | ✓ | | ✓ | | ✓ | | | | | | | | | ✓ | p | | | | |
| | Variability in traffic conditions (traffic density, congestion) | p | | ✓ | | ✓ | | ✓ | | ✓ | | | | | | | | | ✓ | p | | | | |
| | Curb parking | | ✓ | ✓ | | | | ✓ | | | ✓ | | | | | p | | | | | ✓ | | | |
| | Variability in travel demand: | | | | | | | | | | | | | | | | | | | | | | | |
| | • within day | p | | ✓ | | | ✓ | | | | | ✓ | | | | | p | | | p | | | | |
| | • day to day | p | | | ✓ | | ✓ | | | | | ✓ | | | | | p | | | p | | | | |
| | Composition of passengers (number of passengers with bikes, buggies etc.) | p | | ✓ | | | ✓ | | | | | ✓ | | | | p | p | | | p | | | | |
| | Passenger volume at stops | p | | ✓ | | | ✓ | | | | | ✓ | | | | | p | | | ✓ | | | | |
| **Properties** | Length of the route (higher probability for delay occurrence and propagation) | ✓ | | | | | | | | | ✓ | | | | | ✓ | | | | ✓ | | | | |
| | Layout of the bus stop (accessibility etc.) | ✓ | | | | | ✓ | | | | | | ✓ | | | ✓ | | | | | ✓ | | | |
| | Provision of bus lane (w/o bikes) | ✓ | | | | ✓ | | ✓ | | | ✓ | | | ✓ | | p | | | | | ✓ | | | |
| | Location of the bus stops (road/ bus bays) | ✓ | | | | | p | ✓ | | | | | ✓ | p | | ✓ | | | | | ✓ | | | |
| | Potential for self-obstruction (several buses/trams at the same time at a "small" stop) | p | | | | | | | | | | | ✓ | ✓ | | ✓ | ✓ | | | ✓ | | | | |
| | Distance from the stop to the terminal (higher probability for delay occurrence and propagation) | ✓ | | | | | | | | | ✓ | | ✓ | | | ✓ | | | | ✓ | | | | |
| | Scheduled turning times | ✓ | | | | | | | ✓ | | | | | ✓ | | | p | | | ✓ | | | | |
| | Scheduling system (e.g. headway) | ✓ | | | | | | | | | | | | ✓ | | ✓ | | | | | ✓ | | | |
| | Supervision strategy (e.g. intervention of control centre) | ✓ | | | | | | | | | | | | ✓ | | ✓ | | ✓ | | | ✓ | | | |

| | | Expect-ability | | Regularity | | Composition of travel time | | | | Involved entity | | | | | | Level of potential influence | | | | Quanti-fication | | Source of variability (for events only) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Yes | No | Regular occurrences | Exceptional conditions | Driving | Dwell | Stopping | Turning | Traffic | Route | Passenger | Stop | Bus operation | Environment | Strategy | Tactical | Operation | Not influenceable | Yes | No | Duration | Point of time | Location |
| **Properties (cont.)** | Network robustness (flexibility, redundancy, interdependency) | ✓ | | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | | | | | ✓ | | ✓ | p | | | p | | ▨ | ▨ | ▨ |
| | Bus loading/capacity | ✓ | | ▨ | ▨ | | ✓ | | | | | | | ✓ | | ✓ | | | | ✓ | | ▨ | ▨ | ▨ |
| | Number of junctions/ probable severity of interaction | ✓ | | ▨ | ▨ | | | ✓ | | ✓ | ✓ | | | ✓ | | p | | | | ✓ | | ▨ | ▨ | ▨ |
| | Number of pedestrian crossings/ probable severity of interaction | ✓ | | ▨ | ▨ | | | ✓ | | | ✓ | | | | | | | | ✓ | ✓ | | ▨ | ▨ | ▨ |
| | Number of ensured connections at considered stop | ✓ | | ▨ | ▨ | | ✓ | | | | | | ✓ | ✓ | | ✓ | | | | ✓ | | ▨ | ▨ | ▨ |
| | Number of intersections (signalized, priority)/ probable severity of interaction | ✓ | | ▨ | ▨ | | | ✓ | | | ✓ | | | | | | | | ✓ | ✓ | | ▨ | ▨ | ▨ |
| **Events** | Technical perturbations | | ✓ | | ✓ | | | ✓ | | | | | | ✓ | | | | | ✓ | p | | ✓ | ✓ | |
| | Minor accidents | | ✓ | ✓ | | | | ✓ | | | | | | ✓ | ✓ | | | | ✓ | | ✓ | ✓ | ✓ | |
| | Major road works | ✓ | | | ✓ | ✓ | | ✓ | | | | | | | ✓ | | | | ✓ | | ✓ | ✓ | | |
| | Minor road works | ✓ | | ✓ | | ✓ | | ✓ | | | | | | | ✓ | | | | ✓ | | ✓ | ✓ | ✓ | ✓ |
| | Calamity/ major incidents | | ✓ | | ✓ | ▨ | ▨ | ▨ | ▨ | | | ✓ | | | ✓ | | | | ✓ | | ✓ | | ✓ | |
| | Blocking of entrance doors (intentionally/ high passenger volume) | | ✓ | ✓ | | | ✓ | | | | | ✓ | | ✓ | | p | | | ✓ | | ✓ | ✓ | ✓ | ✓ |
| | Staff and bus shortages | | ✓ | | ✓ | ▨ | ▨ | ▨ | ▨ | | | | | ✓ | | | | | ✓ | | ✓ | | ✓ | |
| | Dependability of staff (e.g. reporting late to work, starting trip late) | | ✓ | | ✓ | ▨ | ▨ | ▨ | ▨ | | | | | ✓ | | p | | p | | | ✓ | ✓ | ✓ | |
| | Variability in driver behaviour and experience | | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | | | ✓ | | | | | ✓ | | ✓ | ✓ | ✓ | |
| | Public events | ✓ | | | ✓ | ▨ | ▨ | ▨ | ▨ | | | | | p | ✓ | | ✓ | | | | ✓ | ✓ | | |
| | Weather conditions | | ✓ | ✓ | | ✓ | | | | | | | | | ✓ | | | | ✓ | | ✓ | | ✓ | |

Legend:

✓applicable

**p** partially applicable

☐ not applicable

## 3.4 Measuring performance and reliability

### 3.4.1 Performance measures in the transport sector

A coherent performance-oriented planning process in public transport requires the definition of objective performance measures that relate to the operator's goals and objectives, but also capture the effects of problems from the perspective of users. The way a public transport operator measures system (or facility) performance, will impact the types of projects selected to improve performance and meet goals. In other words, performance refers to how well the system achieves its intended goals and objectives. Measuring performance is essential because it provides information on how well the service is being provided, and when it is not, it helps to diagnose problems and find solutions.

Performance measures in transportation involve a number of dimensions that make performance-based planning more challenging than in other sectors. They may for example be related to very broad goal categories such as mobility, safety, or economic development. A compromise must be made between the different roles taken by the transport activity. As mentioned in Cambridge Systematics (2000), "the main strategic business areas (movement of people and goods) must share the stage with other roles" (e.g. redressing economic inequities imposed by society, managing environmental effects, or providing for the economic health of a region).

A classification of performance measures can be made according to whether they are mode-specific or multimodal, by the system level to which they apply (system wide, corridor, line, etc.), or by the planning jurisdiction to which they are most relevant. Another classification is the perspective, i.e. whether the selected measure describes performance in the eyes of the actual users, the general public, the city, or that of the planning agency or system operator.

It is useful to take into account the different dimensions involved when selecting and implementing a set of performance measures for any particular planning or operational process. This may reduce the effort required by eliminating irrelevant performance measures, and at the same time will ensure that an adequate breath is involved in the planning process to address all relevant issues.

Another important issue is the selection criteria for performance measures in public transport. Work by Cambridge Systematics (2000) presents a list of common criteria for selecting performance measures and a discussion of each. The most relevant are: measurability, forecast ability, multimodality, clarity, and usefulness, among others.

### 3.4.2 Reliability measures in public transport

Users experience public transport reliability mostly through punctuality (with the associated additional waiting time at the stop) and travel time (consistency and variability of travel times).

A transit operator will focus on a number of system features to characterize reliability, such as schedule deviation, regularity, and percentage of completed trips, among others.

According to Cham (2006), public transport *service reliability measures* are the set of aggregate metrics used to characterize overall service, measure performance and evaluate service delivery. Service measures are required to compare the promised (planned) with the actual (delivered) level of service, and are an essential part in characterizing service reliability. They are basically summaries of individual trip outputs, such as calculated running time, schedule deviation, dwell time, headway deviation and passenger loads. Operators make use of them to assess the delivered service and establish both the actual level of reliability and its variation (improvement or not) over time. However, it is important to include measures that take into account the impact of service reliability on passenger's experience, such as waiting time and crowding.

The relevance of public transport reliability to both users and operators, discussed in section 3.2.3, justifies the need to identify and develop clear measures of reliability in public transport that describe the variability in service and reflect its impacts on both users and operators. As mentioned by Abkowitz (1978), such measures would help transportation planners and the public transport industry to:

- Identify and understand reliability problems
- Identify and measure improvements
- Relate improvements to strategies
- Modify strategies, methods and design to achieve greater reliability improvements

Early on-time performance studies were generally concerned with either the shape of the probability distribution of observed versus scheduled arrival times, or with evaluating service reliability, namely: running times, run time variation and headway variability. Work by Strathman and Hopper (1993) reviews them, and an attempt is made to bridge the two approaches.

Furthermore, as reviewed and summarized by Gattuso, Galante et al. (2010), contemporary methods to analyse performance in the public transport industry are classified in two types:

- Parametric (such as stochastic frontiers and econometric models), and
- Non-parametric (like Data Envelopment Analysis and analysis through indicators)

This work seeks to assess public transport service reliability by performing route and stop- level analysis of running times, punctuality, headway regularity, as well as estimating measures of their variation. Passenger waiting time is analysed at the route level.

In general, high frequency services are those offering headways ≤ 10 minutes. In Zurich, all services are scheduled regardless of their frequency (even for 5-minute headways), for this reason both punctuality and regularity analyses are carried out to evaluate performance.

As mentioned by Kimpel, Strathman et al. (2000), bus performance should be measured at intermediate locations along the line and not only at terminal stations. In this work, bus performance is measured at the route and stop levels for running times, punctuality and headway regularity. Additionally, an on-time performance (OTP) indicator, defined as the share of trips departing punctually, is calculated at the stop level. Punctuality is defined in Zurich as a bus leaving no earlier than 30 seconds before, and no later than 60 seconds after the scheduled departure time.

The following non-exhaustive list of public transport service reliability measures is summarized from the literature. Some less frequent, or system specific measures are excluded. These measures focus on passenger waiting time, travel time, punctuality and regularity. Table 9 includes waiting time performance metrics, which are passenger-oriented measures. Table 10 describes operator-oriented reliability metrics.

Table 9 Passenger-oriented reliability measures in public transport

| **Performance metric** | **Defined as** | **Comments** |
|---|---|---|
| *PASSENGER WAITING TIME* | | |
| Mean waiting time E [W] | 0.5 *(Mean Headway)*(1+cv$^2$) | Time between passenger arrival at stop and next vehicle departure. Headway <= 10 minutes and random passenger arrival assumed. CV is the coefficient of variation. |
| Mean waiting time E [W] | Ideal + Excess (waiting time) | Concept that separates the impact of operations from that of planning |
| Ideal waiting time | 0.5*(Schd. H/way)*(1+cv$^2_{\text{Sched. H/way}}$) | Describes the incremental impact of planning in mean waiting time. Random passenger arrival is assumed. |
| Excess waiting time | E [W] – Ideal waiting time | Describes the incremental impact of operations in mean waiting time. |
| Budgeted waiting time ($W_{95}$) | 95th percentile of waiting time distribution | Passengers must allow more time for waiting than mean waiting time, otherwise they will reach their destination late about half the time. By budgeting $W_{95}$, the probability of arriving late is limited to 5% |
| Potential waiting time ($W_{potential}$) | $W_{95}$ – E [W] | Is the time a passenger has to include in his or her travel budget, but is normally not spent waiting. It represents a hidden cost for users, spent at the destination end of a person's trip. |
| Equivalent waiting time | E [W] + (b/a). $W_{potential}$ | Weighted waiting cost function, where a and b are unit costs (minutes of in-vehicle waiting time per minute of waiting). b/a = 0.5 |
| Excess equivalent waiting time (wt) | Actual equiv. wt – Ideal equiv. wt | Metric that reflects the impact of operations in customer service by accounting for the hidden cost of potential waiting time. |
| % of passengers with excessive waiting time | Share of passengers with waiting time above a certain threshold | e.g. share of passengers waiting more than the scheduled headway, or 2 minutes more than the scheduled headway. Serves for quality assurance. |

Source: Furth and Mueller (2006)

Table 10 Operator-oriented reliability measures in public transport

| **Service Measure** | **Defined as** | **Source** | **Comments** |
|---|---|---|---|
| *TRAVEL TIME (TT)* | | | |
| TT reliability (1) | Mean / std. dev of TT | Liu & Sinha (2007) | Allows for comparison of variations in bus routes or sections of a route with different mean values. |
| TT reliability (2) | 1 / std. dev. of TT | Polus (1976) | Higher reliability achieved with smaller variability. |
| Run time ratio (RTR) | Observed / Scheduled TT (in %) | Strathman et al (1999) | Values > 1 indicate insufficient time in schedule. |
| Run time delay | Actual – Scheduled TT | Kimpel (2001) | Positive values identify links where vehicles have problems getting through. |
| Run time coefficient of variation | Std. dev / mean TT | Various | Statistical measure that standardizes the variation in run times, allowing comparisons across routes, time periods, service frequencies, etc. |
| *PUNCTUALITY* | | | |
| Schedule adherence | Actual – scheduled departure time | Many | Important measure for infrequent users, timed transfers, and less frequent services. |
| Standard deviation of schedule adherence | Standard deviation (of Schedule Adherence) | TRCP 113 (2006) | Indicator of how unpredictable and out of control an operation is. |
| Weighted Standard deviation of schedule adherence | As above, but weighted by passenger on-offs | TRCP webdoc 23 (2003) | Weighting by passenger volumes provides relevance to those stations where most passenger transfers take place. |
| On-time performance | % of buses departing "on-time" | Many | Particularly useful for timed transfers and less frequent services. |
| *REGULARITY* | | | |
| Headway ratio | Observed / Sched. Headway | Strathman et al (1999) | Standardized headway indicator. |
| Headway delay/deviation | Actual – Sched. Headway | Kimpel (2001) | Effectively measures spacing between vehicles. |
| Headway variance weighted by number of passengers at stop | $\frac{\sum_{j=1}^{n} \# pass_j . \mathrm{var}_j \, hdway}{\sum_{j=1}^{n} \# pass_j}$ | Chapman (1976) | Passenger activity directly influences this measure, which can be calculated at stop or route level. Minimizing the weighted mean variance will improve service reliability for more passengers. |
| Regularity index | Mean of absolute headway deviation divided by mean headway | TRCP 113 (2006) | An alternative measure to cv of headways |
| Share of acceptable headways | % of headways within a certain threshold | TRCP 113 (2006) | e.g. share of headways <= 1.5 times the scheduled headway. |
| Headway Standard deviation | Standard Deviation of absolute mean headway | Chapman (1976) | Measure of spread of values about a mean, provides an indication of service regularity. |
| Headway coefficient of variation | Standard deviation of headway over mean headway | Abkowitz (1978) | Operator-oriented statistical measure that standardizes the variation in headways, allowing comparisons across routes, time periods, service frequencies, etc. |

Section 5.4 quantifies the service reliability measures used to characterize the reliability of bus Line 31 in Zurich, as well as measures of their variation.

### 3.4.3 Threshold values

For all of the previously mentioned service measures, a decision must be made on the threshold values or the ranges of values that classify a service as reliable or unreliable. The threshold values should be based on the level of service the operator can deliver in a cost-effective way, on the passenger's expectations, and may vary by type of route and time of day.

The literature indicates that for low frequency services, the users time their arrival to the stop based on the schedule (adapted to their own experience) in order to reduce their expected waiting time. On the other hand, for high frequency services (10-min headway or less) the literature normally assumes random passenger arrivals due to lack of confidence in the schedule and low expected waiting times. Therefore, the threshold values of deviations should be different for high and low frequency services, due to the different impacts on users. Likewise, trips during different times of day may be subject to different levels of exterior disturbances (e.g. vehicle traffic) and passenger demand.

In Zurich, all services are scheduled regardless of their frequency, and a large effort is made to remain true to the schedule throughout the day. This effort also contributes to maintaining even vehicle headways and improves service regularity.

The key points any public transport operator should consider when deciding on service reliability threshold values are discussed in detail by Cham (2006) and grouped in four main categories: on-time performance, headway adherence, passenger loads and percent of trips. Additionally, passenger-waiting times are included in this work using the methodology developed by Furth and Muller (2006). These last service measures incorporate the effect of service reliability.

For on-time performance, the operator (or authority) needs to define the range around the scheduled time in which a vehicle is considered to be "on-time". This is needed to give meaning to on-time performance. The threshold values can depend on the type of route, scheduling practices and location on the route. Common on-time performance threshold values are set to 1-minute before to 5 minutes after the planned departure time.

In Zurich, all vehicles throughout the day are given the same punctuality threshold range: between 30 seconds before and one minute after the planned departure. Table 11 summarizes the threshold values used to define "on-time" in Zurich.

Table 11 Punctuality threshold values in Zurich. All vehicles, all day. Departures

| Description | From | To |
|---|---|---|
| Very late | -03:00 | - |
| Late | -01:00 | -03:00 |
| *Punctual* | *+00:30 (early)* | *-01:00 (late)* |
| Early | +01:30 | +00:30 |
| Very early | - | +01:30 |

To define headway adherence threshold values, absolute or relative values can be used. An example of absolute values would be to consider any bus with a 1-minute headway (or lower) to be bunched. Relative values would consider any bus with actual headway less than or equal to, for example, 0.30 of the scheduled headway to be bunched. Relative values should be preferred on routes where consecutive headways are not equal (for appropriate comparisons), but care is needed, as relative values might be interpreted different for different headways.

Another threshold value useful to evaluate regularity in high frequency services is the coefficient of variation (cv), a normalized measure of variation included in Table 10. The values included in Table 12 are from TCQSM (2003), p. 3-50.

In Zurich, the maximum acceptable delay (for 95% of the trips) is tolerated according to the headway: 2, 3, 4 and 5 minutes of delay for headways <=7.5, 10, 15 and 30 (or more) minutes, respectively. The following threshold values are defined for this work in the table below.

Table 12 Regularity threshold values used in this study

| Measure | Aim | Value | Remarks |
|---|---|---|---|
| Absolute headway | Bunching | ≤ 1 minute | Headway dependent |
| Relative headway | Bunching | ≤ 0.2 of planned headway | Headway independent |
| Relative headway | Gaps in service | ≥ 1.5 of planned headway | Headway independent |
| Coefficient of variation (cv) | Variability | ≤ 0.30 | LOS B: Vehicles slightly off headway |
| Coefficient of variation (cv) | Variability | ≤ 0.21 | LOS A: Service provided like clockwork |

Passenger loads are an important measure of crowding, which can have a large impact on service delay and cause bunching. Overcrowding thresholds values are based on seating capacity and an acceptable number of people standing. They may be set as the average maximum load over a time period (e.g. particular time or day, or maximum span of time, say 30 minutes).

In Zurich, the threshold value for passenger crowding follows two principles:

- 90% of all courses in the rush hour should have a value lower than 2 passengers / $m^2$. i.e. $q_{90} < 2$ P/$m^2$ in all courses of the rush hour (peak demand period).
- 99% of all courses during the day should have an occupancy value lower than 3 passengers / $m^2$. i.e. $q_{99} < 3$ P/$m^2$ in all courses of a day.

Another useful threshold is the share of trips that need to be on time to consider the service as reliable. For each service attribute (running time, schedule adherence, headway adherence), this share can vary depending on frequency and time of day. For high frequency routes (and peak demand time periods), operators should be stricter in keeping regular headway than for lower frequency routes, due to the higher levels of passenger demand and a higher probability for delay to propagate.

Below, Table 13 shows typical percent threshold values describing on-time performance[8] and the corresponding level of service (LOS), according to the Transit Capacity and Quality of Service Manual.

Table 13 On-time performance Levels of Service (LOS)

| Level of Service (LOS) | On-time performance (%) |
|---|---|
| A | 95 – 100 % |
| B | 90 – 94.9 % |
| C | 85 – 89.9 % |
| D | 80 – 84.4 % |
| E | 75 – 79.9 % |
| F | < 75 % |

Source: TCQSM (2003)

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[8] “On-time“ in this particular case defined as 0 to 5 minutes late applied to either arrivals or departures.

In the case of passenger waiting times, no threshold is currently established for these service measures as they are derived from the recent work by Furth and Muller (2006) and are not used in the public transport industry. However, these service measures can be derived using existing AVL data, and are expressed as the share of passengers having to wait a defined amount of time (waiting time bin).

The process involves determining the passenger's cumulative waiting time distribution and calculating the share of passengers in various waiting time ranges (or bins). By choosing bin thresholds corresponding to various levels of passenger expectation, it is possible to see what fraction of passengers had various levels of service. The authors propose two thresholds for a three-level gradation (good, marginal, poor). The mean scheduled headway ($H_{schedule}$) is the lower threshold (because for perfectly regular services no passenger will have to wait more than the headway), and $H_{schedule} + x$ is the other one, where x can take a value (e.g. 2 minutes) that reflects customer expectations. For this work, the thresholds are defined as follows:

Table 14 Passenger waiting time threshold values used in this study

| Gradation | Relative to Headway | Value for 7.5-min headway | Value for 10-min headway |
|---|---|---|---|
| Good | $0 - 0.4.H_{schedule}$ | 3 min | 4 min |
| Good | $+0.4.H_{schedule} - 0.7.H_{schedule}$ | 5 min | 7 min |
| Good | $+0.7.H_{schedule} - H_{schedule}$ | 7.5 min | 10 min |
| Marginal | $H_{schedule} - (H_{schedule} +2$ min) | 9.5 min | 12 min |
| Poor | $> (H_{schedule} +2$ min) | > 9.5 min | > 12 min |

One assumption of the methodology is random passenger arrival at stops. A clear advantage is that determining waiting-time distribution supports service standards related to extreme values of waiting time. An example of service quality standard that could be derived is, for example, "no more than 1% of passengers should wait longer than the scheduled headway +2 minutes".

## 3.5 A major consequence of unreliability: delay propagation

The outcomes of unreliable bus services vary depending on where, when and how often vehicles run. On bus lines with long headways, transfers become undependable, which may force users to take an earlier trip to guarantee a given connection, consequently increasing their total travel time. On bus lines with higher volumes and short headways the consequences of unreliability are somewhat different. Punctuality normally becomes less relevant and regularity more important, as the waiting time for a passenger is expected to be not more than the scheduled headway. A special cause of service unreliability, particular of high frequency urban services due to the short time intervals between vehicles, is the tendency of delay to propagate throughout a line, which in extreme cases leads to vehicle bunching or package building. This section discusses this phenomenon, its causes and its most influencing parameters.

### 3.5.1 Bus bunching: a result of propagated delay

When a vehicle on a high frequency line experiences a certain delay, i.e. falls behind schedule, there is a tendency for this delay to increase and propagate along the line. As the distance between the vehicle experiencing the initial delay and the previous one increases, the delayed vehicle must deal with greater passenger loads that cause additional delay. Simultaneously, the vehicle following it is left with lower passenger loads than expected, which allows it to run faster as the dwell time needed for passenger exchange is lower.

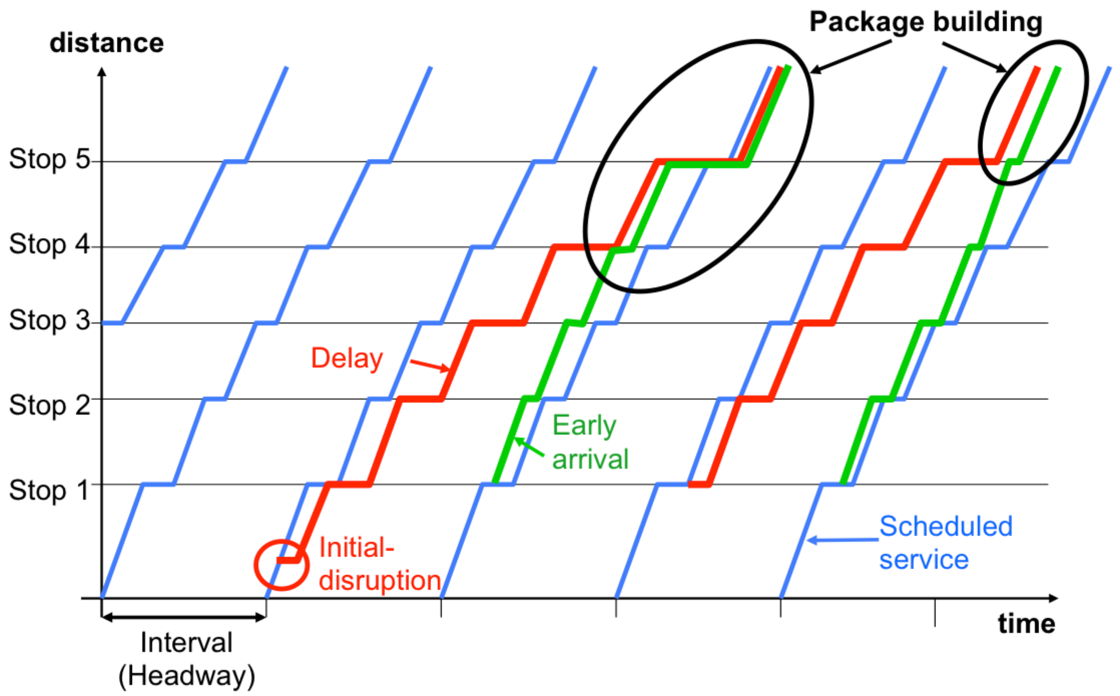
This dynamic process tends to propagate as buses run along their route and eventually the two vehicles travel as a pair. In extreme cases this bunching may develop into a package of many vehicles. Therefore, delay propagation is the phenomena responsible for vehicle (bus) bunching.

As mentioned by Kimpel (2001), bus bunching represents a “poor use of agency resources since uneven passenger loading can require the use of additional vehicles to serve the same number of passengers”. The impacts of irregular headways and bus bunching on passengers are (a) overloaded vehicles, with the resulting low level of comfort for the user and the possibility of not being able to board, and (b) the increase in average waiting times at the stop.

In the case that several lines share a corridor, depending on its length, users might perceive this corridor as a single bus line. Weidmann (2008) proposes a minimum length of 1 to 2 Km in central areas and between 3 and 4 Km in peripheral zones. The higher value corresponds to corridors with around 20 vehicles per hour. The lower value applies to corridors with very high frequencies (around 40 vehicles per hour).

Figure 8 illustrates the propagation of delay and the resulting bus bunching as a function of time and distance.

Figure 8 Delay propagation principle and subsequent bus bunching



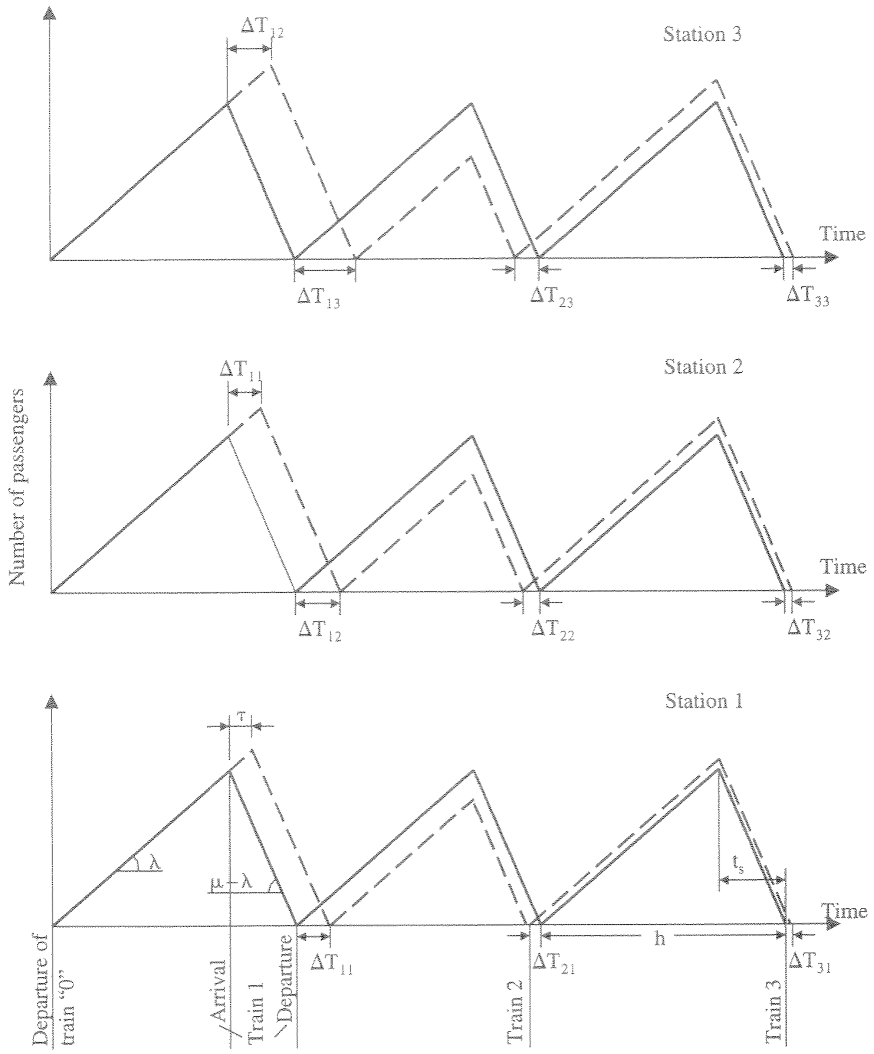
Source: courtesy of Pascal Lippmann – Verkehrsbetriebe Zurich (VBZ)

### 3.5.2 The mechanisms of delay propagation

A theoretical model to describe delay propagation was first developed by Vuchic (1969) to examine the effect of factors that contribute to the tendency of vehicles to build packages as they travel along the line. The model aims to explain the pairing of vehicles (bus bunching) in terms of the arrival and boarding rates of passengers at stops. It assumes that changes in the time that passengers require to exchange are the main cause of bus bunching, and does not take into account external influences on vehicle travel. Other main assumptions of the model are: that vehicles initially travel at uniform headways; that the rates of passenger arrival (at the station) and vehicle boarding is constant; that each vehicle picks up all waiting passengers at each station and departs as soon as they have boarded; and that vehicle travel time between stops is constant.

Figure 9 graphically shows operations (passenger accumulation, train arrival, boarding, departure, etc.) at three subsequent stations. Solid lines represent the accumulation of passengers at a uniform rate $\lambda$ until the vehicle arrives. Then the rate begins to dissipate at a rate $\mu-\lambda$ (passengers continue to arrive while they board the vehicle at rate $\mu$). As the vehicle departs (when all passengers board) the accumulation of passengers at a rate $\lambda$ begins again and the next triangle begins to form.

Figure 9 Delay propagation model over time and distance



Source: Vuchic (2005)

In order to observe the phenomenon occurring after a delay, the arrival of train 1 at station 1 is depicted with a delay $\tau$. The delay causes a slightly higher accumulation of passengers at the stop. From that point on, the situation caused by delay is depicted using dashed lines. The delay of train 1 allows train 2 to depart earlier, which in turn, causes a slight delay in the departure of train 3. The triggering delay results in the vehicles beginning to oscillate around their scheduled times.

As vehicles move on to the following stations, the initial delay is augmented for the courses running late. In turn, courses running early have fewer passengers to pick up, and depart earlier at each following station. Eventually early vehicles catch up to delayed vehicles and packages form.

### 3.5.3 Parameters influencing bus bunching

The diagram depicted in Figure 9 can be used to develop analytical expressions for the delays, as explained in work by Foulkes, Prager et al. (1954) and by Vuchic (1969). A major conclusion is that the behaviour of delays (and resulting stability of operations) greatly depends on the ratio of the rate of passenger arrival at stops ($\lambda$) to the rate of dissipation of the accumulated passengers ($\mu-\lambda$) between vehicle departures.

In practical terms, this means that for stable operations, the rate of passenger boarding should be very high in comparison to the rate of passenger arrival at the stops. Therefore, one possibility of reducing the probability of bus bunching is to accelerate the passenger boarding process (boarding times), as this will decrease its propensity to increase delays, improving reliability.

Additional to the passenger arrival and vehicle boarding rates, work by Turnquist (1981), based on Turnquist and Bowman (1980), extends the work of Vuchic (1969) by including two elements: the effects of “batch” passenger arrivals from connecting lines, and the variability in link travel times. Moreover, since network structure (e.g. grid, radial) impacts service reliability, a variable was included in their model to account for this factor. Their experiments relate vehicle bunching to frequency of service, level of demand, and the variation of link travel times. In particular, their results illustrate the importance of reducing variability in vehicle travel time as a way to prevent packages from forming.

Large variability in link travel times can reduce the benefits of increasing frequency of service because of the tendency of vehicles to bunch together. Moreover, the impact of transfers points highlight the importance of scheduling in ensuring on-time arrival of vehicles at major transfer stations, especially in radial networks. In practical terms this means that excess (buffer) time should be ideally allocated (scheduled) at points where large numbers of passengers transfer, to increase the probability of successful connections.

Work by Weidmann (2008) discusses the influence of service frequency and vehicle access elevation in delay propagation. It is shown that particularly in high demand corridors with short intervals between vehicles, vehicle accessibility (collective of vehicle features affecting passenger exchange time) plays a big role in improving operational stability (reducing delay propagation). This is because increases in delay are slowed down and vehicles tend to bunch only further down the line. This speaks in favour of low-floor vehicles, level boarding and similar measures, as a way to improve operational stability in public transport.

## 3.6 Automatic data collection systems and service reliability

A large amount of research exists on the potential of Automatic Vehicle Location (AVL) and Automatic Passenger Counting (APC) systems to enhance operations, performance monitoring, scheduling and planning. Some early examples include the work of Tomazinis (1975) and Vuchic (1981). More recent work by Fu and Yang (2002) focused on operational strategies. Bertini and El-Geneidy (2003); Strathman, Kimpel et al. (2003); and El-Geneidy, Horning et al. (2008) worked on performance measures. Wilson, Zhao et al. (2005) focused on the potential impacts to planning. Finally, some of the works focusing on AVL and reliability are those by Cham (2006); Furth (2006); and Pangilinan, Wilson et al. (2008). Naturally, many more exist.

Additional business units throughout a public transport agency are also involved in a variety of ways in AVL system implementation and use. Among them are maintenance, customer service, security, information technology (IT), revenue and marketing, as discussed by Parker (2008).

### 3.6.1 Evolution of Automatic Data Collection Systems (ADCS)

Work by Vuchic (1981) makes a historical review of ADCS, together with their past and potential applications in service planning, scheduling, performance evaluation and system management. A description of the historical uses of AVL and APC systems takes place in the first part of the work. It is emphasized that for most AVL systems, the focus has been on real-time applications for operations control and emergency response. It is mentioned that many systems were not designed to provide useful archived data, because public transport agencies basically did not require it during procurement and design. On the other hand, APC systems were designed for off-line data analysis, and have been regularly used to evaluate performance.

Technological advances involving ADCS described in that study (among others) are:

- Development and improvement of location-based technologies such as Global Positioning Systems (GPS) and Geographic Information Systems (GIS).
- Rapid evolution of computers and communication technologies, making the former smaller, faster, cheaper, and more capable; while the latter have improved significantly with the implementation of wireless networks and more efficient radio transmissions.
- Systems integrations, combining “smart bus” design with functionalities of other systems, e.g. passenger information, fare collection and scheduling.

### 3.6.2 Benefits and costs of ADCS

The literature in general agrees that “ADCS allow for statistically valid evaluations of service reliability for the first time”, as stated by in Furth, Donner et al. (2000). This is basically due to the nature in which data is collected compared with previous approaches (manual counts). A summary by Wilson, Zhao et al. (2005) of the differences between manual and automatic data collection can be found in Table 15.

According to Parker (2008), the benefits of implementing an AVL system can be categorized as quantitative or qualitative. Some of the benefits can be quantified in monetary terms or otherwise, but often there are also qualitative benefits that are still important to consider.

In most cases, a benefit can be classified in both categories, with a more broadly stated qualitative benefit complemented by some specific aspects of a quantifiable benefit. In the mentioned work, many agencies interviewed on the implementation of their system did not systematically evaluate aspects of benefits that might have been quantifiable, as they did not see a need to undertake the additional evaluation.

According to Parker, some expected benefits of a bus AVL system for fixed-route operation are:

- Improved situational awareness and additional voice communications management capabilities.
- Schedule adherence feedback to dispatch, drivers, and supervisors, which helps maximize on-time performance and reliability.
- Dispatchers can be proactive in addressing operational issues, including more timely and effective reaction to service disruptions.
- Covert alarm monitoring supports the ability of drivers to quickly inform dispatch about an on-board emergency.
- Automated next stop announcements provide consistent information for passengers, while reducing the workload for drivers.
- APC equipment provides a cost effective alternative to the use of human ride checkers, as well as comprehensive and reliable data samples.
- The system can provide real-time next bus predictions to customers both pre-trip and en-route, relieving the driver from the task.
- More comprehensive historical data collection and incident reporting allows for more effective and detailed analyses.

Table 15 Transition from manual to automatic data collection technology

| Manual | Automatic |
|---|---|
| + Low capital costs | - High capital costs |
| - High marginal costs | + Low marginal costs |
| - Small sample sizes | + Large sample sizes |
| - Aggregate | + More detailed, disaggregate |
| - Unreliable | + Errors and biases can be estimated and corrected |
| - Limited spatially and temporally | + Ubiquitous |
| - Not immediately available | + Available in real-time or quasi real time |

Source: Wilson, Zhao et al. (2005)

According to Parker (2008), public transport agencies can categorize costs as capital or operational. The former refer to those costs incurred once during the implementation, while the latter are the ongoing (and in some cases recurring) costs to keep the system in effective operation once it is in revenue service. Common capital costs are:

- On-board equipment, workstations and server hardware and software
- Mobile data communication system improvements
- Installation
- Integration, training and documentation
- Project management, design review and acceptance testing
- Warranty and initial supply of spare components

According to Cham (2006), for APC systems, the main limitations have been the large investments involved in implementation and maintenance of equipment, and the need to develop software (mostly in-house) to analyse the collected data.

### 3.6.3 Uses of archived AVL – APC Data

Work by Furth (2006) deals with the main uses for archived AVL and APC data. One of the most important applications identified is in "running time analysis", including the design of scheduled running times and the monitoring of schedule adherence. Using AVL data it is possible to use extreme values such as 85 and 95 percentile (instead of only average or median) running times as a basis for scheduling.

Archived AVL data can also be applied to monitor and improve schedule adherence, headway regularity, and passenger waiting time. In this area, extreme values are just as important as mean values. In particular, public transport agencies are looking for measures of service quality that reflect passenger's experience and point of view. Moreover, AVL and APC data allows customer-oriented service quality (and reliability) measures to replace (or complement) operations-oriented service standards. An example by Furth (2006) is the coefficient of variation (cv), a normalized measure of variation useful for analysts, but of no use or meaning to customers. Instead, from a large sample of data, it is possible to measure the percentage of passengers waiting longer than a given threshold of minutes, which could then lead to quality standards that are clear and real to passengers.

The exploration of archived AVL and APC data can also enable transit agencies to find hidden trends or systematic occurrences that may help explain irregularities in operations and suggest new ways of improvement.

Moreover, for any of the analyses mentioned, there is also an interest on higher-level analyses that involve tracking trends over time, comparing routes or periods of time, and so on. A final example is the use of GIS-based analyses that take as input passenger use and service quality statistics. For a detailed example, see Berkow, El-Geneidy et al. (2009).

### 3.6.4 Key dimensions of collected data

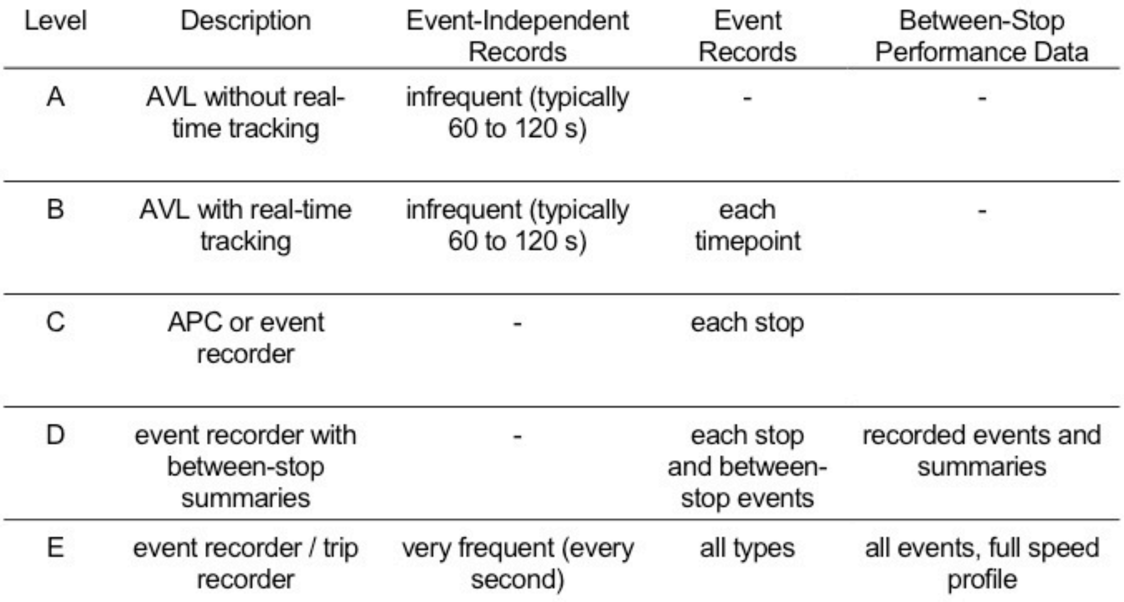
During the data collection process, it should be kept in mind that the purpose of these data is to improve public transport management and performance. In order to make data useful, it is convenient to first analyse four key dimensions of the core data involved. In Vuchic (1981), the authors define these as:

- The level of spatial and temporal detail
- Complete vs. exception data
- Fleet penetration and sample size
- Data quality control

The first refers to a hierarchy on the levels of detail available, depending on the type of system used. A summary is found in Table 16.

The second dimension deals with the way data records are produced. Either routinely, defined by a time interval or a location-related event, or if it is triggered by an unanticipated time of occurrence of an event, or an unanticipated event itself. The third dimension deals with the extent to which vehicles are equipped with AVL and APC systems (a common practice in the public transport industry is to equip all vehicles with the former, and between 10% and 15% of the fleet with the latter). Sample size is also important to ensure route and daily variations are taken into account. The last dimension refers to the need of good quality control and post-processing of the data to correct any errors. A concise summary and discussion on this subject can be found in Cham (2006).

Table 16 Levels of spatial and temporal detail for data capture



| Level | Description | Event-Independent Records | Event Records | Between-Stop Performance Data |
|---|---|---|---|---|
| A | AVL without real-time tracking | infrequent (typically 60 to 120 s) | - | - |
| B | AVL with real-time tracking | infrequent (typically 60 to 120 s) | each timepoint | - |
| C | APC or event recorder | - | each stop | |
| D | event recorder with between-stop summaries | - | each stop and between-stop events | recorded events and summaries |
| E | event recorder / trip recorder | very frequent (every second) | all types | all events, full speed profile |

Source: Furth, Hemily et al. (2003)

## 3.7 Summary

This chapter introduced the concepts of performance and reliability in public transport. The relevance of reliability in public transport was emphasized and the different elements that have and influence of service reliability were described and classified. In the following sections, the operationalization of reliability and performance was discussed, as different metrics and measures were introduced to the reader. Particular measures related to passenger waiting time, travel time, punctuality and regularity in operations.

The delay propagation phenomena, responsible for the formation of vehicle packages under unstable operations, was also depicted and explained. Moreover, its most important parameters and their influence on reliability were described, as well as possibilities to reduce their effect, which may lead to improvements in service reliability.

# 4 Public transport service planning

## 4.1 Chapter overview

This chapter addresses the public transport planning process. First, planning as such is discussed and related to both urban transportation as a whole and to public transportation in particular. Second, a generic planning process based on the literature is proposed for the different levels of planning in public transport. Subsequently, the public transport planning process is focused in the case of Zurich. Finally, the theoretical planning is compared with the practical case study to determine the general similarities and particularities of public transport planning in Zurich when compared to a generic planning process.

## 4.2 Urban transportation and public transport planning

Planning is a basic activity that encompasses many areas in society. Public systems (and facilities) such as an urban road network or a public transport system normally require more intricate planning processes than those needed for private enterprises, due to the greater complexity and number of actors involved. The objectives of public systems are also more diverse than those of private companies, as they involve not only financial indicators, but also include impacts on the general public and on the city or urban area.

Inter- and multimodal transportation systems build upon different networks and modes, requiring complex infrastructures that in turn consume considerable (and sometimes scarce) physical space. For a transportation system to work efficiently, the networks, infrastructure and vehicles must be planned as coordinated systems. Additionally, because transportation interacts with most activities in urban areas (e.g. industry, housing, services, etc.) the planning of transportation systems must be coordinated with land use plans, urban shape and the different individual characteristics of an urban area. Therefore, all these aspects must be planned (and designed) in the context of comprehensive, long-term planning procedures.

Transport systems requiring permanent facilities such as terminals or tracks fit into this category and require long-term, comprehensive planning. Without such planning, urban public transportation systems will hardly be able to meet the mobility needs of their users. This is partially because the coordination required between urban form, land use and a public transport system can only be achieved through long-term planning. Another reason is the considerable time and financial resources normally needed to plan and build networks and fixed facilities.

In order to increase the efficiency of public transport systems, they must be carefully planned together with the other modes in the transportation system, including their interaction with land uses. Because of the interdependencies and increasing complexity of urban areas, public transport planning needs to be related to all relevant city planning, economic and social aspects of cities and urban areas. It must also include all geographic areas that function together, instead of being limited by administrative boundaries. This is the ideal situation, unfortunately it is not always the case, and planning in many cities lacks the comprehensiveness and interdisciplinary it requires to meet the needs and requirements of all involved urban actors. For more details on other related aspects, see Vuchic (2005).

### 4.2.1 Planning horizons

Urban transportation planning is generally classified in two categories by planning period. They vary in their nature, kind of objectives and characteristics. These periods are not fixed and provide only a general guideline.

#### *Short-term planning*

Includes projects and measures that can be implemented in 3 to 5 (sometimes up to 8) years, and usually do not involve major investments and infrastructure construction projects. It may include detailed schedules, acquisition of new vehicles, modification of existing, or opening of new (bus) lines, small infrastructure changes, to name a few. Short-term planning is dependent on present conditions and near future trends because the changes made are relatively easy to modify or even reversed. Short-term planning should always follow and be compatible with long-term plans.

#### *Long-term planning*

Involves the planning of major infrastructure elements, lines, networks and such facilities. These plans may involve large capital investments, construction or even the development of new vehicles. The planning horizon is normally 10-25 years. Long-range planning aims at meeting the public transport needs of an urban area in the year of the adopted horizon. Because of the nature and scale of the projects involved in this type of planning, and because such developments are permanent, they have a great number of impacts and interactions with other activities. Their long-term effects should be modelled and evaluated very carefully. The financing of public transport projects of this scale needs to be evaluated together with the economic, social and environmental benefits and costs to the community as a whole. Some examples are the construction of a new rail line, network or major public transport terminals, reorganizing the network, building a control centre, etc.

Long-term planning activities are not the scope of this work and consequently will not be further discussed.

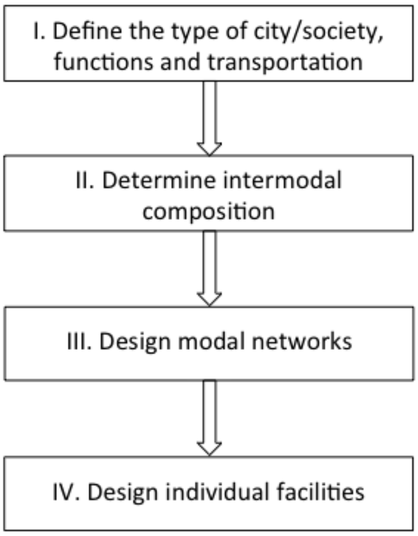
### 4.2.2 The urban transportation system planning process

In most cities around the world, the focus of transportation planning has traditionally been on the highway or automobile system, even though a comprehensive approach should include all modes. In many places, some modes such as cycling and walking are often not even included, and public transport is rarely given enough attention.

The roles that public transport and other modes play in a city are closely related to both the urban (physical) form and the type and character of the urban activities that take place in a city. Ideally, the sequence of planning a transportation system for a city (and its region) should start by defining the type of city or region concerned. This vision should then be translated into the goals for the transportation system, more specifically its intermodal composition, because the roles of different roles have a major and distinct impact on a city's physical characteristics, activities and environment. A city with highly concentrated skyscrapers in the central business district (CBD), large manufacturing sectors and dense housing needs a high-capacity and very efficient public transport system. Other situations will require different solutions. In any case, networks of other modes complement the major roles of individual modes with relative significance depending on local conditions and the adopted goals.

The process of intermodal urban transportation planning consists of four levels of analysis and decision-making. The starting point is the vision of the desired urban area in the future and the required goals at the 1st level. The goals from that vision should then be translated into the plan for relative roles of different modes and their relationship at the 2nd level. The decisions taken at this level define the role that public transport and other modes should have, and what their interrelationships should be. The 3rd level consists of the individual design of each mode. The public transport system is defined here, determining the modes and their networks. Finally at the 4th level of the planning procedure, individual lines and facilities are planned and designed. A detailed sequence of public transportation planning can be found in Vuchic (2005).

Figure 10 Four-level planning sequence in urban transportation



Source: Vuchic (2005)

The approach and flow of the planning process vary with the conditions, scope, and goals of transportation planning. Public transport planning is more focused than urban transportation planning and requires special expertise in the plan development, selection of modes, and design of networks.

## 4.3 Public transport generic planning process

The general process of public transport planning comprises the design of the system modes and network as well as the individual lines and their operation, as previously mentioned. In section 2.2.2, the functional structure of public transport was addressed, which consists of three hierarchical levels. These levels deal with the planning and delivery of the service to the public: they are the strategic, tactical and operational levels.

This **functional structure** can be divided into the design (or planning) part and the service delivery (or operation) of public transport. The strategic and tactical level are also related to the planning horizons mentioned in section 4.2.1 as most strategic planning activity has a long-term planning horizon, while tactical elements of planning mainly involve short or medium-term planning.

This section briefly discusses the strategic level of public transport planning and focuses on the tactical level, which uses the results of strategic planning to produce the information required to operate the vehicles and provide service to the users.

### 4.3.1 Strategic planning level

At the strategic level, the network is designed. The expected ridership for the year of the planning horizon, the budget, geographical characteristics (among many others) are the input for the design of the service line network, which consists of the lines and main frequencies (capacity). An infrastructure network might also be designed for given modes (e.g. energy supply, signals, etc.)

The network of lines (with their stops and stations) represents the main infrastructure component of a public transport system. In general, modes with a higher segregation from other modes such as metros and railway lines require much higher amounts of planning and investment, given their permanence character and impact in the urban development. A number of issues to be considered in the design of a network are: the planning objectives, passenger attraction, and the network's operating efficiency. Some geometrical considerations are the spacing between lines, the length and alignment of lines, and the level of integration (or independence) of given lines.

**Design objectives** for a public transport network should aim at performing the maximum transportation work, achieving the highest possible operating efficiency and creating positive impacts. Elements influencing passenger attraction are the area coverage, the operating speed, the directness of travel and the level of simplicity, connectivity and ease of transfer that can be achieved.

Some characteristics that define the **operating efficiency** of a network are the continuity and balancing of the lines, the operating flexibility, the level of integration with other modes, the location of complimentary facilities such as terminals depots and yards, and finally and often most decisive, the cost of the system. Often at this level, the public transport authority takes the decision regarding the network, supported by the advice and experience of the operator and consultants, as mentioned by van Oort (2011).

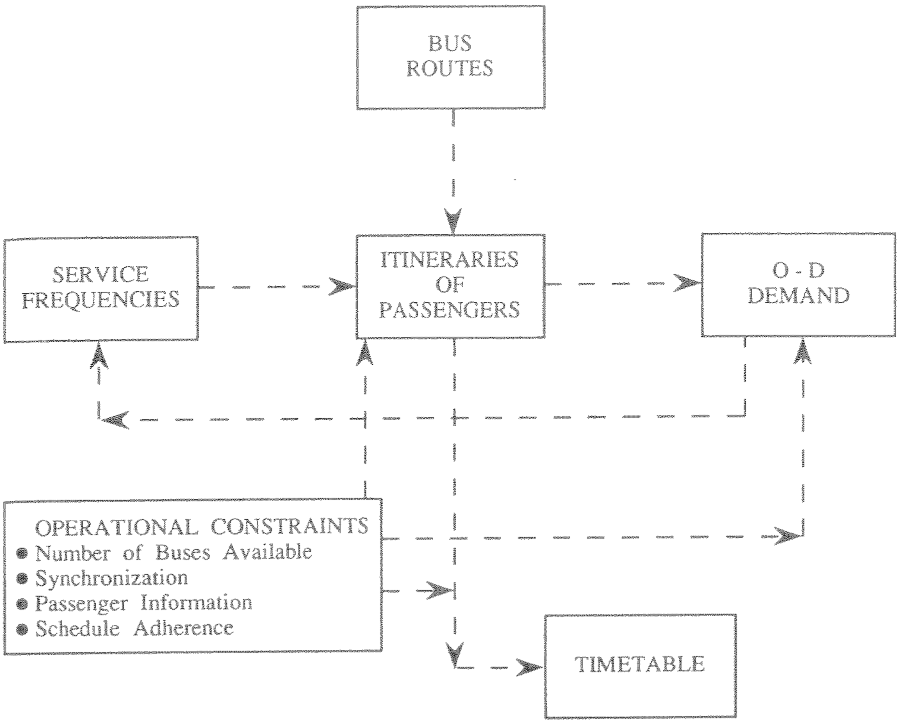
The outputs of the strategic planning process serve as inputs for the next level, the tactical planning level. For a detail study of public transport network assessment and design focused on reliability, the reader is referred to the work by Tahmasseby (2009).

### 4.3.2 Tactical planning level

This is the stage that follows the strategic planning process. At this level, the inputs of the strategic level are used to determine the details of the service plan, i.e. the timetables for passengers, vehicles and crew. Additional to the input from the strategic planning level, it is common to use historic data from the operations, particularly running times, in order to design and refine timetables. Besides service scheduling, vehicle maintenance should be scheduled as well. A large body of literature deals with the topic of scheduling, including timetable design, vehicle and crew scheduling. The focus of this work is on the design of the public timetable, scheduling activities involving vehicle and crew are not considered.

At this planning level the main actor is the operator, who normally is in charge of designing schedules. The aim is to minimize the total required resources, for a required level of service. The public transport authority normally has to approve the output. Within the operator, drivers (i.e. unions) and their regulations play a role in accepting the timetables, especially regarding trip and layover times, as well as the length of breaks and working hours. Additionally, existing user groups may also have some influence. In the figure below, the tactical planning level is illustrated with the interactions involved in the production of a public timetable.

Figure 11 Tactical planning level in public transportation planning



Source: ReVelle (1997)

In the following section, the scheduling process and the timetable-related activities are the focus. Timetable and schedule are used interchangeably throughout the document. Vehicle and crew scheduling are only briefly discussed.

### *Service scheduling process*

Public transport scheduling is the process of calculating the frequency of service, the required number of vehicles to provide that service, their travel time and a few other related operating elements. The outputs of the scheduling process include both graphical and numerical timetables for operators, supervisors and for the public (passengers). According to Boyle (2009), a schedule is “a document showing trips times at time points along a route.” These points are normally the planned stops, though this is more the case in Europe than in the United States and the rest of the world.

Scheduling is a very important element of public transport that has an impact at several levels. For the **users** of the service, a timetable provides the information needed to make a trip; it defines departure and arrival times as well as the trip duration; and also guarantees enough capacity for the passengers to be comfortable during their trip. A timetable is the promised service to the users and a vital link between the operator and its clients.

For **drivers**, a schedule defines their workday. They are in close contact with customers, and their interaction can be affected by running and layover times. Layover time is the time between the scheduled arrival and departure of a vehicle at a terminal stop/station. Good schedules, trusted by the drivers, can reduce the inherent levels of stress, improve morale and reduce absenteeism.

To public transport **operating agencies**, scheduling represents the service they offer to the users, and a benchmark to which they must comply to provide a reliable service. Additionally, scheduling provides data and information for other sectors such as marketing, planning, operations and systems such as AVL, APC, trip planners and real time information systems.

For **managers** and the **administration personnel** of an operating company, scheduling has a major impact on the quality and cost of operations. This is because the scheduling activity has a good understanding of how and where cost efficiencies can be achieved in daily operations as well as on the impacts of specific elements to the overall efficiency.

In the design stage, variable headways are sometimes used for infrequent services, or for those operating only during peak hours, which are determined by demand, cycle times, operator requirements and several other constraints. For the case of regular public transport lines, uniform headways during a given scheduled period represent the optimum operation for a number of reasons. In the first place, for random passenger arrivals, uniform headways minimize waiting times. Second, they reduce the probability of delay propagation, or bus bunching, which contributes to higher capacity and service reliability levels. The use of clock headways simplifies information and increases convenience for regular as well as for occasional users. Furthermore, repeating timing patterns for a given scheduling period (e.g. same departure minute every hour from a given stop) makes a timetable easier to remember for regular users, and resembles rail services. Readers interested in a very detailed description of the scheduling process for basic and advanced users are encouraged to see the work by Boyle (2009).

### *Components of the scheduling process*

The scheduling process can be divided into three basic phases, the input phase, the actual scheduling work, and the output phase. Figure 12 in the following page, condenses these sub processes as a flow chart.

The **input** to the scheduling process corresponds to the preparation of data required for scheduling, which includes a number of line characteristics, timetables of connecting lines, passenger volumes, service standards and considerations, vehicle characteristics, operational factors and special considerations for each line, and work rules and standards. Naturally, these data include fixed numbers (e.g. line length), data that needs periodical update (e.g. passenger volumes), as well as several characteristics and standards, which schedulers introduce during their work.

The **actual scheduling** work is the central component of the scheduling process, and in most cases it is divided into three major elements:

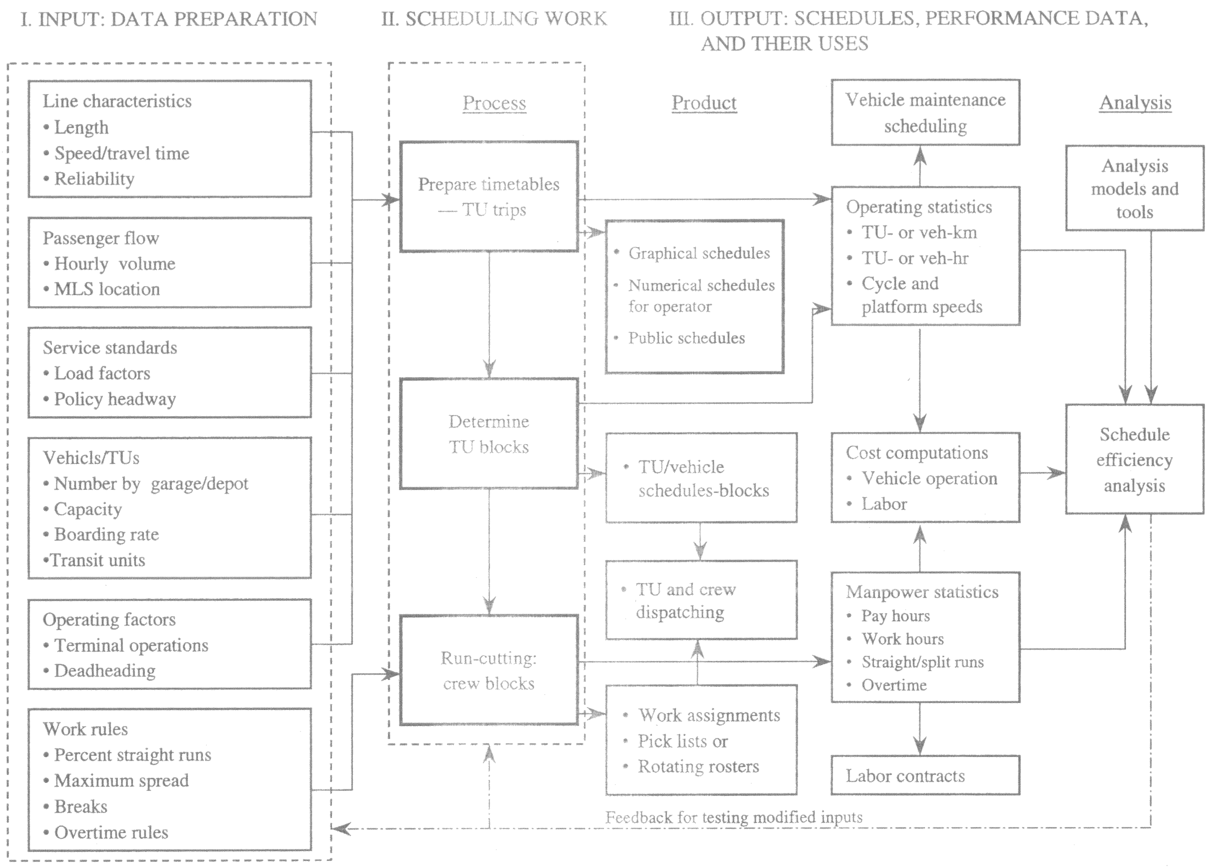
- Preparation of timetables (trip building), which determines headways, terminal times and other elements. Its outputs are graphical schedules (or string charts) and numerical schedules for operational personnel and for the public.
- Determination of blocks (block building), which assigns vehicles to all trips specified in the timetable. The outputs of this element are blocks, or work schedules for each vehicle for a day.
- Run cutting (or crew blocks), which corresponds to the assignment of work duties for each driver during the day. The outputs are work assignments that are put together into pick lists or rosters from which drivers select (or are assigned) a specific run, which can be straight, split, include overtime, etc.

The **output** of the scheduling process, in addition to the direct products (schedules, blocks, runs, etc.) consist of various performance data, such as vehicle-km, pay-hours, work-hours, etc. These data are used for cost computations, various reports on public transport operations, and of particular importance, analysis of schedule efficiency.

The process shown in Figure 12 as a sequence of steps, from the input of required information to the output of schedules and rosters, is normally quite complicated. This is due to the great number of input elements, such as policy headways, types and sizes of vehicles, load factors and many others, which allow the testing of alternate schedules and improvements in the initially developed schedule. Therefore, the entire process often has a **feedback** step, which allows the testing of possible changes in parameters and the evaluation of their impact on the final schedule. This could be called a "what-if" analysis. Such testing is common with computerized scheduling procedures because the testing of many different situations is rather easy and fast.

Actually, it often happens that the last step in the process, schedule efficiency analysis, leads to the conclusion that the solutions are not satisfactory and requires modifications in the input or scheduling process.

Figure 12 Public transport generic scheduling flow process



Source: Vuchic (2005)

### *Timetable design principles*

Any schedule of a public transport line must satisfy two **basic requirements**: it must provide **adequate capacity** for a given passenger volume, and it must offer a certain **minimum frequency of service**, or maximum acceptable headway.

During peak hours (and during all times on heavily travelled lines) the first requisite is critical: an operator must provide adequate capacity on a line, which would normally exceed the minimum frequency. During low passenger demand periods and on less demand intensive routes, if service would be based on capacity requirements, the frequency might be unacceptably low and lead to lower ridership levels. Therefore, minimum headways of e.g. 15 minutes should be adopted even if it leads to low utilization ratios.

The **basic information** needed to schedule a public transport line is the **expected volume of passengers and its distribution in distance and time**. A passenger load profile diagram displays the passenger volumes between stops along a line for a given period, including the highest volume, or maximum load section (MLS). The volume on the MLS is essential to determine the required scheduled capacity.

Outside the MLS, the average passenger volume of a line is compared to the offered line capacity (in seats and standing places per hour) to determine the basic type of service. In cases where the volume is much greater on one portion of the line than on others, it may be appropriate to operate some short-turn services or to divide the line in two (or more) branches where the volume decreases.

A temporal variation diagram, or the distribution of passenger volumes throughout the day, is useful to determine scheduling periods. These are time intervals with rather uniform travel volumes, during which a fixed schedule is operated.

Based on the temporal distribution of passenger volumes of a line, the number and duration of different scheduling periods are determined. The general procedure defined here is rather basic, and much more sophisticated analysis can (and should) be used in real practice, given the importance of scheduling for both passengers and the operator. One possibility is to determine with precision the MLS on a line for each hour by location along the line and its direction, because in some cases the MLS is not always between the two same stations. Another possibility in analysing demand is to consider detailed variations in time, because during the peak hour variations of passenger volumes are sometimes considerable. In this case, the hourly volume equivalent to the (for example) 15-minute peak volume should be used as the design volume.

Scheduling must be done for each scheduling period separately. The transitions between periods should be gradual and fitted to changes in demand. In the beginning of peak periods capacity may be increased in two ways: shortening headways or increasing the capacity (number and/or size of vehicles). A combination of the two is also possible. However, there are implications in abrupt changes in capacity, changes in frequency (less of a problem for high frequency lines) and deadheading time, in cases where fleet changes are necessary, for example from smaller to bigger buses.

The procedure for selecting vehicle size, frequency and load factor is described by Vuchic (2005). A **scheduling procedure** for a time period can be summarized in five steps, namely:

1. Prepare data and determine factors. Line length, running time, vehicle capacity, policy headway, load factor (for the MLS), design volume (in persons/hour), and minimal terminal time.
2. Calculate headway and frequency. If the computed headway is larger than 6 minutes, round it down to the nearest of the following: 6, 7.5, 10, 12, 15, 20, 30, or 60. Compare the obtained headway with the policy headway and adopt the shorter one.
3. Determine fleet size.
4. Calculate cycle and terminal times.
5. Calculate cycle speed.

As previously mentioned, the final products of the scheduling process are numerical and graphical representations of public transport line operation for the use of both the operator and the general public.

A good scheduling process should deliver schedules that are accurate, realistic, and efficient. An optimal schedule provides the adequate level of service at the minimum possible cost. It is the key to an efficient and sustainable public transport operation.

### *Schedule optimization in the literature*

A large body of literature exists on the topic of timetable design and optimization, as well as techniques that aim to improve the quality, stability and reliability of operations by improving schedule design. The reader interested in more detail is encouraged to address the literature, in particular Boyle (2009) addresses the entire scheduling process in a comprehensive and pragmatic way, presenting a number of scheduling tools, techniques and their capabilities. Chapter 9 in ReVelle (1997) presents an in depth look into the operational planning process of public transport, including system methods and algorithms to solve the scheduling problem. A textbook by Ceder (2000) deals with efficiency in timetable design and vehicle scheduling.

Moreover, a study of optimal running times is presented in Furth and Muller (2007), while different holding strategies are included in Fu and Yang (2002) as well as in van Oort, Wilson et al. (2010). Other recent works on the topic include the work by Altun and Furth (2009), where the question of ideal scheduling for signal priority is dealt with, as well as optimality conditions for public transport schedules with time point holding, by Furth and Muller (2009).

Finally, an interesting text that documents passenger responses to changes in transportation systems, is included in the work by Evans (2004).

## 4.4 Service planning state of practice in Zurich

In the following, a short summary of the strategic planning practices in Zurich is followed by a more thorough overview of the schedule design practices and considerations by Zurich's public transport operator, the Verkehrsbetriebe Zürich (VBZ). Subsequently, a summary of the operating practices taking place in Zurich is found. Some of these practices were developed in house and represent decades of daily work and experience with the network.

### 4.4.1 The strategic level

As previously mentioned, public transport in the city of Zurich is provided by the VBZ, a multimodal operator of trams, trolley buses and diesel buses of different sizes. Heavy rail commuter services throughout the Canton and in the city are provided by the Swiss Federal Railways (SBB), operated on their network, and paid for by the public transport authority, the Zürcher Verkehrsverbund (ZVV). The tram network is the backbone of the city's urban transport, with buses and trolleybuses playing a complimentary role. Currently there are 13 tramlines, 6 trolleybus, and around 60 lines of different hierarchy (including lines extending to the suburbs) operating in the city.

Zurich's mobility policy, adopted after the double rejection (by referendum) of an underground project in the 60's and 70's, focuses on providing excellent surface public transport while restricting the use of private automobiles. This institutional framework supported by Zurich's politicians and citizens, and backed with considerable investments throughout the last 40 years, has given way to one of the most dense and heavily used urban public transport networks in the world.

The planning of network changes and expansions in Zurich, i.e. new tram and trolleybus lines, is a complex process that involves many actors and several years and will not be described in detail here. To summarize the process, studies are made (usually by consultants, together with representatives of the city's engineering office, the ZVV and the VBZ) on the current weaknesses of the network, as well as on the future needs of the city, considering land development projects that will generate mobility needs. Growth potential is identified and correlated to ongoing transportation projects, such as recent extensions of the tram network, expansion in capacity on the heavy rail network, the new underground railway station, etc.

The focus of the planning, in particular for the long-term horizon, is on tram infrastructure as well as on tram and most important bus lines. Normal planning horizons for trams and trolley bus lines in Zurich are 25-30 years. Other bus lines require less infrastructure and their planning horizon is consequently shorter. The mobility strategy of the city is an important foundation for the strategic planning of public transport in Zurich. The network development should contribute to the implementation of the strategy's objectives.

The principles of the public transport network design for Zurich, according to INFRAS and VBZ (2006) are:

- Travelling in Zurich should be fast and require the least possible amount of transfers.
- Optimize the design the radial network, to provide connection of city districts to the city centre.
- Provide direct and efficient connections between future development areas.
- Optimize the network crossing city limits into important neighbouring communities.
- Increase interaction and synergies between the VBZ and the S-Bahn networks.

Once the vision and the objectives for the development of the city and of the network are in place, individual projects are developed in cooperation with a large number of actors, and evaluated from every possible technical, financial, social and environmental aspect.

Different possibilities and ideas for new tram and bus lines are already the topic of discussion years before the actual planning starts. The planning process then proposes and evaluates different alternatives, and selects those that align to the general needs and objectives on the city's public transport policy. Therefore, a comprehensive network expansion concept is developed, which needs to have a long-term focus and be market oriented, with clear priorities and implementation stages. The concept should be integrated into the expansion plans for the heavy rail network, as well as aligned with the urban settlement development.

The result is a solid proposal, which is either approved or rejected by a popular referendum. If a project is accepted by referendum, then it is adopted in the city's construction plans and given a green light for implementation.

### 4.4.2 The tactical level: scheduling and service planning

This section is mostly based on interviews done at the VBZ throughout 2010 with the head of the scheduling department, Mr. Rene Aeberhard and with Ms. Susanne Reumüller, also from the scheduling department.

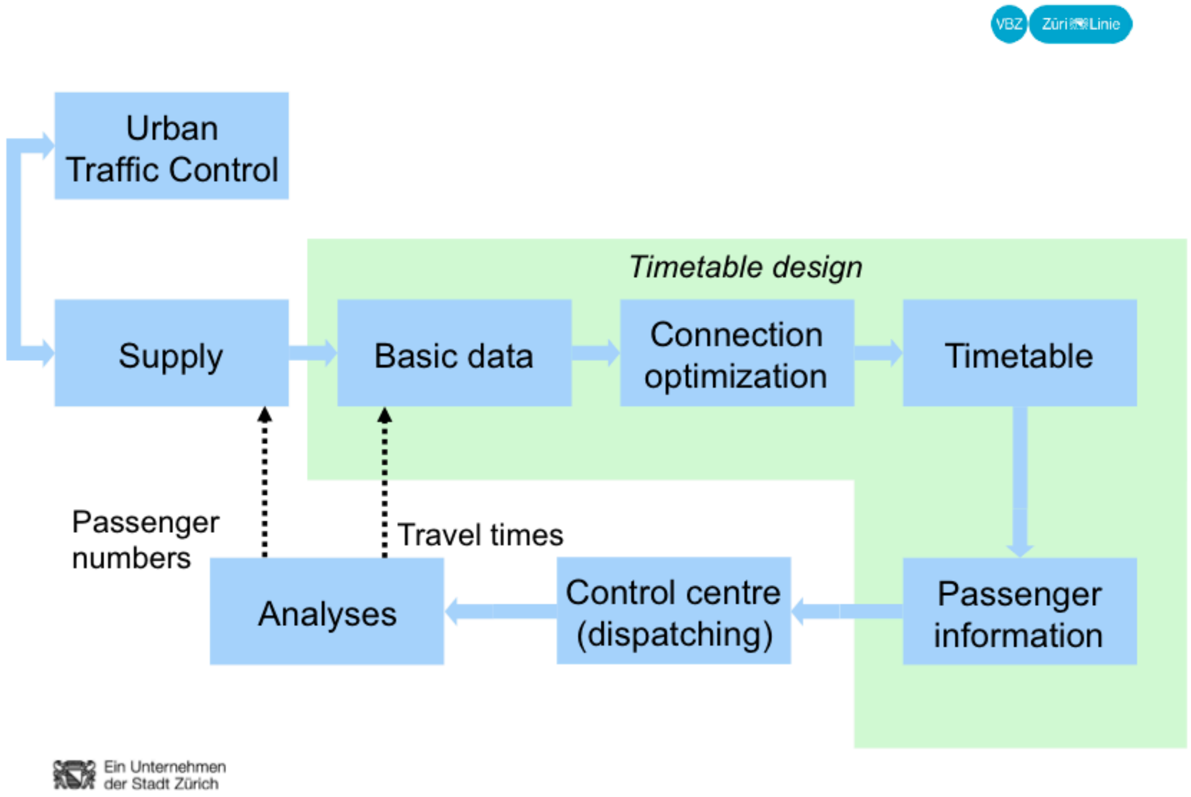
At the VBZ, the **scheduling process** is seen as the interface between planning and operations. Computers were first used for scheduling purposes at the VBZ in 1988. The currently used commercial scheduling package DIVA is used throughout the full sequence from timetable generation, vehicle scheduling and driver scheduling. However, they rely to a large extent on their own experience and have developed their own approach to scheduling. It is also worth mentioning that they are in close contact with their suppliers and collaborate in the further development of the scheduling tools and software they use.

The general scheduling process at the VBZ is shown in Figure 13, up to the level of public timetables. Vehicle and crew scheduling were not part of this project. The basic and most important **inputs** to the process are the passenger numbers (demand) and the travel time of a line. These data are then fed into a tool that optimizes connections with other lines for a given set of priorities.

The **output** is the graphical timetable, which is then adjusted by hand. The connection optimization and the scheduling process are at the core of the tactical planning process. Timetables are then used to feed dynamic passenger information systems and as a tool for the control center to supervise schedule adherence. Finally, analysis and feedback in the operations level are used to refine and adjust the timetables for the next period.

When described in general terms, the scheduling process seems simple at first sight. However, there are a great number of considerations, guidelines and details that come into play when elaborating a schedule. Moreover, the experience of the scheduling personnel plays an important role in managing the tools and the partially automatic outputs these produce. In the following lines, the different elements of the tactical planning process are described in detail.

Figure 13 General scheduling process at the VBZ



Source: VBZ

The following is a description of the process for creating a timetable for a new line. In Zurich this is not very common, as the public transport network is well developed and quite dense. However, it serves as a guideline for understanding their approach to timetable design, as well as the multiple considerations and restrictions at the different levels of the process. In practice, existing timetables are slightly adjusted and updated every year, or also modified to adopt changes due to road works affecting operations. The following process is descriptive and aims to identify the most relevant information obtained from the interviews.

### *Stop Location*

This is the first step in the scheduling process. Every stop in the network is disaggregated to the curb level, i.e. where the vehicles of each line serving that particular stop are planned to halt and allow passengers to alight and board the vehicle. A different curb is taken for each direction of travel. Each curb is then identified with coordinates (in the Swiss coordinate system) and compass direction. This is the level of precision at which the timetable is designed, which allows the scheduling department to modify timetables according to their needs, but the data assigned to the curbs, such as location, distance and travel time between them, remains as the basic data to which all timetables are designed.

In the event of a construction site affecting operations, a new (temporary) curb can be defined. Stops and their curbs can also be moved for a number of reasons, such as redesign of a public square, lack of demand, or an adequation for handicapped persons. Sometimes the lack of physical space is a problem for an optimal stop layout, especially for the case of bigger stops with several lines crossing, such as the case of Meierhofplatz. Locating stops in Zurich must comply with the policy of a stop within a 400m radius of any inhabited part of the city, as well as not exceed the distance between stops of 300m.

### *Distance calculation*

Once the stops (curbs) are located, the distance between them is estimated using a Geographical Information System (GIS) web tool, such as GIS Browser[9]; or using a measuring vehicle wherever it is possible. Once the line is operational, the distance is rectified and adjusted using historical data from the vehicles. Given that vehicles that run on rubber tires can have small variations due to drivers not always stop at exactly the same place, and GPS systems level of precision (particularly in urban areas); the tolerance for identifying when a vehicle has arrived to a station is 10 meters.

### *Travel time determination*

With the distance between stops defined, the next step is setting the travel time between stops for each direction. This can be achieved using a measuring vehicle when possible, or an average measurement from other lines. The level of precision for travel times is 0.1 minute, e.g. 0.3 minutes is equal to 18 seconds. Establishing the travel time between stops is a crucial step in creating a timetable. In Zurich, different travel time profiles are defined, based on the time of day (level of demand, traffic volumes), the time of the year (weather effects, holiday seasons) and particular events that impact demand (e.g. the beginning of the semester for local universities). The travel time profiles in Zurich are included in Table 17.

Moreover, the number of time profiles for a given line is defined by the headway. For headways of 30 and 60 minutes, only one time profile is used, for 15-minute headways two or three may be used according to the particular situation. For lines with 10-minute headway or less, three travel time profiles are used.

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[9] www.gis.zh.ch/gb4/bluevari/gb.asp

Table 17 Travel time profiles defined in Zurich

| **Traffic time Monday to Friday** | | | **Travel time profile** |
|---|---|---|---|
| Normal Traffic Time | (NVZ) | Begin of operation until 6:30 | RVZ or NVZ |
| Rush Hour Traffic | (HVZ) | 6:30 – 8:30 | HVZ or NVZ |
| Normal Traffic Time | (NVZ) | 8:30 – 16:00 | NVZ |
| Rush Hour Traffic | (HVZ) | 16:00 – 19:00 | HVZ or NVZ |
| Normal Traffic Time | (NVZ) | 19:00 – 21:00 | RVZ or NVZ |
| Low Traffic Time | (RVZ) | 21:00 until end of operation | RVZ or NVZ |

| **Traffic time Saturday** | | | **Travel time profile** |
|---|---|---|---|
| Low Traffic Time | (RVZ) | Begin of operation until at least 6:30 | RVZ or NVZ |
| Normal Traffic Time | (NVZ) | 6:30 until at least 17:00 | NVZ or RVZ |
| Normal Traffic Time | (NVZ) | 17:00 – 19:00 | RVZ or NVZ |
| Low Traffic Time | (RVZ) | 19:00 until end of operation | RVZ or NVZ |

| **Traffic time Sunday** | | | **Travel time profile** |
|---|---|---|---|
| Low Traffic Time | (RVZ) | Begin of operation until around 10:00 | RVZ or NVZ |
| Low Traffic Time | (RVZ) | 10:00 – 19:00 | RVZ or NVZ |
| Low Traffic Time | (RVZ) | 19:00 until end of operation | RVZ or NVZ |

Source: VBZ

Finally, priorities are set for setting travel times. In the urban area, the first priority is to have a regular operation for lines with headway equal or less than 7.5 minutes, and punctual operation for lines with a longer headway. The second priority is avoiding the need for any additional vehicles to be operated in the line. The third priority is the protection of transfers (or connections). Lastly, is the noticeability of the timetable, i.e. the level of ease to which the users can remember it (e.g. same departure minute every hour).

Dwell times are set according to the time profile, the type of stop (size, infrastructure availability, passenger volume), and other particular conditions, such as in Kunsthaus, where the required dwell time is only 0.3 minutes, however, the traffic light cycle at that particular point is long, and even though the bus requests priority, it does not get a green light immediately. For this reason the planned dwell time at that stop is 1 minute. All timetables of the ZVV (except for S-Bahn services) are planned in this way, from stop to stop.

Special issues with travel time arise due to road works and their impact on operations. Road works are known since at least one year before they happen. However, a timetable is design to accommodate them only 2 months before, so that possible changes or delays do not translate into additional work for the scheduling department. If the travel time due to a construction site impacts travel time only to a certain degree (approximately up to 3-4 minutes), and the duration is only a couple of months, then travel times are not adjusted in the schedule and vehicles are allowed to run late. If necessary, an additional vehicle is brought into service and buffer times at the terminal stations are lengthened. The reason behind this is that delays may not be systematic, and if travel times are adjusted, in many cases buses will have to wait 3-4 minutes to avoid going ahead of schedule, and this has a negative impact in the quality of service, which is perceived by the affected passengers. The threshold to change the travel time in the schedule is when delay reaches the length of one headway. For construction sites that will last more than 6 months, the yearly travel time (and schedule) is adjusted correspondingly.

Once a line is operational, travel times are adjusted using the historical data of the line. At that point, the median value of the travel time for the observed period and time of year is taken as the guide to adjust travel times and schedules. The VBZ recognizes that longer and less-segregated lines (from other traffic) have a higher probability to incur in delay and schedule deviations. Another factor adding to the variability of the running time is the driver behaviour. For new lines, the required time to obtain true travel times for a line is estimated at four years. This is because (especially for tram lines), drivers need time to adjust to the new line, as they are much more careful at the beginning. Another reason is the impact of the frequent construction works that take place in the city. Four years might seem like a very long time, but it is only a fraction of the planning horizon of 30 to 40 years, in the case of a trolleybus or tram line.

### *Connection optimization*

After calculating an initial travel time value between stops for the different profiles and having all the information on stop metrics, the VBZ does a “connection optimization”. This optimization process aims at increasing the connectivity of the lines, and at providing a more integrated, reliable and “seamless” travel regardless of the mode. The ultimate goal is to increase customer satisfaction, increase public transport attractiveness and generate model shift towards public transportation.

For the optimization, VBZ uses a tool within the scheduling software DIVA, called ALOG (Anschlusslogik, or connection logic in English). This tool has been developed at the VBZ in collaboration with the software supplier, and the collaboration continues in the development of new features. All operators of the ZVV have access to this tool, but only the VBZ makes use of it.

The travel time between curbs at each stop, required walking times, certain guidelines such as the headway, infrastructure restrictions, and a set of priorities, are the input to the connection optimization tool. Transfer optimization starts in Stauffacher. This station is special because four tramlines at a 7.5-minute headway are serving it, and infrastructure is limited to two tracks. Instead of having a 1.5-minute headway (plus dwell time), lines 2 and 14, as well as lines 3 and 9 are scheduled to arrive at the same time and allow passenger transfers. All other transfers in the VBZ network arise from that first planned connection at Stauffacher. Priorities for connections are planned according to the amount of passengers impacted and the available infrastructure. Busier lines have higher priority. For bus lines, planned connections become obligatory stopping stations and also act as holding points when vehicles are running early. Longer dwelling times are planned at these stations to wait for connecting passengers.

Different amounts of priorities are assigned to transfers. An internal measure of quality for a schedule is the level to which it achieves (in the planning) the different connections. If 5 connections are planned, and 4 are achieved after the optimization process, then the schedule quality is quantified at 80%.

A particular policy for transfer protection in Zurich is that a person living in any place in the city is guaranteed to have a service that will reach a train departing from the main station at 6:00 am. Similarly, any person arriving at midnight to the main train station is guaranteed a connection to any stop in the city, except for very small lines.

### *Graphical schedules*

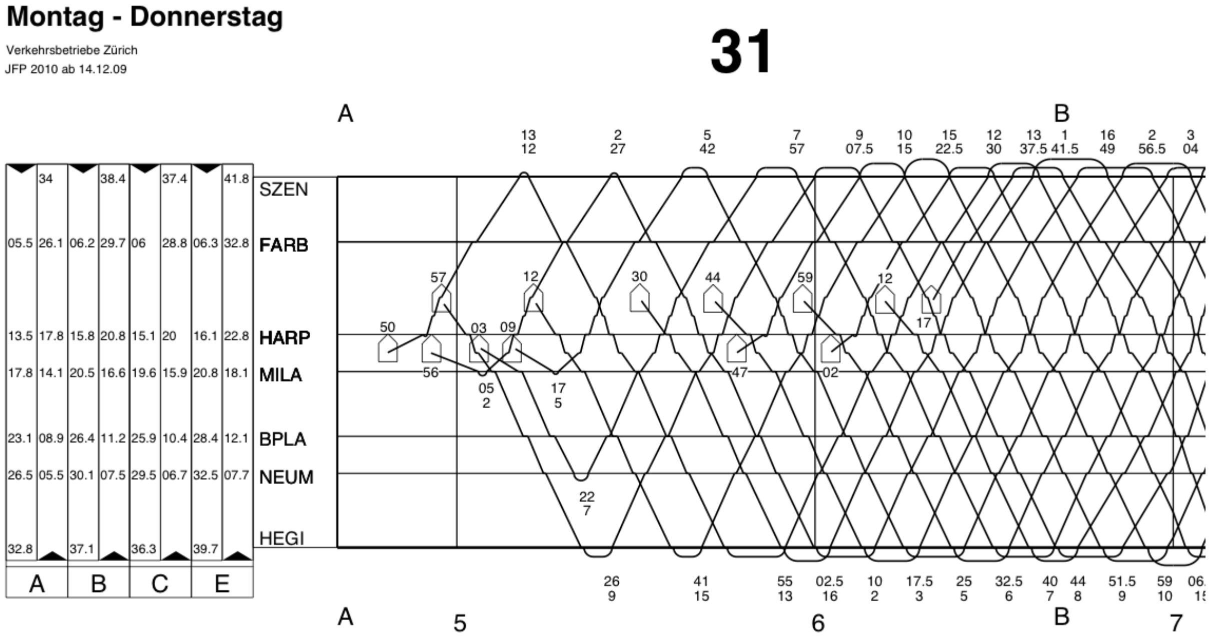
The outputs of the connection optimization tool are departing times from the terminal for each travel time period, the type of vehicle, and the pull in- and out courses. Driver union restrictions are also included. The departure times are fixed throughout the period with the corresponding headway to create raster graphical schedules, or patterns. Once these are created, they are controlled for feasibility, and smoothing is done for the headway and time period transitions. Vehicles pulling in and out of service are also edited manually.

The graphical schedules allow operating costs to be derived and budgeted. Optimizations are done where possible according to specific situations and the scheduler's experience. An example of an adjustment is the waiting time at terminals, which was agreed with drivers to be 1 minute at one terminal and 5 minutes at the other, with at least 10% of the overall travel time. This is easier for longer lines, but sometimes complicated for shorter ones. During the AM and PM peak these restrictions do not apply. Buffer times are added to some extent by the tool, the rest is done by hand according to experience and feedback from operations. A particularity case is that of vehicles pulling out of service. These do not hold to the headway after arriving for the last time to a terminal station, but depart right away to avoid unproductive time that adds up and over time represents a significant cost.

A sample of a graphical timetable for line 31 (both ways), from beginning of operations until around 7 am is shown in the Figure below.

This particular timetable is used from Monday to Thursday, as in Fridays service is provided with higher frequency in later hours of the evening compared to Monday through Thursday. On the left, the different time profiles are seen (A through E), with planned running times and scheduled running times at given stops during the run. On the right side, the different vehicles pulling in can be seen, with the minute at which they begin service. On the upper (and lower) part, the course number (integer) is displayed together with the planned departing time from the terminal station.

Figure 14 Graphical timetable sample. Line 31



Source: VBZ

## *Passenger information*

Precise schedule information is required for real time information systems, as scheduled time is compared to operations to predict next vehicle arrivals, as well as connections at the next stop, with the available time and status. Printed timetables are also published at every stop of the network. Real time information is available at mayor stops, inside every vehicle as well as on the Internet and via mobile devices.

Planned operational changes are also communicated via the passenger information system.

### *Control Centre*

The responsibilities of the control centre include supervising and managing operations, with the aim of adhering as much as possible to the schedule. It also reacts to incidents to bring operation back to normal as soon as possible, organise assistance by ambulance or police when needed, and deviate courses to minimize the effect of larger disruptions to the service.

Additionally, it manages passenger information and coordinates internal information with drivers and technical personnel.

From the planning perspective, the control centre is an essential part of the tactical planning activity and is in very close contact with the scheduling department. Both departments are in the same level of the same building and cooperation and communication takes place on a daily basis. The control centre identifies problems that occur in operations, communicates them to scheduling, and may also suggest ways to improve a timetable.

### *Evaluation, analysis and feedback*

Once a line is in operation, historical data is used to analyse its performance and provide feedback to the planning department to improve the quality of the schedules. The control centre provides summary operational statistics on a regular (monthly or more frequent if needed) basis. It also identifies problems and communicates them to the scheduling department.

Drivers are another a source of information and feedback, however planning is careful not to attend to wishes for longer breaks or such. In Zurich, many schedulers have driving experience, and they require around two years to become experienced schedulers and produce high quality timetables.

From the operational data analysis, systematic delays and problems are investigated in detail. This may include site visits and physical observation by the planning personnel. Issues such as delays with traffic lights are communicated to the DAV (Zurich’s Traffic Control department). They look for ways to reduce public transport delay without compromising the capacity of the intersection. It is a parallel and constant optimization process, taking place at different levels.

## 4.5 Planning method comparison

After describing a generic planning methodology at the strategic and tactical planning levels, a short comparison is made in this section between the generic procedure, and the way public transport service is planned in Zurich.

### 4.5.1 Strategic level

Strategic planning practices in Zurich follow to a large extent the lines of the proposed generic planning process. If anything, the planning process in Zurich is more complex, given the many actors, institutions, restrictions, and considerations, added to the requirement by the citizens to approve a project of the magnitude that infrastructure development normally requires. The planning process in both cases identifies current and future needs, and develops individual projects that are compatible with the general transportation and spatial development policies in place. Infrastructure projects should help the city reach the strategic objectives outlined in its transportation master plan.

Planning horizons in both methods are similar, though in Zurich long-term planning tends to be at least 30 years for public transport lines requiring significant investments in infrastructure, such as new tram and trolleybus lines and extensions.

The most important actors at this planning level are the operator (VBZ), the city's civil engineering office, or Tiefbauamt Zürich (TAZ), and a number of private engineering firms and consultants that develop the market studies, technical projects, and the different array of evaluations for these projects.

### 4.5.2 Tactical level

The tactical planning level is the focus of this study, and as such, was the level at which most information was gathered and compiled.

The generic tactical planning process described the steps for creating timetables, and this process was later the subject of analysis at the VBZ. The steps will not be repeated here, and the focus will be on the similarities and differences between the two methodologies.

In general, the VBZ follows a classic approach to service planning in the tactical level: it uses input data from stop location to determine running times. This is done for different times of day and periods of the year, to consider changes in demand, traffic volume and weather.

Differences observed between the generic process and the VBZ planning process at this level are the following:

- The level of precision for defining and identifying vehicle stopping points, in particular for larger stations, is very high at the VBZ. However, a tolerance of 10 meters is provided for GPS localization.

- The distance between stops is rectified and adjusted once vehicles start operations. Again, precision is a goal in all stages of planning.

- The level of adaptability to planned construction sites that impact line operation (for defining new, temporary stopping points when required) is quite developed and part of their daily business. Road works and construction is a constant activity throughout the city, and coordination with other city offices allows the VBZ to plan and be prepared for these disruptions.

- Policy (minimum) level of service (required by the ZVV) and vehicle capacity determines the required number of vehicles, instead of number of vehicles being a restriction. Cost reduction is an important issue, and the VBZ understands that the potential to operate more vehicles is limited in their dense network. A shift towards higher capacity vehicles is observed.

- A clear policy and priorities are in place to determine the number and type of travel time profiles for a given line. The main parameters are the type of service, the headway, time of day, and day of the week.

- A headway policy, or "families of headway" is in place at the design stage in Zurich. These are used as an input in the schedule creation process and are not an output. This allows the VBZ to improve the quality of their connections.

- Dwell times at stops are correlated to the travel time profiles. They vary depending on the type and size of stop, the planned connections at the stop, and the available infrastructure for a vehicle to wait (without obstructing other vehicles). Particular situations that may increase planned dwell time at certain intersections, such as traffic light cycles times, are also contemplated.

At the VBZ the level of precision throughout the tactical planning stage is high. Schedulers have a good knowledge of the network and understand its many particularities, as many of them drive buses and trams on a regular basis. This situation increases the quality of the planning and avoids mistakes. The size of the city is definitely an advantage, as this level of precision for a large metropolis with a multimodal public transport network is hard to imagine.

Once the running times of each line are known between each stopping point for the defined time periods, a connection optimization process takes place. The generic planning process proposes a measure of synchronization for schedules, however in Zurich this is a crucial step in timetable design. It is considered to be a key element of developing efficient, high quality schedules that are passenger-oriented and comply with policy guidelines.

The most interesting features of the connection protection process are:

- The starting point of all connections is Stauffacher. Restricted infrastructure availability for the number of lines serving it is the reason. All connections originate from there.
- A list of priorities for the connections is defined, at the top are those connections that must take place at busy stations where large number of passengers transfer. Down the list are important connections and at the end, good-to-have type of connections.
- The quality of a schedule is defined as the share of achieved connections from the list of priorities (in the planning, in operations this share is lower due to variations).
- One particular policy that integrates the network and increases the quality of service is the guarantee that a person can reach a train departing from the main station at 6:00 no matter where that person lives in the city. Similarly, a person arriving at the main station at midnight has the guarantee that he or she will be able to get back home using public transportation.

Subsequent to the running time determination and the connection optimization process, graphical schedules are produced for each line, day and time period following the lines of the generic planning process using a software package.

Agreed resting times with driver unions, headways and other input data serves to create a consistent timetable. In Zurich a high level of importance is given to clock face schedules, i.e. vehicle departures from a stop at the same minute past the hour, for a period of the day. This feature makes the schedule easier to memorize for frequent users, and increases the attractiveness of the service. This practice is more common in European cities than in other parts of the world.

Finally, graphical headways are smoothed out by hand and vehicles pulling in and out of service are inserted by hand. At every stage of the process the experience of the scheduler has an impact on the final result. In Zurich it is clear that no software can replace an experienced scheduler, as automation only reduces the repetitive tasks, it does not solve the underlying problems, considers particular situations, or produce an optimal schedule from scratch. However, scheduling software allows for the testing of different alternatives to be much easier.

Something that remains to be defined is the efficiency in the allocation of buffer times in schedules by the personnel. As connection optimization specifies holding points per se, part of the time is allocated there. However in Zurich the rest of the time is allocated by experience. It remains to be researched if more scientific methods can optimize this allocation.

## 4.6 Summary

The objective of this chapter was first, to relate public transport planning to the greater objective of urban transportation planning; second, to describe a generic planning process for public transport; and third, to describe current public transport planning practices in Zurich. At a later stage the two planning processes were compared, whereby similarities and differences were identified.

It can be said that in general terms Zurich follows the lines of a generic planning process as described in the literature. However, the level of precision at the different steps is likely higher. The objective of this precision is to achieve efficient and optimal schedules for the public, but also for the operators. Efficient and precise schedules can optimize the use of resources and this is very clear for the VBZ.

Another important difference of the planning processes is that in Zurich, a very high degree of importance is placed on connections, and the degree to which they are achieved. The objective of this policy is to provide an integrated service, where the required connections represent a lower burden on the users and at the same time increase the attractiveness of service.

The VBZ relies to a large extent in the experience of their scheduling personnel, and scheduling software is used to optimize schedules, try new approaches, and reduce the effort required to repeat tasks. Computers have been used for this purpose in Zurich only since 1988, and the current tools are designed, tested and developed together with the software provider through a close working relationship over a long period of time.

Finally, the evaluation and feedback from the operations department is used to optimize and improve timetables for the next period (normally one year). Feedback comes from the control centre, from vehicle drivers, and from a series of statistical analysis on historical data.

# 5 Public transport service delivery analysis

## 5.1 Chapter overview

This chapter quantifies public transport service reliability in Zurich using off-line operational data, including Automatic Vehicle Location (AVL) data. The first section describes the selected case study, Bus Line 31 in Zurich. This bus line was selected because it is one of the most important bus lines in the city, crossing it diametrically and serving many different parts of the city. It also transports a large number of passengers, more than some tram lines in Zurich.

In the following sections, the aggregate and disaggregate data made available for this study is described. Subsequent sections show the results of detailed travel time, speed, punctuality and regularity analysis, together with reliability oriented performance measures. These correspond to operator-oriented measures. An analysis of passenger-oriented measures of reliability focusing on different measures of waiting time closes the chapter.

## 5.2 Line 31 characterization

Line 31 is one of six trolley-bus lines currently providing service in Zurich. It is operated by the Verkehrsbetriebe Zurich (VBZ), which is the responsible transport company for the area around and including the City of Zurich. Line 31 runs from Schlieren train station (SZEN) in the neighboring community of Schlieren, west of Zurich, to Hegibachplatz (HEGI) in the south east of Zurich (Figure 15). It crosses the city serving important stations along its way, such as the terminal of Tram Line 2, Farbhof (FARB), the busy train station Altstetten (BALT), a large shopping mall, Letzipark (LETP), the densely populated area around Kanonengasse (KANO), Zurich main train station (BPLA), and the busy tram node, Central (CENT).

Line 31 runs along 10.9 Km, with an average distance between stops of 415 m. It provides service every day of the week, from 5:12 to 1:00, with a frequency of 8 vehicles per hour (7.5- minute headway) all day long until around 20:00, when headway increases to 10 minutes. Service headway during the weekend is 10 minutes until 10:00, after 20:00, and all Sunday. A total of 27 stops are served by Line 31, transporting around 20'000 passengers every working day[10]. Since 2008, service is provided using 25-m double articulated, electric vehicles (see Figure 16). The vehicles are 100% low-floor, air-conditioned, with 60 seats, 5 doors and a technical capacity of 202 passengers (4 persons /m2). These vehicles were introduced due to capacity problems with single-articulated vehicles that were reaching their service life. An internal study at the

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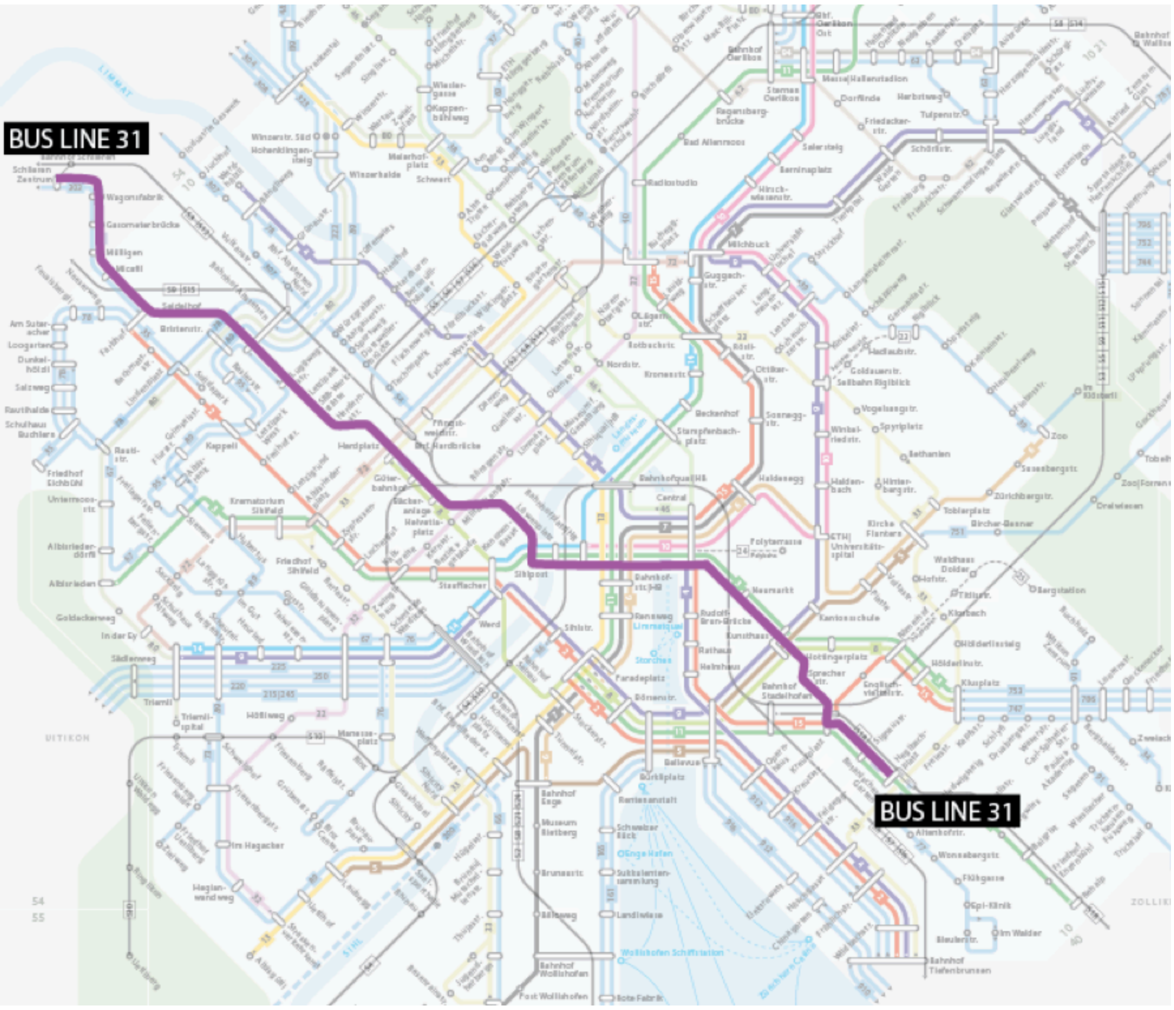
[10] In 2009. Source: VBZ.

VBZ was undertaken in which current and expected passenger growth trends were evaluated in two scenarios: higher vehicle frequency or higher-capacity vehicles. Results clearly favoured the use of larger vehicles, which are more cost-effective and provide a higher level of service.[11]

Figure 15 Topological map of Zurich's public transport network. Line 31 highlighted



Source: modified from www.zvv.ch

Most passenger activity along Line 31 takes place in the stations Farbhof, Altstetten, Letzipark, Hardplatz, Militär-/Langstrasse and the stops just before, at, and after Zurich main train station (Bahnhofplatz/HB), as seen in Figure 17.

Zurich has been a pioneer in vehicle detection technology and traffic control management since its citizens voted against the construction of an underground subway in the early 70's, and the City invested heavily in improving the quality of public transport. For a comprehensive review from the planning and technical perspective, see Nash (2003) and Furth (2005).

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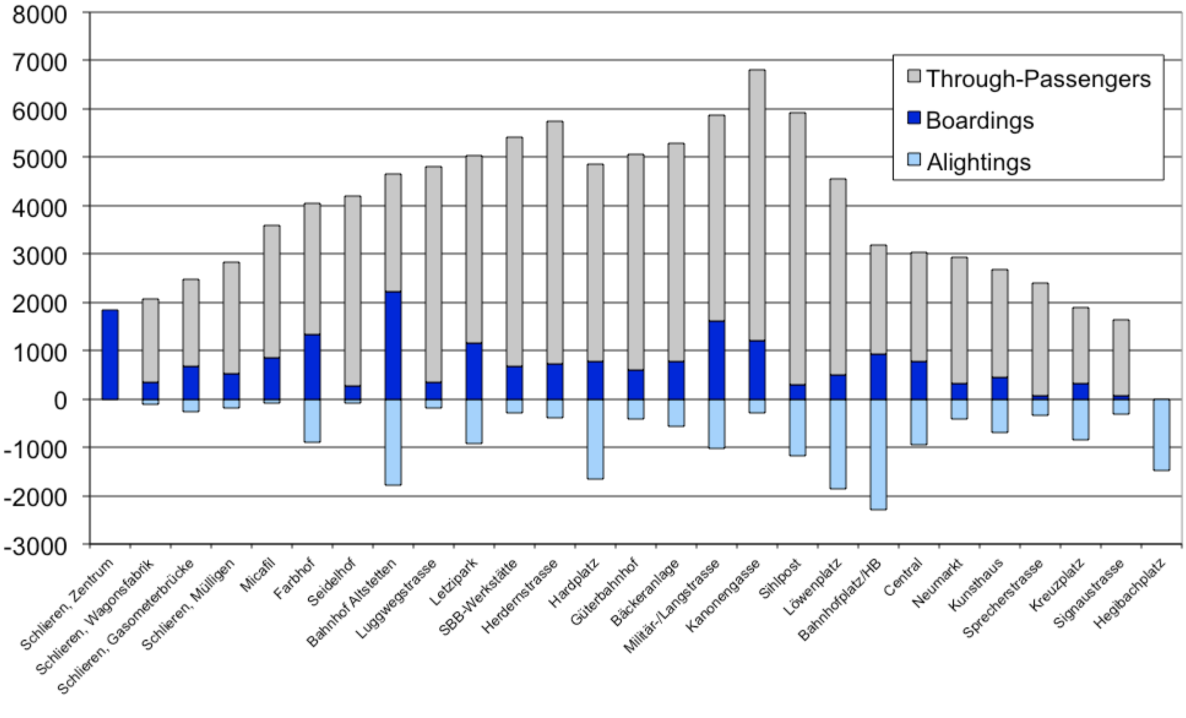
[11] Source: internal, unpublished VBZ report.

Figure 16 Double articulated trolley buses providing service in Line 31

Source: Verkehrsbetriebe Zurich (VBZ)

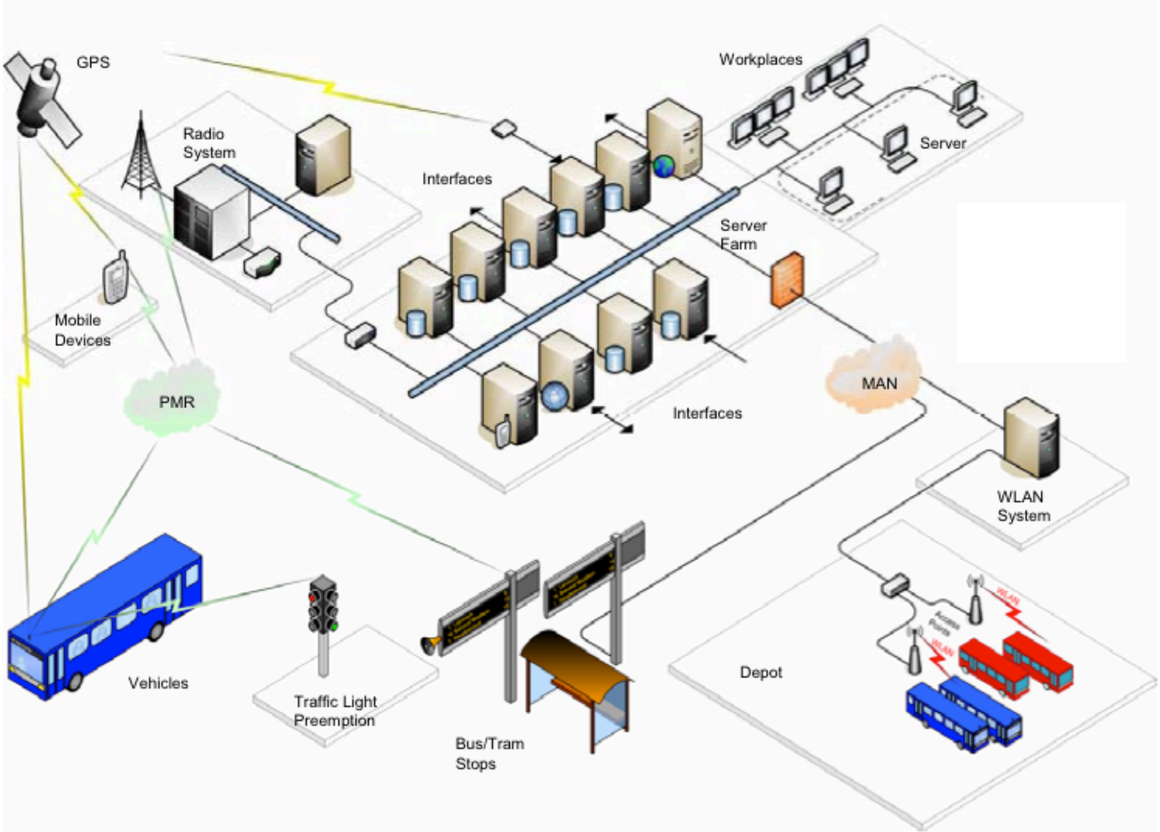
Figure 17 Average daily passenger distribution (Mon - Thu) 2009. Line 31 eastbound



Source: VBZ

Since around 2006, a new Automatic Vehicle Location (AVL) system has been deployed, involving all the operators providing services in the greater Zurich region and regulated by the transport authority, the Zürcher Verkehrsverbund (ZVV). See Figure 18. The project involved not only real-time location and communication technology linked to a modern control centre, but also high-quality information for passengers and the subsequent collection of large amounts of operational data of high value for off-line analysis and planning.

Figure 18 Schematic AVL system architecture in Zurich



Source: Trapeze ITS

## 5.3 Service reliability characterization

This section starts with the description of a first set of non-representative observations that was done prior to the representative data acquisition, together with some initial, mostly qualitative results. The description of the data that was available for this study follows, together with the data inputs and output calculation.

Next, the different service reliability analyses are presented, i.e. speed, travel time, schedule adherence (punctuality), headway (regularity) and passenger waiting time. These analyses include descriptive statistics at the route and stop level for most measures, together with the calculation of service reliability measures summarized from the literature and included in section 3.4.2. They have the aim of providing quantitative measures of reliability from a number of perspectives.

The section closes with a summary of the results obtained for each of the service reliability measures. The methodology and criteria for the analysis is based on work by Cham (2006).

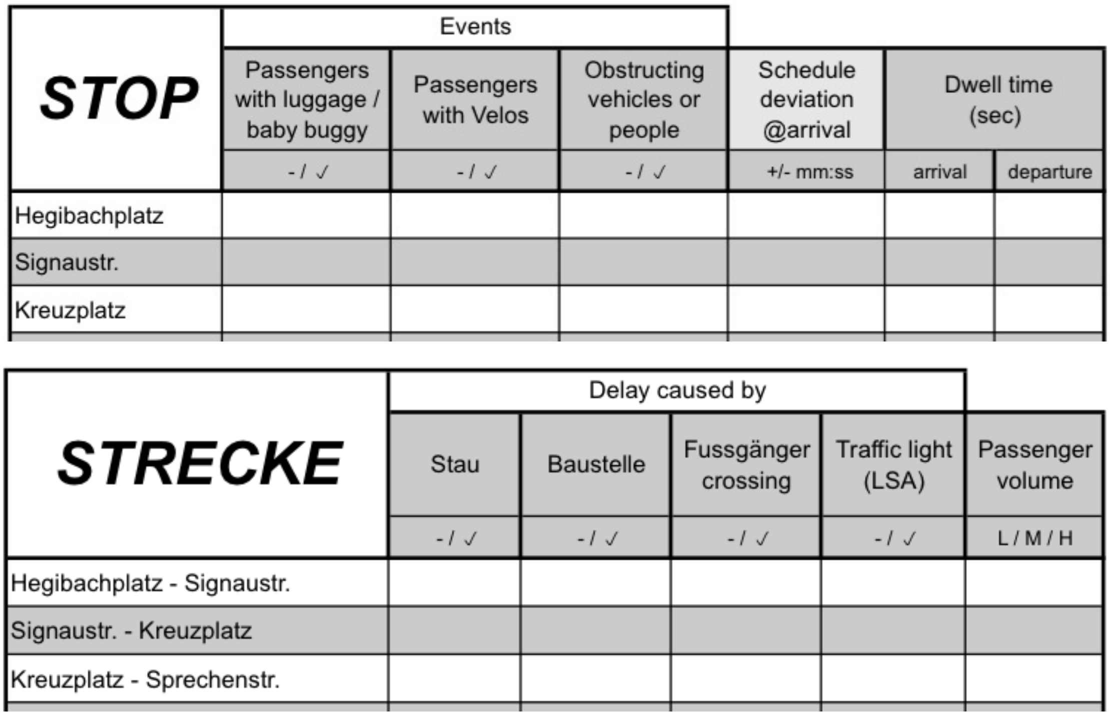
### 5.3.1 Initial observations and first insights

Given that the AVL data acquisition took place on the course of the project, a first set of observations was done to get an insight into the behaviour and characteristics of Line 31. This sample of 19 observations is not statistically representative, and rather had the aim of recording events that were perceived as to cause delay both at, and between stops. The observations took place on Monday 12th and Wednesday 14th of April 2010, during the morning and afternoon peak periods (7:00-8:30 and 16:30-18:00).

To register the observations, five persons boarded a Line 31 vehicle in different parts of the city at the same time, for 90 minutes (a complete cycle). Observers were distributed as to cover every second vehicle in service. They stood next to the driver and observed both the events taking place at and between stops, as well as passenger activity. Additionally, they registered the arrival and departure time at each stop, as well as the schedule deviation directly from the driver's display. A sample of the format used is shown in Figure 19.

Events recorded between stops were: congestion (Stau), construction site (Baustelle), pedestrian (Fussgänger) crossings, and traffic lights. During the observation period, road works were taking place between the stops Militär-/Langstrasse and Sihlpost, which are clearly visible in the results.

Figure 19 Form used to register observations at stops and between them (Strecke)



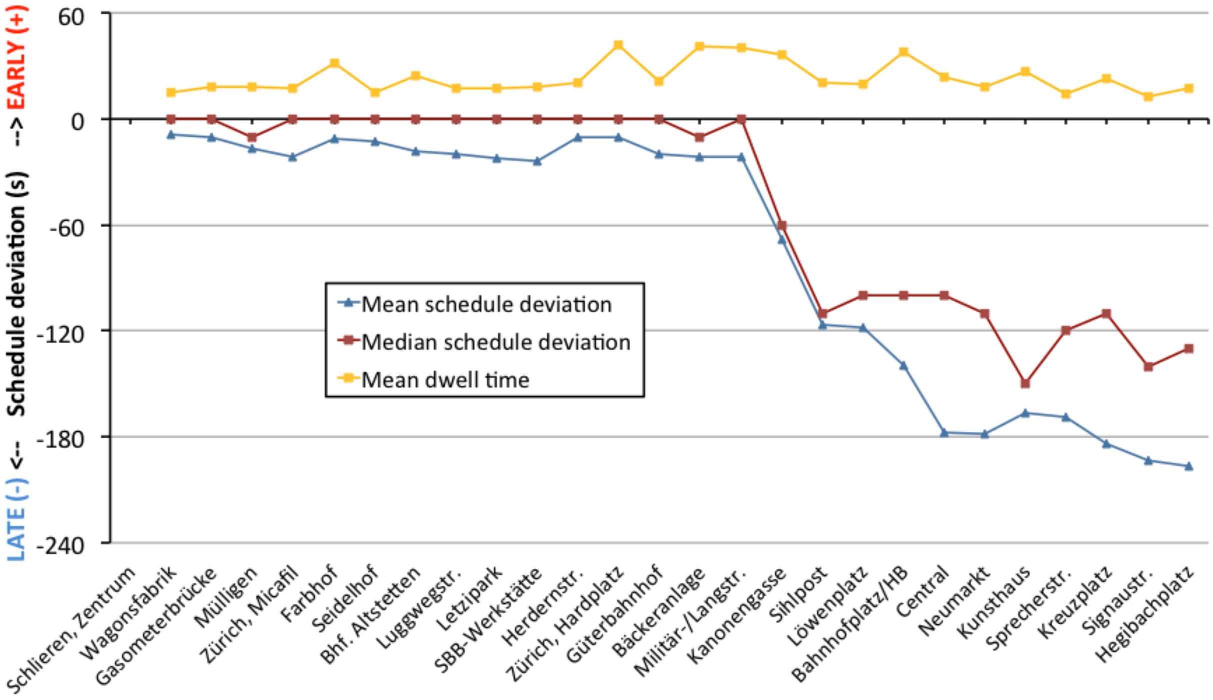
| | | | | | | |
|---|---|---|---|---|---|---|
| **STOP** | Events | | | | | |
| | Passengers with luggage / baby buggy | Passengers with Velos | Obstructing vehicles or people | Schedule deviation @arrival | Dwell time (sec) | |
| | - / ✓ | - / ✓ | - / ✓ | +/- mm:ss | arrival | departure |
| Hegibachplatz | | | | | | |
| Signaustr. | | | | | | |
| Kreuzplatz | | | | | | |

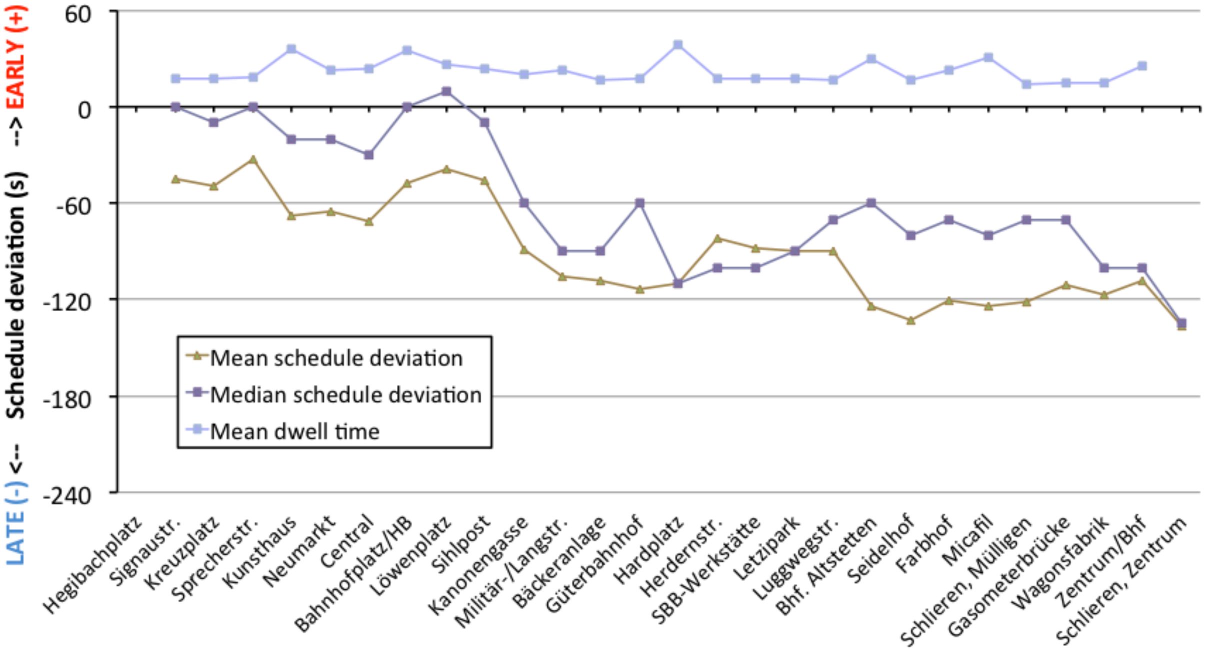
| | | | | | |
|---|---|---|---|---|---|
| **STRECKE** | Delay caused by | | | | |
| | Stau | Baustelle | Fussgänger crossing | Traffic light (LSA) | Passenger volume |
| | - / ✓ | - / ✓ | - / ✓ | - / ✓ | L / M / H |
| Hegibachplatz - Signaustr. | | | | | |
| Signaustr. - Kreuzplatz | | | | | |
| Kreuzplatz - Sprechenstr. | | | | | |

The results of these first observations revealed a first (though rather subjective) picture of the performance on Line 31. Dwell times were determined from arrival and departure time, while simple mean and median values were calculated for the set of observations. Figure 20 summarizes schedule deviation at the stop level for all observations. The upper figure corresponds to eastbound trips, the lower to westbound trips.

The impact of road works in the results is clearly visible in Figure 20, in particular for eastbound trips. Stops where dwell times were consistently higher include Farbhof, Bahnhof Altstetten, Hardplatz and Hauptbahnhof for both directions, as well as Kusthaus for westbound trips. For the observed eastbound trips at the stop level, mean schedule adherence is remarkably good (below 30 seconds late) until the point where roadwork begins. At this point, a systematic delay can be observed, leading to up to 2 minutes of delay that is not recovered in the rest of the run.

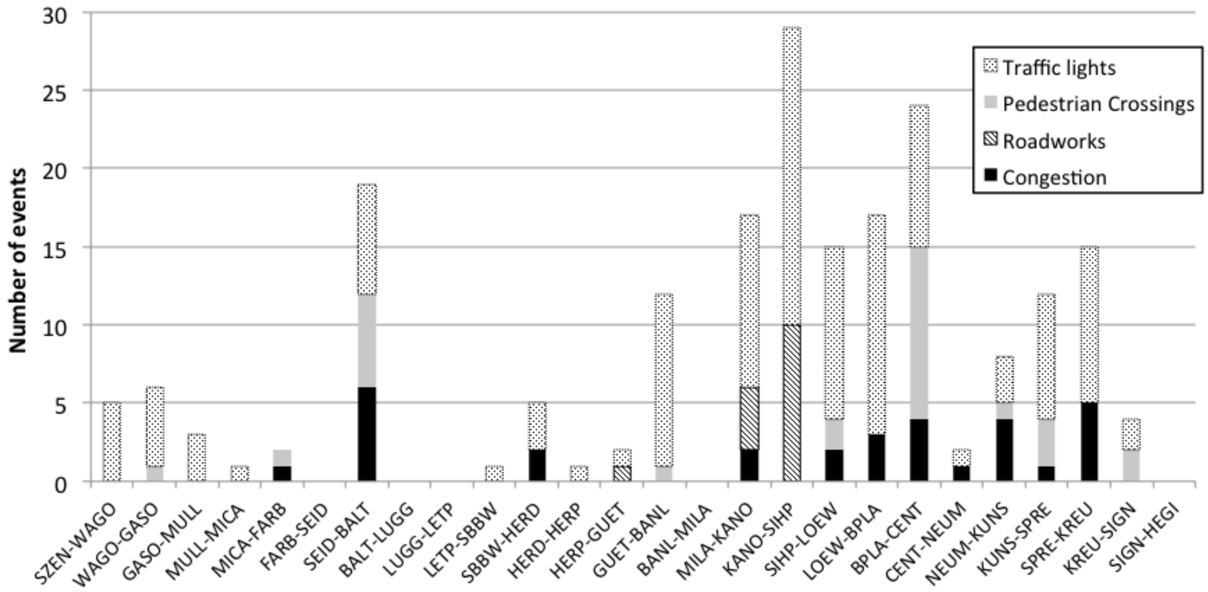
Figure 20 Schedule deviation for all observed trips. East (up) and Westbound trips





Between stops, all events that were perceived as contributing to delay along the line were aggregated in Figure 21. The influence of congestion and pedestrian crossings can be clearly seen as vehicles approach Altstetten train station, even though they are not reflected in the schedule deviation summary. It is assumed that these systematic delays are dealt with by adjusting the running time in the schedule, or by adding buffer time for the section.

Figure 21 Perceived delay-causing events between stops. All observations.



Construction works are also clearly visible in the section mentioned before, as well as delays due to pedestrian crossings around Central. Surprisingly, even though Line 31 has priority at all traffic lights, these were perceived to be a consistent source of delay more or less along the entire line, especially closer to the city centre, where a total of 9 traffic light signals are present.

This section has provided an overview of the available data for this study, and a first impression of performance using a small sample of subjective observations.

### 5.3.2 Data availability and description

The statistically representative operational data made available by the VBZ consists of two main data sets: the first set is a series of spread sheets containing aggregate information on speed and running time during working days (Monday to Friday) in March of 2011. Summary statistics on speed and travel time (mean, median, std. deviation, 5, 16, 84 and 95 percentile values, min, max) were available for Line 31, with an aggregate summary record every 25 meters.

The second dataset corresponds to stop-level data in the form of a relational database (RDB) for all records of February 2011. All VBZ vehicles are equipped with AVL equipment, which has clear advantages for their real-time supervision and control tasks, but also for the off-line analysis of data, as extreme values are captured. A specific example is the possibility to calculate the share of trips on a route running earlier or later than a given threshold, another is the possibility to use the $87^{th}$ or $95^{th}$ percentile of the running time distribution, as all trips are recorded.

For Line 31, this data availability translated into a total of 226,448 records. However, the period of study was limited to trips during working days (Monday to Friday) in the eastbound direction of travel, i.e. from Schlieren Zentrum (SZEN) to Hegibachplatz (HEGI). This left a total of 84,214 records.

Furthermore, four 90-minute time profiles were selected for the analysis, which is the approximate duration of a cycle (return trip). Only complete trips taking place during these time periods were included. The selected time periods were operated using the same number of vehicles throughout. Table 18 summarizes data availability for each time period.

Table 18 Selected time profiles and number of observations. Line 31

| Time period | Profile name | Number of records |
|---|---|---|
| 7:00 – 8:30 | AM Peak | 6125 |
| 9:30 – 11:00 | Between Peaks | 6181 |
| 16:30 – 18:00 | PM Peak | 6130 |
| 21:00 – 22:30 | Late Night | 4560 |

Disaggregate passenger activity data in the form of automated passenger counters (APC) were not available for this study, and only aggregate data summaries were available. Around 10% of the fleet in any particular route of the VBZ is equipped with APC; however, these data are stored in a different platform than the AVL data, and the two platforms are not yet integrated into one single database.

### *Data Inputs*

From the available AVL records, two main types of data were used in the analysis: Trip specific, and Time-point specific variables. As previously mentioned, passenger activity (boardings, alightings, etc.), as well as vehicle variables (speed, mileage, failures, alarms, etc.) were not available.

Table 19 provides an overview and short description of the main variables (data inputs) used in the analysis. These variables were pre-processed from the original raw data to eliminate double records and such before being delivered to the RDB.

Table 19 Main variables of interest included in the AVL data

| Data group | Description | Data Item | Type |
|---|---|---|---|
| Trip | Identifiers for specific trip | [Date] | Calendar day of planned arrival |
| | | [Service_Date] | Operational day of scheduled trip |
| | | [Day_Type_Id] | Day type identifier |
| | | [Route_Id] | Route identifier |
| | | [Trip_Id] | Trip identifier |
| | | [Block_Id] | Block identifier |
| | | [Pattern_Id] | Sequence of stops for a trip |
| Time Point | Attributes of time-at-location records | [Id] | Primary record key |
| | | [Direction] | Direction of vehicle (1 or 2) |
| | | [Stop_Id] | Stop identifier |
| | | [Stop_Seq_No] | Sequence of stop in pattern |
| | | [Planned_Arrival] | Planned arrival at stop in seconds after midnight |
| | | [Planned_Departure] | Planned departure from stop in seconds after midnight |
| | | [Actual_Arrival] | Recorded arrival at stop in seconds after midnight |
| | | [Actual_Departure] | Recorded departure from stop in seconds after midnight |

### *Service measures*

Using the time-at-location data records described above, service attributes such as actual running times and schedule deviations (among many others) were computed and used to calculate the service reliability measures described in section 3.4.2 and summarized in Table 9 and Table 10.

As previously mentioned, service measures are the set of aggregate metrics used to characterize overall service, measure performance and evaluate service delivery. They are needed to compare the promised and actual level of service, therefore characterizing public transport service reliability.

The service reliability measures included in this work are used to identify reliability problems along Line 31, understand the causes of these problems, and provide an insight into the possible measures to improve service reliability where problems occur. They were calculated at the stop and route level for each of the four time profiles defined in Table 18.

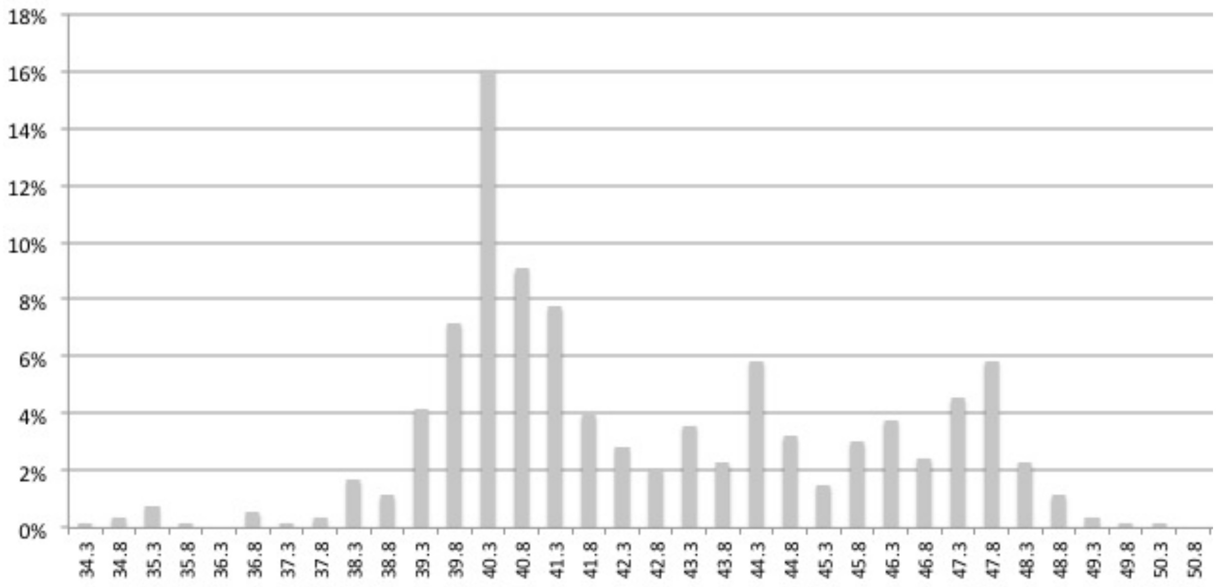
## 5.4 Performance analysis and reporting

In this section, the service reliability measures described in section 3.4.2 and summarized in Table 9 and Table 10 are presented and discussed. The first part of the analysis refers to operator-related measures and focuses on travel time, speed, punctuality and regularity. The second part deals with user-oriented measures, particularly waiting times.

### 5.4.1 Travel time

In a first step, all-day aggregate data from the spreadsheets mentioned in section 5.3.2 was used to analyse travel time reliability along the line. The figure below depicts the frequency distribution of travel time for all working days in March 2011. Three peaks can be observed, around 40, 44, and 47 minutes. The shape of the distribution reflects the different travel time experienced by users at different times during the day.

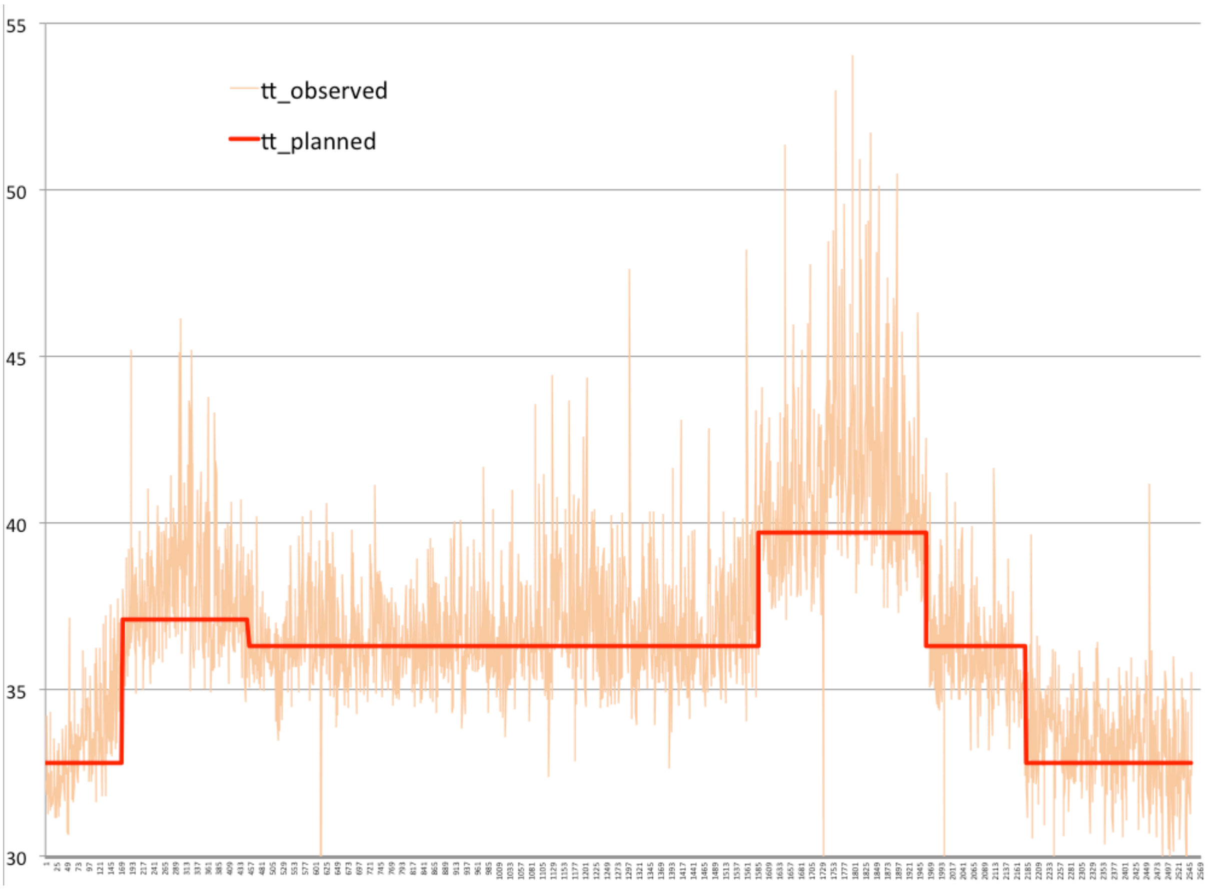
Figure 22 Travel time distribution in minutes for all trips (Mon-Fri) of 03.2011



Source: VBZ (aggregate data set)

Aggregate data can already provide a picture of the travel time along Line 31; however, a much richer level of detail can be achieved using AVL data already at the route level. Figure 23 shows the running time (y axis) for all trips that took place in working days of February 2011, from early morning to late evening (x axis), for eastbound trips.

Figure 23 Travel time distribution in minutes (y) throughout the day (x) for all trips

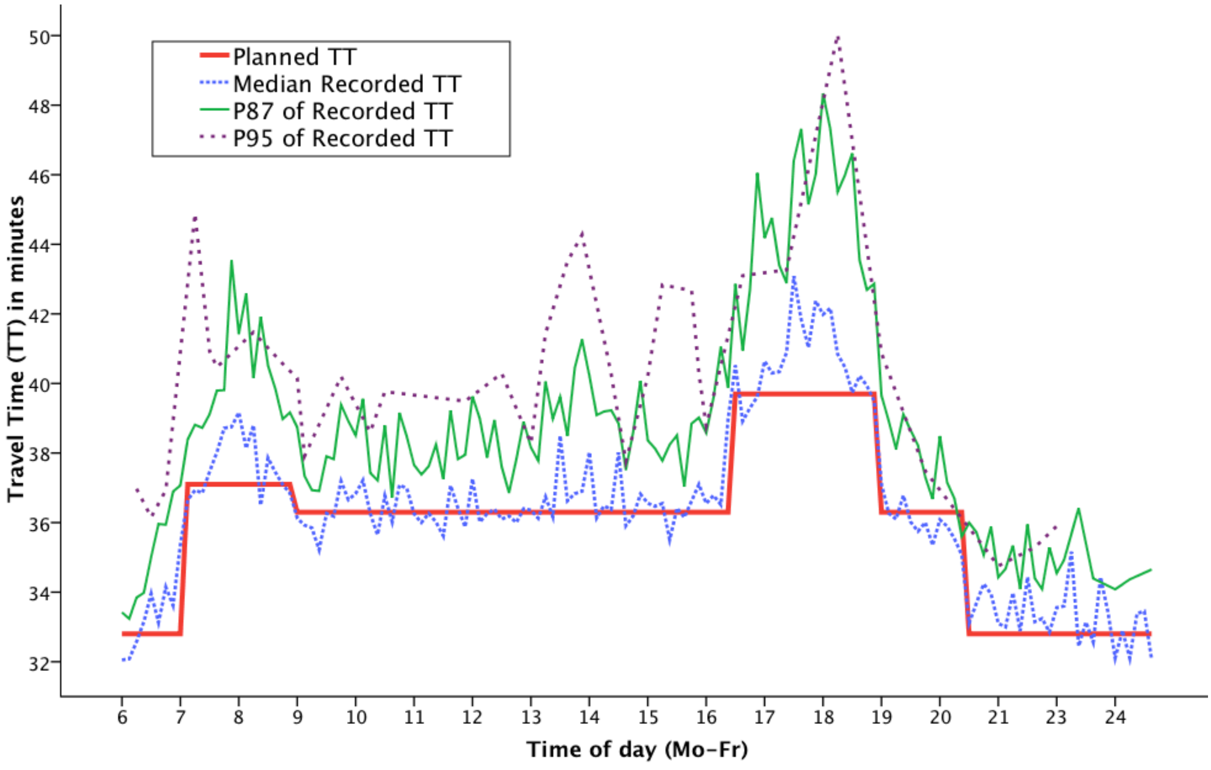


The figure above is a working draft including all data; nevertheless it already provides a much richer description of the actual vehicle travel time than the aggregate data. Note that the thick line corresponds to the planned travel time, which changes throughout the day to reflect changes in demand and traffic conditions. In Figure 22 only the actual travel time is retained in the record, whereas the data displayed in Figure 23 allows for detailed statistical analysis, in different periods of time and different times of day.

A more explanatory graph using the same data can be found in the next page. It compares the planned travel time with the median, 87th and 95th percentile distributions of recorded vehicle travel time during the working days (Monday to Friday) of February 2011. Planned running time adjusts fairly well to the median travel time throughout the day, except during the AM and PM peak hours.

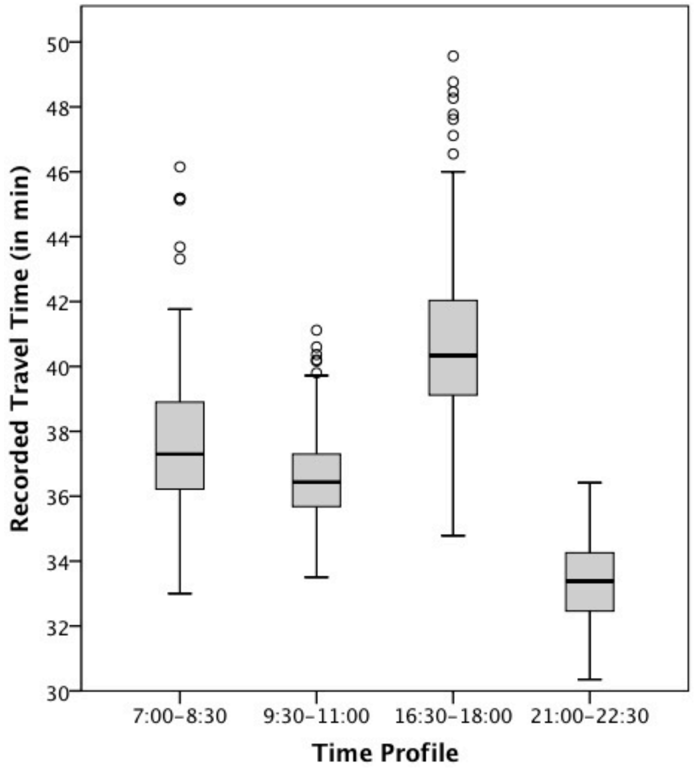
From Figure 24 it is clear that the planned travel time is roughly adjusted to the median of actual travel time, which means that roughly 50% of all trips will achieve their scheduled running time (though this is independent of any recovery, or break time planned at the end stop, which is needed to guarantee an on-time departure for the following trip, and is not considered in the analysis). From Table 20 it is clear that for all time profiles, the planned travel time is (marginally) lower than the median of the observed runs. During the morning and especially in the afternoon peak period the situation is more dramatic due to more extreme values in the distribution. A solution would be to increase the planned travel time, particularly during rush hours. An increment of 1 to 2 minutes would allow a larger proportion of trips to achieve their planned travel time. The impact of this change on the number of vehicles required to provide service (with the corresponding increase in operational costs for the operator) were not investigated.

Figure 24 Travel time distribution for all trips (Mon-Fri) in 02.2011, Line 31



Another graphical description of the data can be found in the following Figure. It illustrates the degree of dispersion and skewness of the data for the four time profiles defined in Table 18. Assuming normal distributions, 50% of the observations are contained in the boxes, while more than 99% of the observations are contained between the whiskers. Peak time profiles display more variation, as well as more skewness toward longer travel times, and more outliers.

Figure 25 Route-level travel time box-plot distribution by time profile, Line 31



Descriptive travel time statistics grouped per profile for all working days of February 2011 are summarized in Table 20.

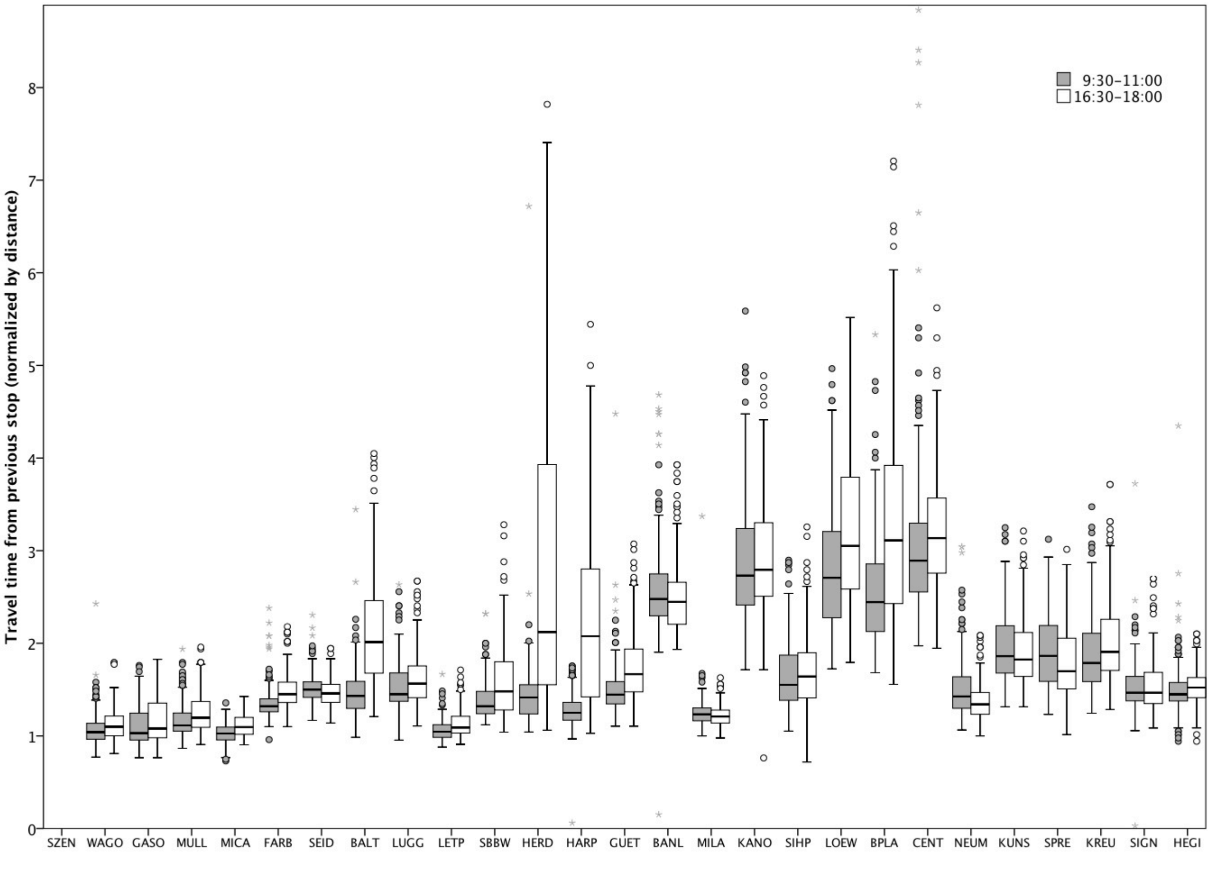
Table 20 Travel time summary statistics per time profile. Line 31 (in min)

| Time | Planned | Mean | Median | Std. Dev. | Max. | Min. | Perc. 25 | Perc. 75 | Perc. 95 |
|---|---|---|---|---|---|---|---|---|---|
| **$7^{00}$–$8^{30}$** | 37.10 | 37.56 | 37.30 | 2.23 | 46.15 | 33.0 | 36.22 | 38.90 | 41.02 |
| **$9^{30}$–$11^{00}$** | 36.30 | 36.55 | 36.43 | 1.69 | 41.12 | 22.52 | 35.68 | 37.30 | 39.32 |
| **$16^{30}$–$18^{00}$** | 39.70 | 40.77 | 40.33 | 2.76 | 53.0 | 29.83 | 39.12 | 42.03 | 45.97 |
| **$21^{00}$–$22^{30}$** | 32.80 | 33.36 | 33.38 | 1.45 | 36.42 | 23.57 | 32.43 | 34.28 | 35.65 |

At the stop level, the link travel time (or travel time between stops) was normalized, i.e. divided by the link length and its distribution plotted for two time profiles along Line 31. The purpose of normalizing is comparing between links, as link length and actual travel time differ from link to link. Figure 26 effectively shows the relation of time required to travel through a link, where more time (y axis) represents comparatively slower travel.

Effectively, axis y represents the amount of seconds required to travel 10 meters along any given link between two stops. From the figure it is clear the dramatic difference between time of day for the links before the stops Bahnhof Altstetten, Herdernstrasse and Hardplatz. Other links are comparatively slower, but the difference between time profiles is not as high as for the previously mentioned links.

Figure 26 Stop-level (normalized) travel time distribution. Selected time profiles



### *Performance measures*

Based on the service reliability measures included in Table 10, Table 21 includes a summary of travel time service measures for Line 31 (in the eastbound direction) at the route level. The travel time reliability performance measures decrease with increasing variability, therefore higher values indicate better performance. From the result of the mean run time ratio (actual over scheduled run time) in average, vehicles need 1 to 3% more time than planned to complete a run.

Table 21 Travel time (TT) performance measures at route level. Line 31

| Time of day | TT reliability (1) | TT reliability (2) – (min) | Mean Run Time Ratio | Mean Run Time Delay (seconds) | Run Time coefficient of variation (cv) |
|---|---|---|---|---|---|
| **$7^{00}$–$8^{30}$** | 16.84 | 0.45 | 1.03 | 69 | 0.059 |
| **$9^{30}$–$11^{00}$** | 21.63 | 0.59 | 1.01 | 15 | 0.046 |
| **$16^{30}$–$18^{00}$** | 14.77 | 0.36 | 1.03 | 81 | 0.068 |
| **$21^{00}$–$22^{30}$** | 23.01 | 0.69 | 1.02 | 34 | 0.043 |

Until now, the analysis has focused on descriptive statistics and service measures are aggregated at the route level. However, AVL data allows for a detailed analysis of travel time at the link level, i.e. between stops. Using planned and actual departure and arrival records for each trip and stop, the run time ratio (RTR) defined in Table 10 was calculated and the result depicted in Figure 27. Values reflect the variation in travel time between the depicted and the previous stop.

Figure 27 Run time ratio from previous to shown stop by time profile, Line 31

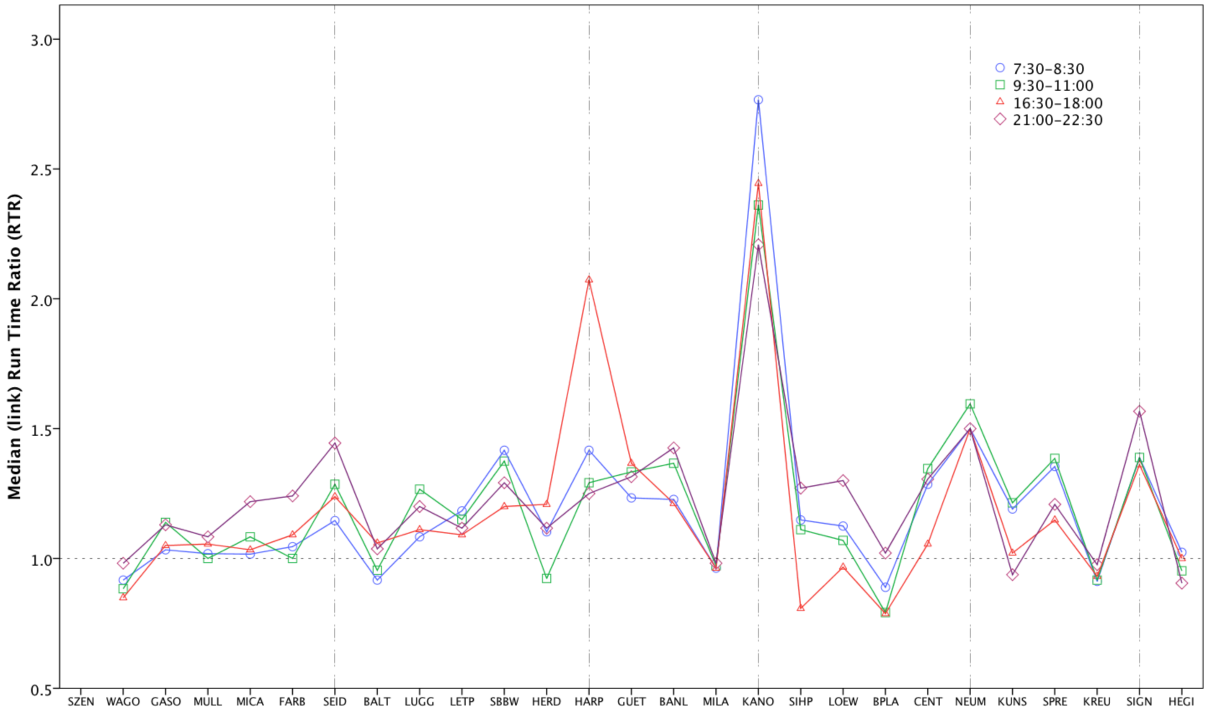


Figure 27 highlights sections of Line 31 where the recorded travel time between stops differs from the planned travel time. A value of RTR = 1 means exact correspondence between planned and delivered service. Values above 1 correspond to sections where vehicles needed more time than was planned, and RTR values below 1, sections where buses needed less time than planned. Care is needed when comparing route and segment level RTR, as the aggregation of the parts does not correspond to the total. Dwell times, buffer times and holding strategies are not part of the analysis and contribute to a large extent to the final travel time of a trip. At the route level, the planned travel time (difference between the planned arrival at the last stop and the planned departure from the first stop) lies between 32 and almost 40 minutes. For individual sections (difference between planned arrival time at a stop and planned departure time from the previous stop) the range is between 24 and 120 seconds, depending on the particular section and the time of day.

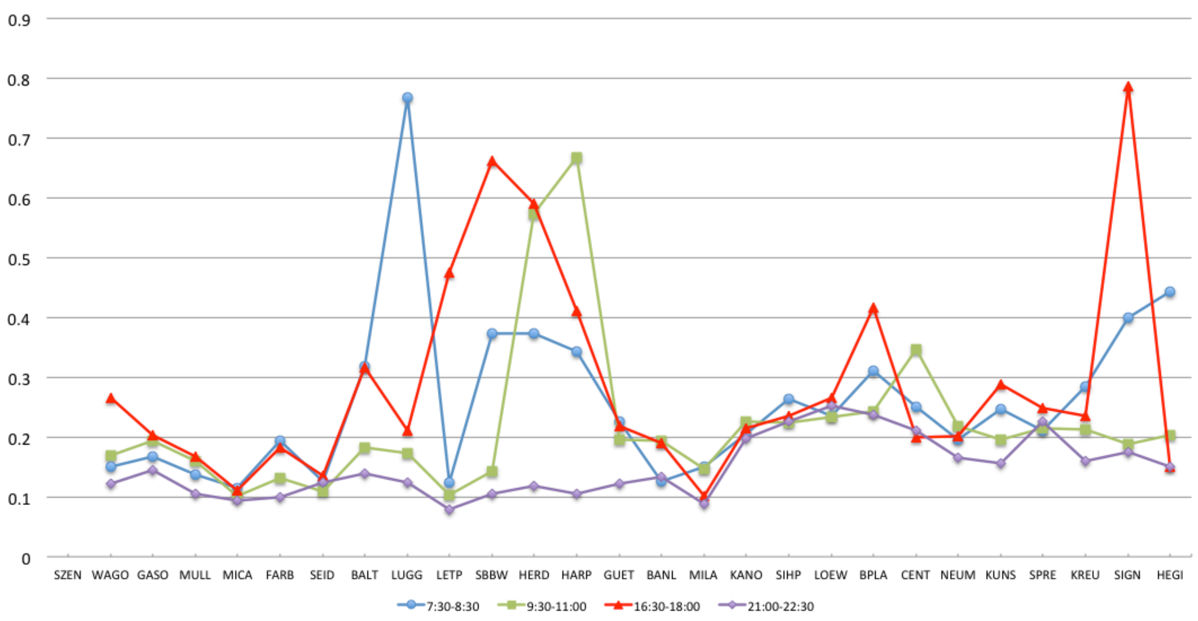
Some sections stand out from others because of their "bad" RTR. Several sections systematically require more time than originally planned. The section between Militär-/Langstrasse and Kanonengasse clearly stands out from the rest of the sample. After consulting with the VBZ, it was determined that road works on that particular link between Militär-/Langstrasse and Kanonnengasse were the reason for this result.

Other sections where systematic disparities occur are the sections before the stops Seidelhof (most deviation taking place during the late night services), Hardplatz (specially during the PM peak), Neumarkt and Signaustrasse. It is not clear why the late night services in particular systematically require more time than planned to reach Seidelhof, as passenger demand and vehicle traffic is assumed to be at the lowest during this period. Before Hardplatz, the most probable cause during the PM peak is private vehicle traffic, as Line 31 drives in mixed traffic along the Hohlstrasse, a main road. Public transport vehicles do have a bus lane just before reaching Hardplatz, however, this bus lane is just over 35 meters long (the bus is 25 meters long) and might not be enough to allow buses to skip the congestion at the traffic light.

Finally, the sections before Neumarkt and Signaustrasse are also somewhat confusing, as vehicles systematically need about 50% more time than planned to travel between the stops, even though in these sections vehicles drive on a central bus (tram) lane with direct access to the stops, additional to priority at traffic lights. Congestion with vehicles of tram Line 3 lane arriving at Neumarkt is a possible reason, as they are scheduled to arrive 1 minute before or at the same time throughout most of the day. Buses of Line 31 arriving to Signaustrasse may have a similar arrival conflict with vehicles of tram Line 11, as these are scheduled to arrive between 1 and 2 minutes before to the stop.

Another useful service measure to evaluate regularity is the coefficient of variation. This normalized (dimensionless) measure of dispersion is independent of the unit of measurement, and thus allows comparisons throughout different times of day or even different routes (different datasets. Figure 28 shows the results for the four selected time profiles.

Figure 28 Run time coefficient of variation (cv) from stop *n*-1 to stop *n*



Because the cv is a measure of variability, extreme values in the data having an impact on the standard deviation will increase the cv. In the previous figure it is clear that the late night services (21:00-22:30) display the lowest cv values throughout the route, and only the route section between Militär-/ Langstrasse and Central (and then again before Sprecherstrasse) show cv values above 0.2. However, no threshold value is defined for this measure. Most variation in travel time is taking place during the remaining time profiles.

During the AM peak, most variation in travel time takes place before and especially after Bahnhof Altstetten. Variation is also observed between Letzipark and Hardplatz, as well as Before Bahnhofplatz and in the last section of the route, after Sprecherstrasse. During the in-between peak period, most variation takes place between the SBB-Werkstätte and Hardplatz, followed by the section between Bahnhofplatz and Central.

For PM peak services, most variation takes place in the section before Bahnhof Altstetten, along the Hohlstrasse between Luggwegstrasse and Hardplatz, before Bahnhofplatz and before Signaustrasse. In the first two cases, the problem is likely to be private vehicle traffic (congestion), whereas in the last two cases, interactions with other public transport vehicles might be the cause.

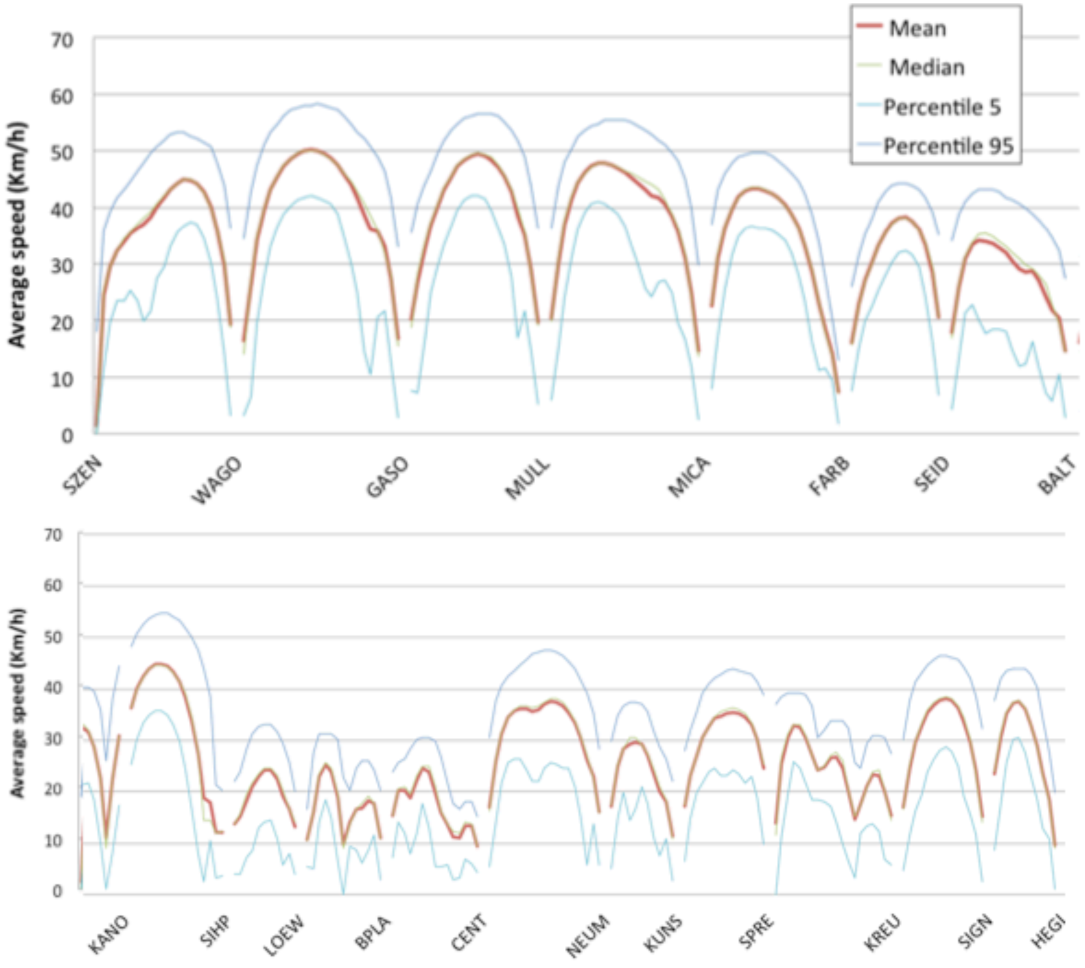
### 5.4.2 Speed

As pointed out by Furth, Hemily et al. (2003), speed and traffic delay analysis "is helpful for identifying locations in which there may be a need for infrastructure or traffic improvements such as signal retiming, turning restrictions, signal priority, or physical priority. It also helps monitor the impact of any change in infrastructure, traffic, or driver behaviour". In Zurich, many of these measures are already in place since decades, and the potential for expanding infrastructure is very low, as the physical street space is limited and used intensely by all mobility actors.

For the speed analysis included in this work, no AVL data was available, and only aggregate data from spreadsheets was at hand. These data included speed records every 25 meters along the route with summary statistics (mean, median and percentile values). Thus, it was possible to plot the speed trajectories and observe those places where vehicles have a hard time getting from one stop to the next. In the context of this work, no service measures were calculated for vehicle speed.

Figure 29 shows the mean (thicker line), median, as well as the 5th and 95th percentile of speed along the lines for all trips in March 2011. Only the first and last sections of the line are included, or 19 out of 27 stations.

Figure 29 Average speed distribution for all trips, first and last third of Line 31



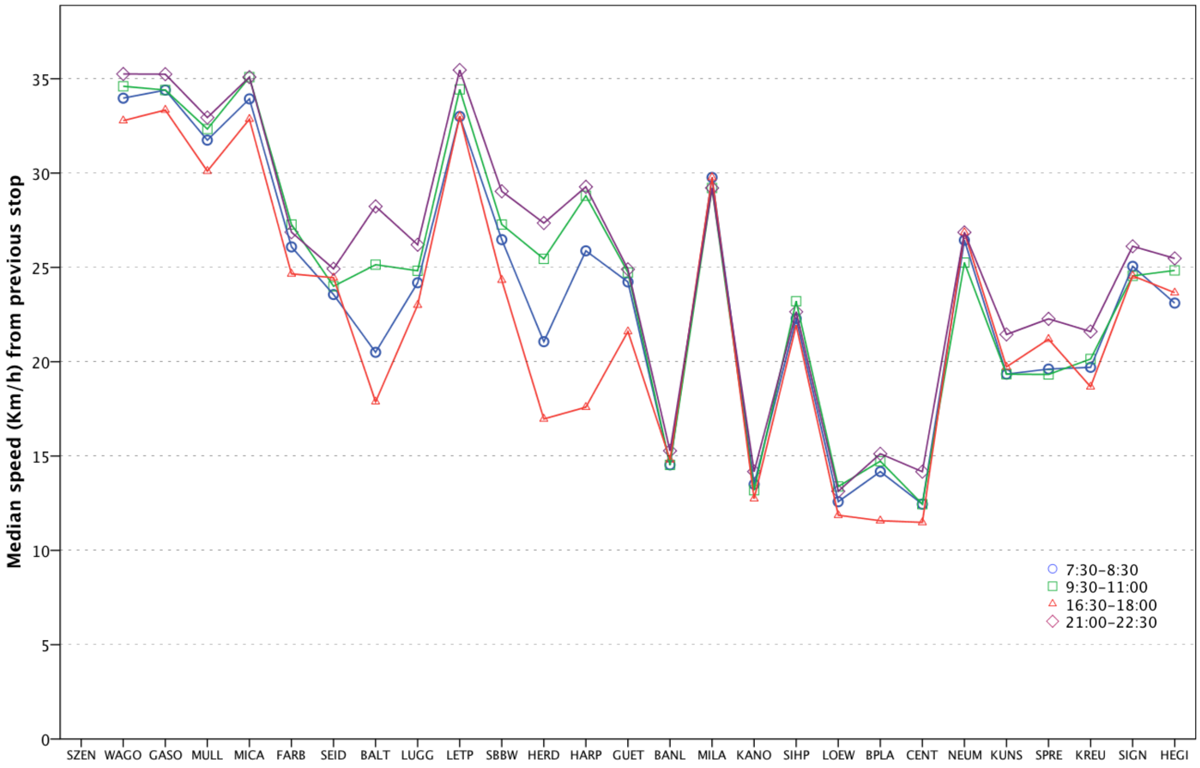
The graph clearly shows relatively smooth runs at average speeds between 45 and 50 km/h from the start of the run until about Farbhof. This station is the terminal of tram Line 2. After this point, peak average speed between stops only exceeds 40 Km/h between Luggwegstrasse and Letzipark (not shown), and between Kanonengasse and Sihlpost, in the lower section of the graph. From Sihlpost until Central, Line 31 shares the road with tram Lines 3 and 14. Just before the stop at Zurich main train station vehicles merge into mixed traffic until Central, where a roundabout and a set of pedestrian crossings require considerable manoeuvring before the vehicle reaches the stop.

Between Central and Kunsthaus Line 31 shares an exclusive lane with tram Line 3, which is reflected in average vehicle speed results. Between Sprecherstrasse and Kreutzplatz a set of traffic lights clearly impacts average vehicle speed.

The previous analysis provides a clear picture of where the buses have a harder time getting from one stop to the next. The slowest average section lies in the heart of the city, between Sihlpost and Central, a section where a total of 8 bus and tram lines converge, significant private vehicle traffic is present, and large amounts of pedestrians coming from and to the main train station constantly cross the street. Peak average vehicle speed is about 25 Km/h along this section. Another clear example is found between Sprecherstrasse and Kreuzplatz, where two traffic lights and 90-degree turns systematically slow down the vehicles.

Given that no AVL records are available between the stops, but distance between stops is known, an aggregate statistical value can be calculated for speed (e.g. mean speed). This is shown in Figure 30 for each time profile. Most variations in speed between stops throughout the day take place between Seidelhof and Bahnhof Altstetten, between the SBB Werkstätte and Hardplatz, and to a lower extent between Löwenplatz and Hauptbahnhof.

Figure 30 Median speed between previous and shown stop. All time profiles



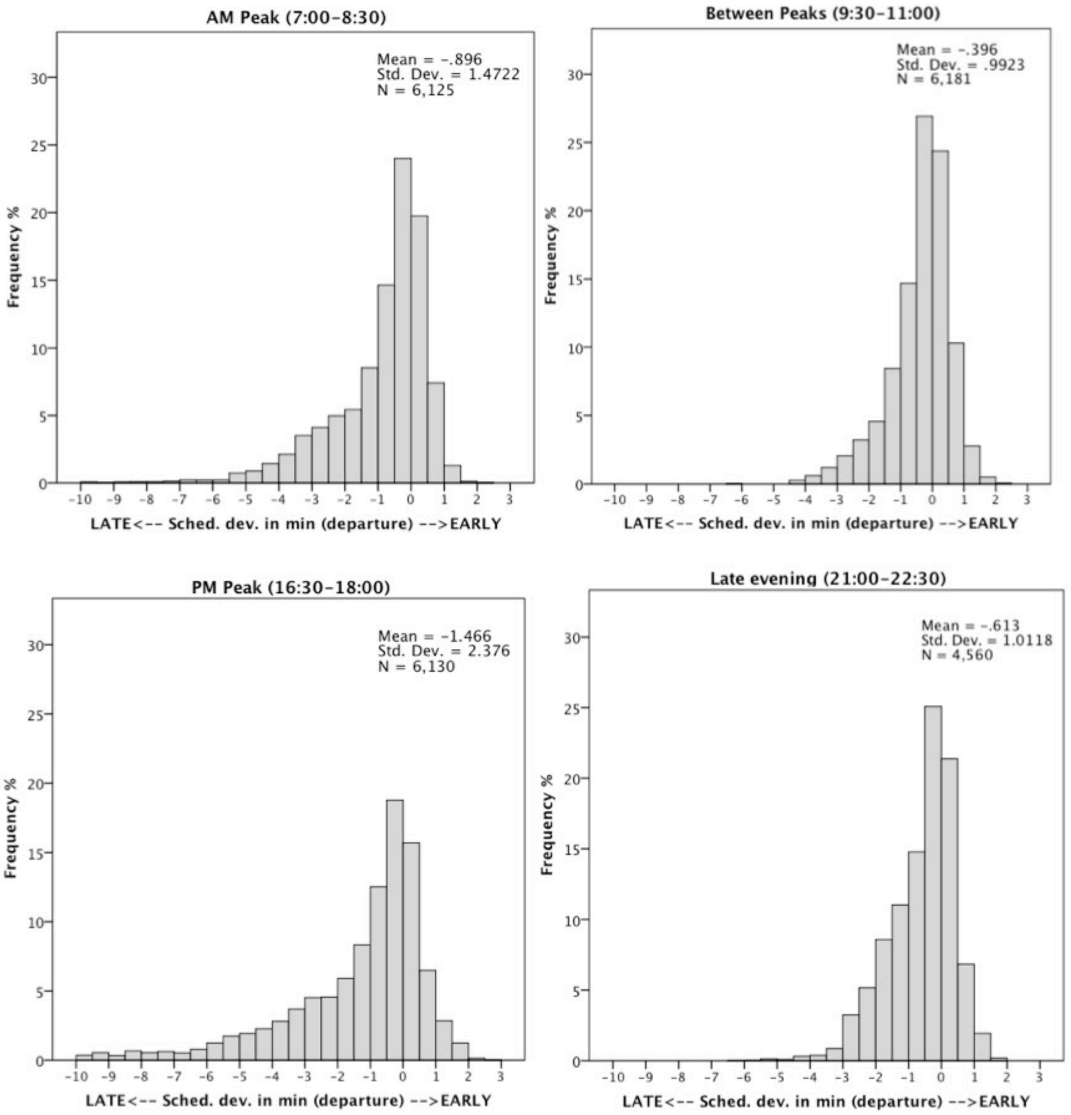
### 5.4.3 Punctuality

Punctuality, understood in this work as both the level of adherence to the schedule as well as on-time performance (subject to the thresholds previously defined) is a valuable management practice. This is because the prerequisite for achieving good schedule adherence are both realistic schedules and good operational control. It is one of the most common analyses practiced in the public transport industry.

Schedule deviation can be calculated for arrivals as well as for departures from the AVL data, however, in the framework of this study only departures are considered, since holding strategies are implemented in Zurich and the policy is to avoid early departures.

In a first instance, the route-level schedule deviation distribution is shown in Figure 31, using the same vertical and horizontal scale. Mean and standard deviation are included in the graph.

Figure 31 Route-level schedule deviation distribution. All time profiles



The bars in Figure 31 are 30-second wide. A clear difference can be observed between peaks and other periods, with a skewed distribution to the left (late departures). The most compact distribution is for the period between peaks (Std. Dev. = 0.99 min), the highest distribution is observed for the PM peak (Std. Dev. = 2.38 min).

At the stop level, AVL data allows the calculation of a series of metrics and measures. Figure 32 shows the mean schedule deviation, in seconds, at the stop level for all time profiles. How close the mean deviation is to zero indicates whether the scheduled running time is realistic.

A systematic deviation recovery is observed for all time profiles between the stops Micafil and Farbhof, as well as between Bäckeranlage and Militär-/ Langstrasse. Courses remain on time (in average) until the SBB Werkstäte. From that point on, during the PM peak period, vehicles deviate (in average) up to 3 minutes from the schedule, but recover up to 90 seconds (most likely by large buffers in the schedule) until being (in average) less than 2 minutes late by the end of the line. Surprisingly, the services between AM and PM peaks are (in average) punctual along the entire line, with higher average schedule adherence than the late night services.

Figure 32 Mean schedule deviation at stop level. All time profiles, Line 31

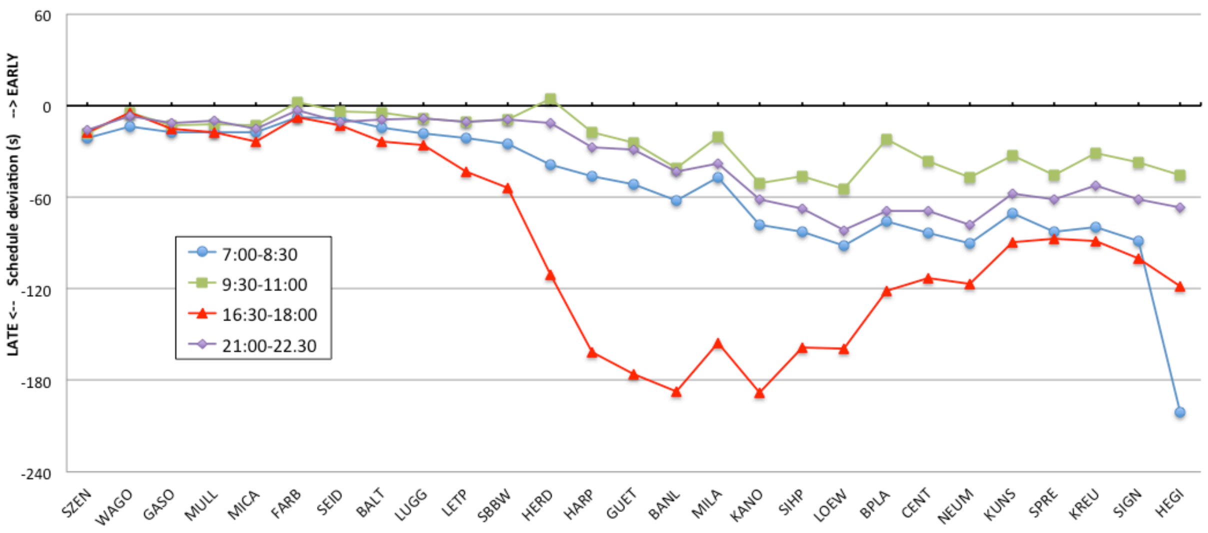
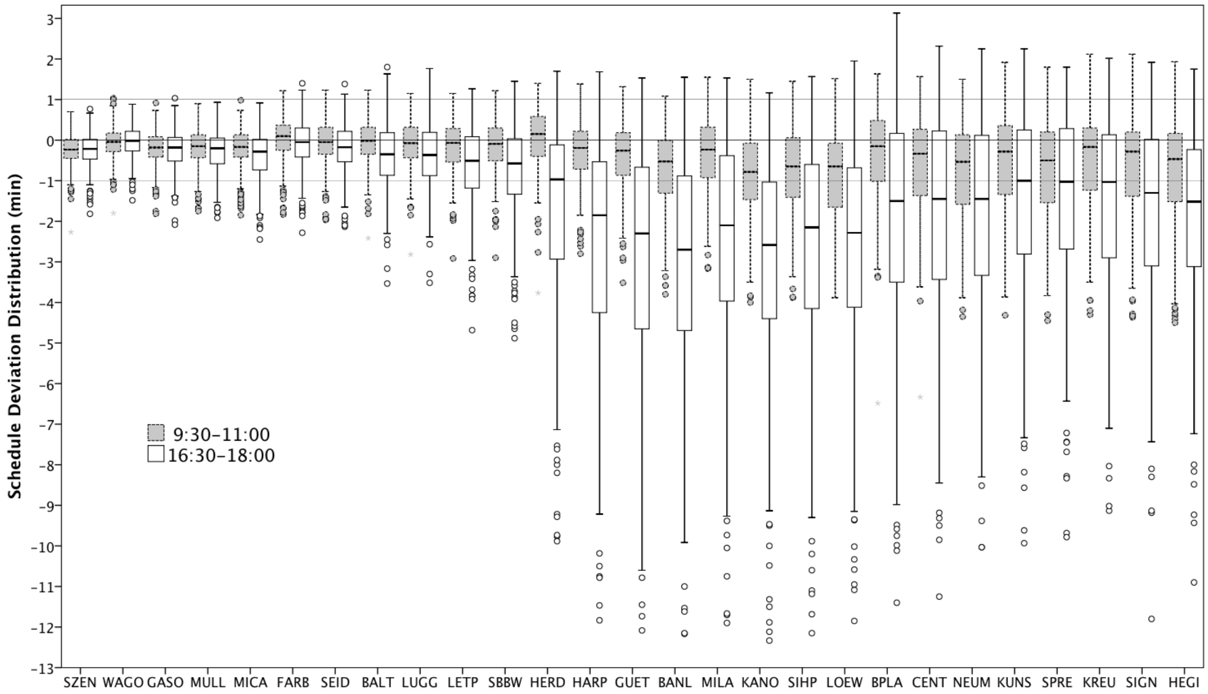


Figure 32 includes only the mean value of the schedule deviation at each stop; however, an interesting measure is the distribution of the deviation at each stop. In the following figure, this information is depicted for the two most contrasting time profiles, the mid morning (between AM and PM peaks) and the PM peak.

Figure 33 Schedule deviation distribution at stop level for two time profiles



A clear contrast can be observed between the distribution schedule adherence for the two selected time profiles. Horizontal lines were included at the 1-minute marks (early, above and late, below zero) for reference. The relation between Figure 32 and Figure 33 for the PM peak profile is clear.

Descriptive schedule deviation statistics per time at the route level are summarized in Table 22 below. Deviation is from planned departures. Positive values correspond to departures before the planned time; negative values are departures after the planned time.

Table 22 Route-level schedule deviation summary statistics (in min)

| Time | Mean | Median | Std. Dev. | Max. (Early) | Min. (Late) | Perc. 5 | Perc. 25 | Perc. 75 | Perc. 95 |
|---|---|---|---|---|---|---|---|---|---|
| **$7^{00}$–$8^{30}$** | -0.90 | -0.55 | 1.47 | 4.7 | -11.62 | -3.67 | -1.57 | -0.02 | 0.58 |
| **$9^{30}$–$11^{00}$** | -0.40 | -0.32 | 1.03 | 6.68 | -4.7 | -2.63 | -0.98 | 0.08 | 0.73 |
| **$16^{30}$–$18^{00}$** | -1.47 | -0.82 | 2.43 | 9.48 | -12.73 | -6.48 | -2.57 | -0.07 | 0.83 |
| **$21^{00}$–$22^{30}$** | -0.61 | -0.5 | 1.1 | 9.52 | -6.05 | -2.77 | -1.4 | -0.07 | 0.55 |

### *Performance measures*

Based on the service reliability measures included in Table 10, Table 23 comprises summary results of punctuality performance measures at the route-level. From the results it is clear that the worst performing time profile is the PM peak, followed by the AM peak. However, the AM peak profile performs considerably better than its counterpart. In average, vehicles during this time of day are punctual (within punctuality threshold), and the standard deviation of their distribution is just above one minute. Similarly, its OTP measure is in the same range with the off-peak profiles. Service taking place outside peak hours is very punctual, with OTP values around 97%, and in average, provide a punctual service. The standard deviation of the sample is slightly higher for the late night services. Service provided during the PM peak profile, is in average late (by VBZ standards), and its schedule adherence more variable. In particular, these services experience a drop in punctuality after departing from the SBB-Werkstätte, which recovers after Central, but remains at lower levels than during the rest of the day.

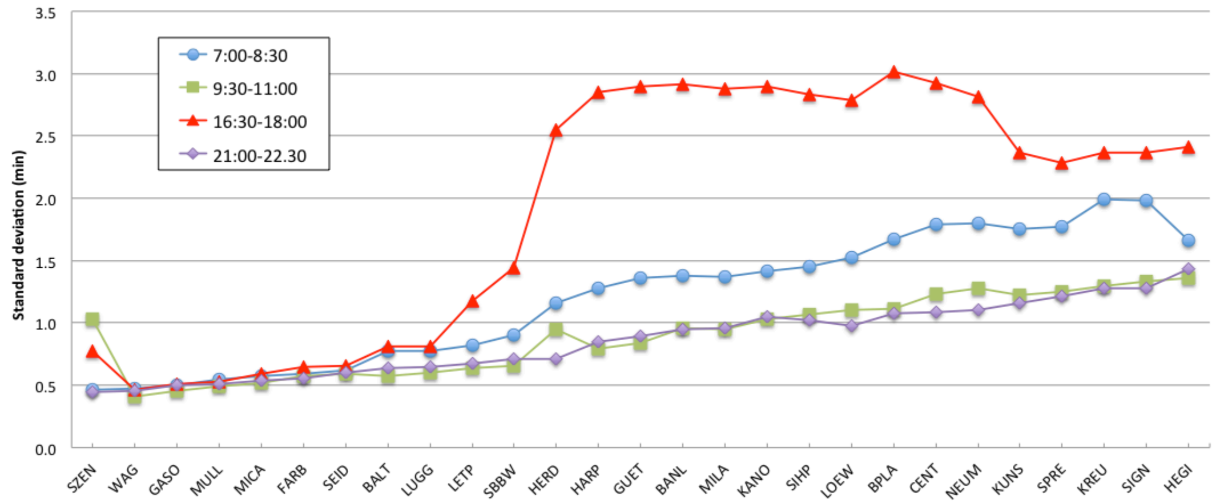
Table 23 Punctuality performance measures at route level. Line 31 eastbound

| Time of day | Mean schedule adherence | Standard deviation of schedule deviation (unweighted) | Mean line punctuality (OTP) (unweighted) |
|---|---|---|---|
| **$7^{00}$–$8^{30}$** | 54 seconds late | 88 seconds | 96.93 |
| **$9^{30}$–$11^{00}$** | 24 seconds late | 60 seconds | 96.74 |
| **$16^{30}$–$18^{00}$** | 88 seconds late | 143 seconds | 87.56 |
| **$21^{00}$–$22^{30}$** | 37 seconds late | 61 seconds | 97.70 |

Schedule deviation at the stop level as shown in Figure 33 is a useful metric by itself, however its variation is another useful measure to detect stops along the line where schedule adherence changes the most. As can be seen in Figure 34, the value of standard deviation surges from the stop SBB-Werkstätte to Herdernstrasse for the PM peak profile to almost 3 minutes, then remains fairly constant, slightly declining after Central, where buses share an exclusive lane with tram Line 3. This is consistent with plunging average speed values in Figure 31 and high values of cv in Figure 28 for the same route segment and time profile.

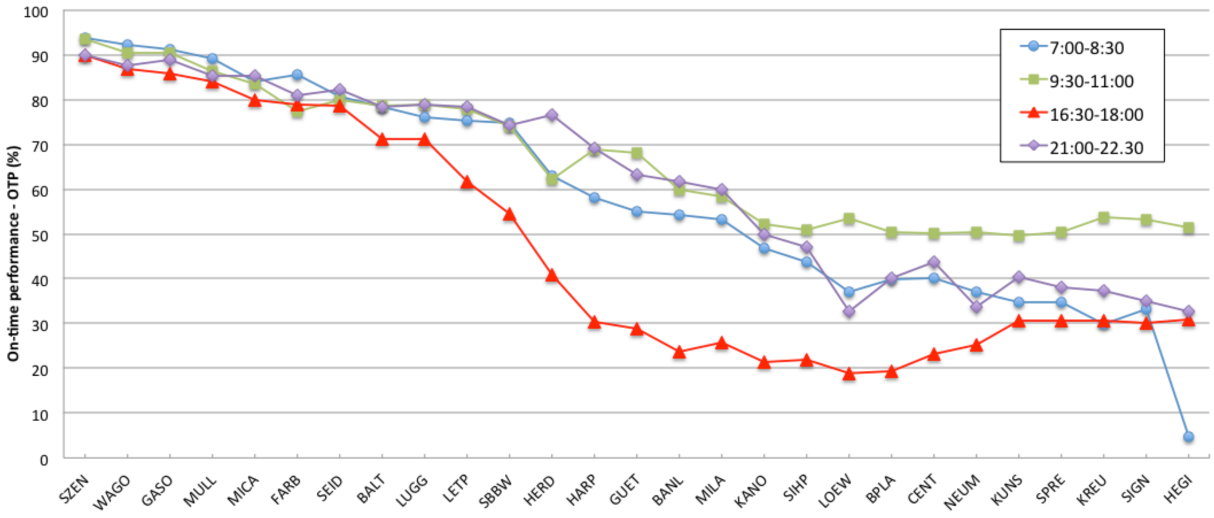
Off-peak time periods display less variation. The AM peak deviation slightly underperforms the in-between periods, however the PM peak deviation surges after the stop SBB-Werkstätte. Schedule deviations for the off-line periods increase slowly but constantly, remaining below 90 seconds by the end stop.

Figure 34 Standard deviation of schedule adherence at stop level



Besides schedule deviation, a usual performance measure used to characterize service punctuality is on-time performance (OTP), or share of trips "on-time", as described in section 3.4.3. Using the VBZ on-time threshold, (30 seconds before and 1 minute after planned departure) Figure 35 below was constructed. It summarizes the results for the OTP indicator for all time profiles at the stop level. The drop for the AM peak profile at the terminal most likely corresponds to vehicles waiting for a previous vehicle to depart from the terminal. See Figure 43.

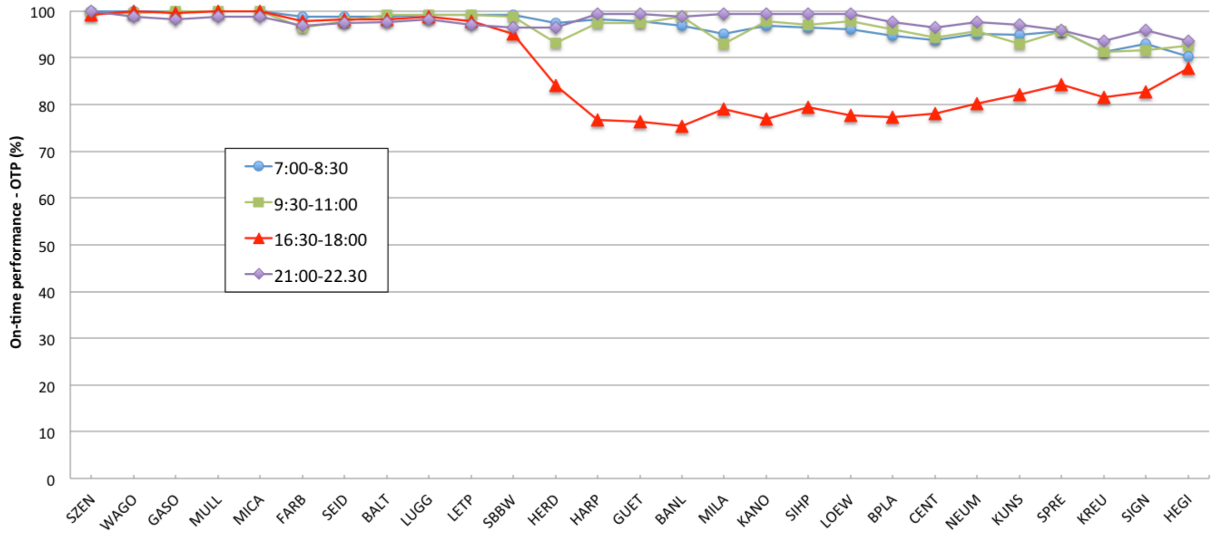
Figure 35 On-time performance at stop level. Zurich threshold



Consistent with the previous figures, the PM peak performs the worst, with a sharp decline after Luggwegstrasse, down from over 70% on-time departures, to just below 20% by the time vehicles reach Loewenstrasse. Services during other times of day are quite similar, with the AM peak slightly underperforming the non-peak periods, and the in between peaks remaining above 50% OTP along the entire line. Sharp peaks are observed for the last section of the line during the late night services, which might be explained by a less strict schedule adherence behaviour from the drivers, possibly waiting for passengers at stops, at a time of day where services are less frequent.

An interesting exercise was to compare the on-time threshold used in Zurich with a common threshold used in other places around the world. Therefore, Figure 36 was built using an on-time threshold of departures 1 minute early to 5 minutes late from planned departure.

Figure 36 OTP at stop level for all time profiles. 1 min early to 5 min late



The figure above provides an insight into the on-time performance of bus line 31 services when a "more relaxed" threshold is used, i.e. less strict than the one in place in Zurich. For this case service during most time profiles remains above 90% on time. Only services during the PM peak experience reduced on-time level, particularly after the stop Herdernstrasse. These measures are not weighted by passenger activity at each stop, which would be desirable (if the data was available) to reflect the impact of service unreliability on passengers.

### 5.4.4 Regularity

In routes with short service intervals, headway regularity is important for passengers because it has a large impact on waiting time at the stop and on crowding levels. For operators it is also important because vehicle crowding tends to have a negative influence on operations, and because a large part of operations control deals with keeping vehicle headways regular.

Headway analysis requires AVL data from successive buses, therefore it is necessary to control for missing values, as a lost trip will impact two headways and can bias the results of the analysis. Using the actual departure time for the sequence of recorded trips, headways (with previous vehicle), summary statistics and service measures were calculated at the route and stop level for all time profiles. The planned headway for all services is 7.5 minutes (450 seconds) except for late night services, for which the planned headway is 10 minutes (600 seconds).

Figure 37 illustrates actual frequency distribution at the route level for all time profiles, using the same vertical and horizontal scale in all four graphs.

From the results of Figure 37, it is clear that the two off-peak time profiles comply to a larger extent with the planned headway, however the in-between peak period deviates less from the mean (Std. Dev. = 1.29 min) than the late evening period (Std. Dev. = 1.45 min). As expected, the PM peak period distribution varies the most (Std. Dev. = 2.00 min), with the highest mean headway (8.01 min) of all time periods.

Figure 37 Headway frequency distribution at route level. All time profiles

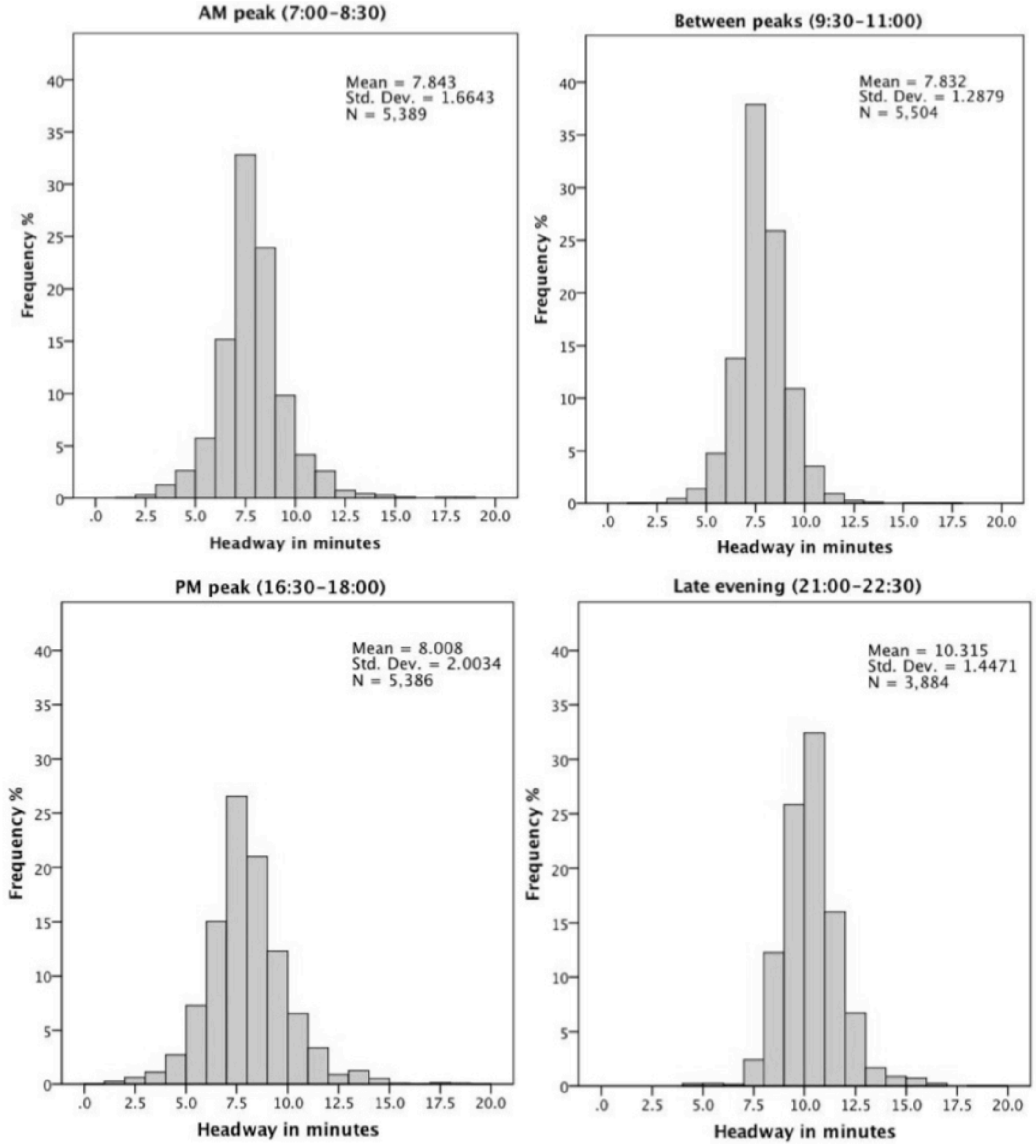
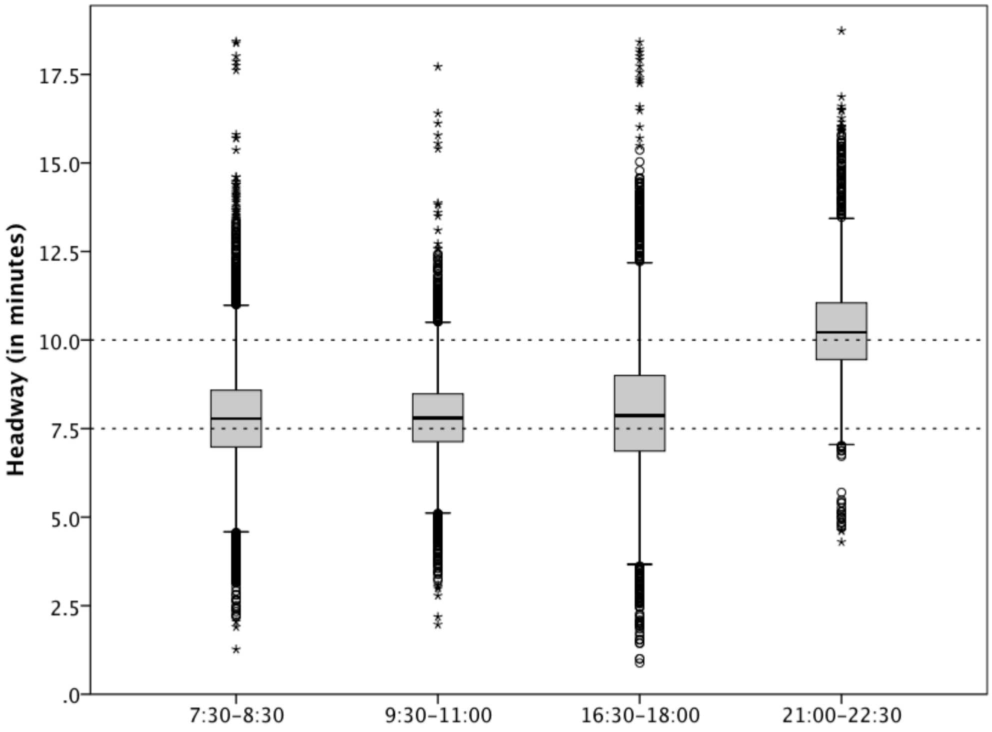


Figure 38 summarizes the information presented in Figure 37 in the form of a boxplot for each time profile. From the distribution of headways it is possible to see how often headways were very short or very long, using any threshold desired. An example of a service measure is the percentage of headways greater than 1.5 scheduled headways, included in Table 10.

Figure 38 Headway box-plot distribution at route level. All time profiles



Descriptive headway statistics at the route level for all time profile are summarized in Table 24.

Table 24 Headways regularity summary statistics. Line 31 (in min)

| Time | Planned | Mean | Median | Std. Dev. | Max. | Min. | Perc. 25 | Perc. 75 | Perc. 95 |
|---|---|---|---|---|---|---|---|---|---|
| **$7^{00}$–$8^{30}$** | 7.5 | 7.84 | 7.78 | 1.66 | 18.43 | 1.27 | 6.98 | 8.58 | 10.75 |
| **$9^{30}$–$11^{00}$** | 7.5 | 7.83 | 7.8 | 1.29 | 17.72 | 1.97 | 7.13 | 8.48 | 9.95 |
| **$16^{30}$–$18^{00}$** | 7.5 | 8.01 | 7.87 | 2.00 | 26.22 | 0.88 | 6.87 | 9 | 11.35 |
| **$21^{00}$–$22^{30}$** | 10 | 10.32 | 10.22 | 1.45 | 19.72 | 4.3 | 9.45 | 11.05 | 12.67 |

At the stop level, Figure 39 and Figure 40 depict the mean actual absolute headway and the average absolute deviation from scheduled headway (respectively) for all time profiles. Three stops stand out from the rest in Figure 39, where systematic increases in headway can be observed at all times of day. These points are Hardplatz, Militär-/Langstrasse, and Bahnhofplatz.

Moreover, increases in headway are observed at Farbhof and Bahnhof Altstetten for time periods with 7.5-minute headway.

Figure 39 Average absolute headways for all time profiles at stop level

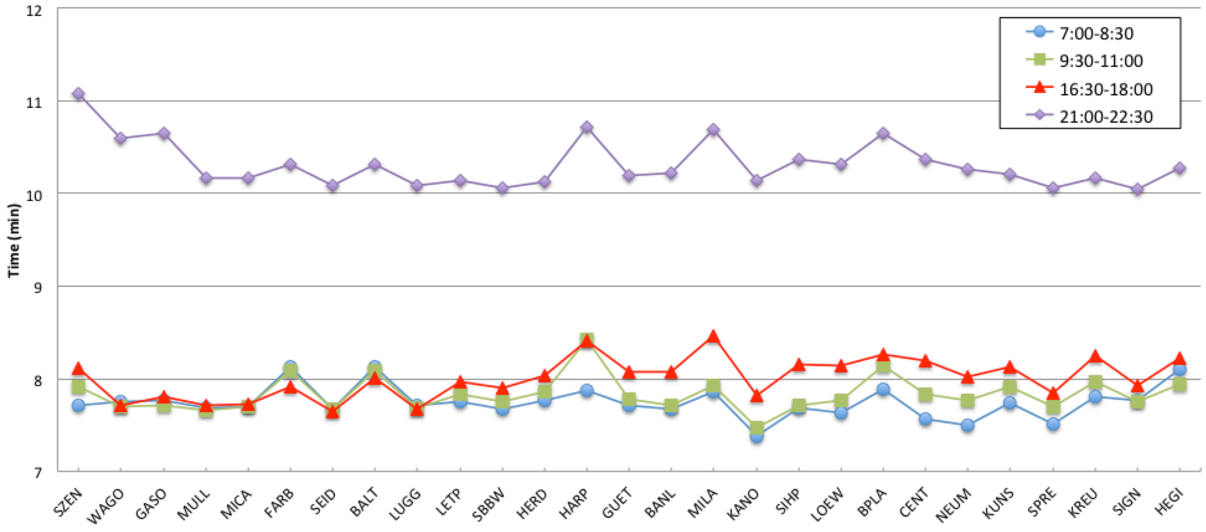
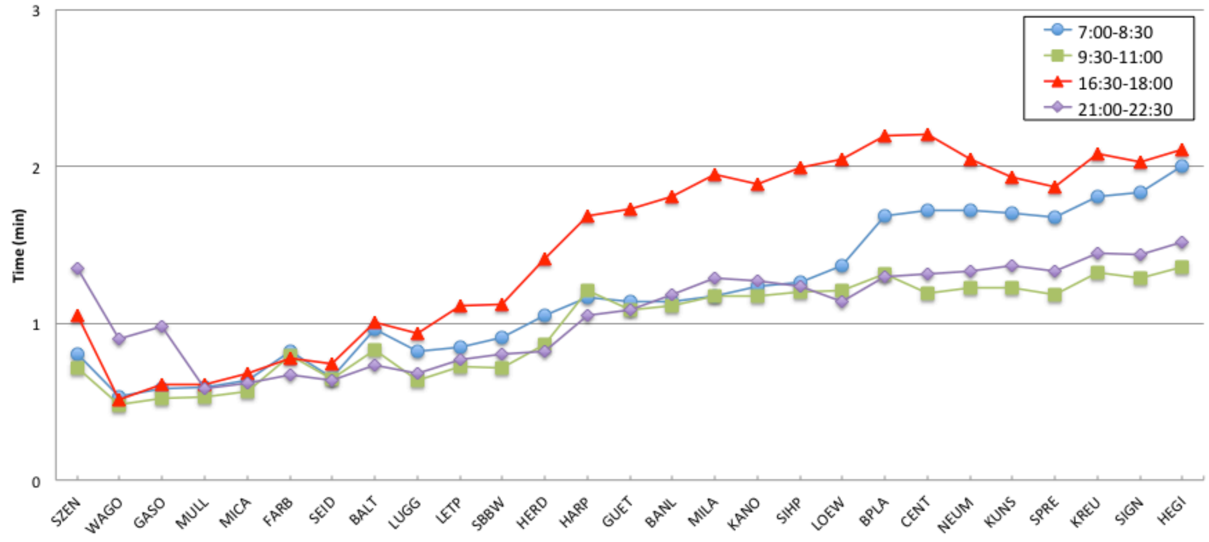


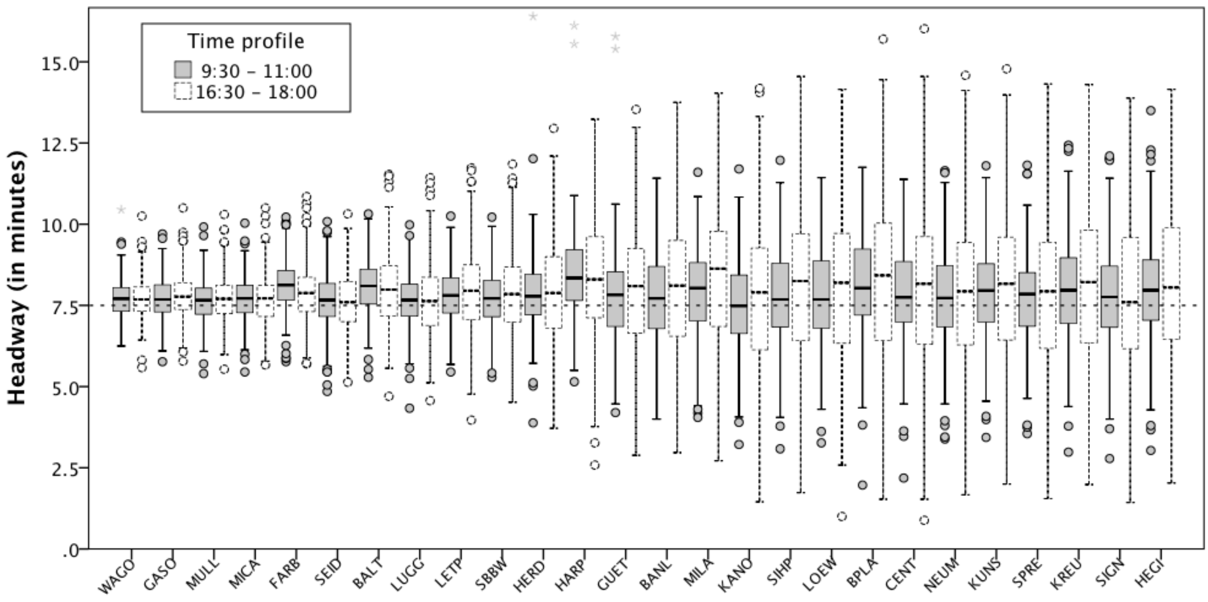
Figure 40 Average absolute headway deviation for all time profiles at stop level



Headway deviation remains fairly constant in the first half of the line, increasing sharply after SBB-Werkstätte for PM peak services. A slight increase is also observed after Löwenplatz for AM peak services. A recovery is also seen during PM peak services after Central.

Figure 41 depicts the headway distribution for the best and worst performing time profiles, i.e. the period between peaks, and the evening peak. A clear difference in performance is observed between the two time periods. The shape of the headway distribution allows to see where and how often headways were shorter or longer than a desired threshold. Some extreme values are also visible in this figure. Several stops stand out along Line 31, where increases in median headway and its variation can be observed. These are all important stops where large passenger boarding and alighting take place, namely Bahnhof Altstetten, Hardplatz, Militär-/ Langstrasse and Bahnhofplatz.

Figure 41 Actual headway distribution at stop level for two time profiles



### *Performance measures*

Table 25 on the following page includes a summary of the route-level headway regularity performance measures described in Table 10. The pattern remains as the PM peak underperforms services during other times of day. Two performance measures show the same value, namely the mean headway ratio and the regularity index, because aggregate measures were used. Because individual values can be calculated at a more disaggregate level, these two measures are not the same at the stop level, however have a similar meaning, as the relation between observed and planned headway.

Mean headway deviation is lowest between peaks, and approximately 50% higher during PM peak services. Variability measures such as the standard deviation and the coefficient of variation are also best for services during late night. The former is lower for in-between peaks, however, given that headway is higher during late night services, the coefficient of variation is a better measure for comparison.

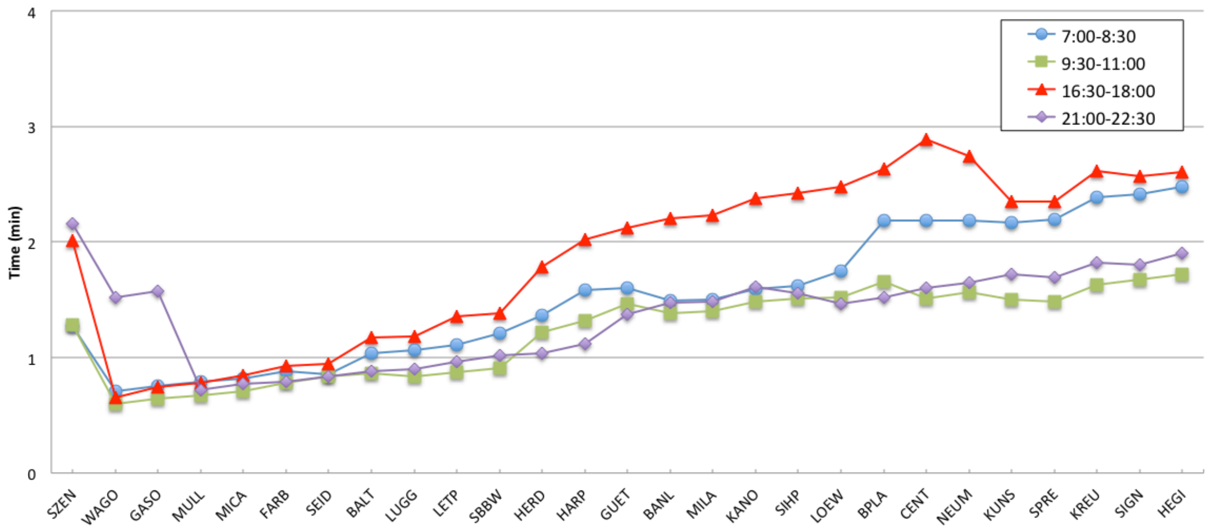
Regarding the acceptable share of headways, the threshold used was 1.5 times the planned headways. It is clear that in between peaks and late night services consistently provide an acceptable headway level (99%). Peak time services are somewhat lower, but remain around the 95% mark.

Table 25 Headway regularity performance measures at route level. Line 31

| Time of day | Mean headway ratio | Mean headway deviation (min) | Actual Headway std. dev. (min) | Actual Headway coefficient of variation (cv) | Regularity Index | Share of acceptable headways |
|---|---|---|---|---|---|---|
| **$7^{00}$–$8^{30}$** | 1.046 | 1.20 | 1.66 | 0.21 | 1.046 | 96.4 % |
| **$9^{30}$–$11^{00}$** | 1.044 | 0.97 | 1.29 | 0.16 | 1.044 | 99.0 % |
| **$16^{30}$–$18^{00}$** | 1.067 | 1.48 | 1.97 | 0.25 | 1.067 | 94.7 % |
| **$21^{00}$–$22^{30}$** | 1.032 | 1.07 | 1.45 | 0.14 | 1.032 | 99.0 % |

At the stop level some initial deviations are registered for all time profiles, as well as a constant increase in the deviation along the line. A clear line section where headway regularity improves is between Central and Kunsthaus, where a tram/bus lane is present.

Figure 42 Standard deviation of actual headway for all time profiles at stop level



Headway deviations at the departing stop can be attributed to the fact that in Schlieren Zentrum (terminal station), the arrival and departure points for buses in the westbound direction are different. Passengers alight the vehicle on the designated stop closest to the train station (Ringstrasse, upper part of Figure 43). However, the first stop of the eastbound courses is located on the Badenerstrasse (lower part of the picture). Some vehicles might wait at the Ringstrasse, while others might do so on the stop at the Badenerstrasse, which brings inconsistency to the records.

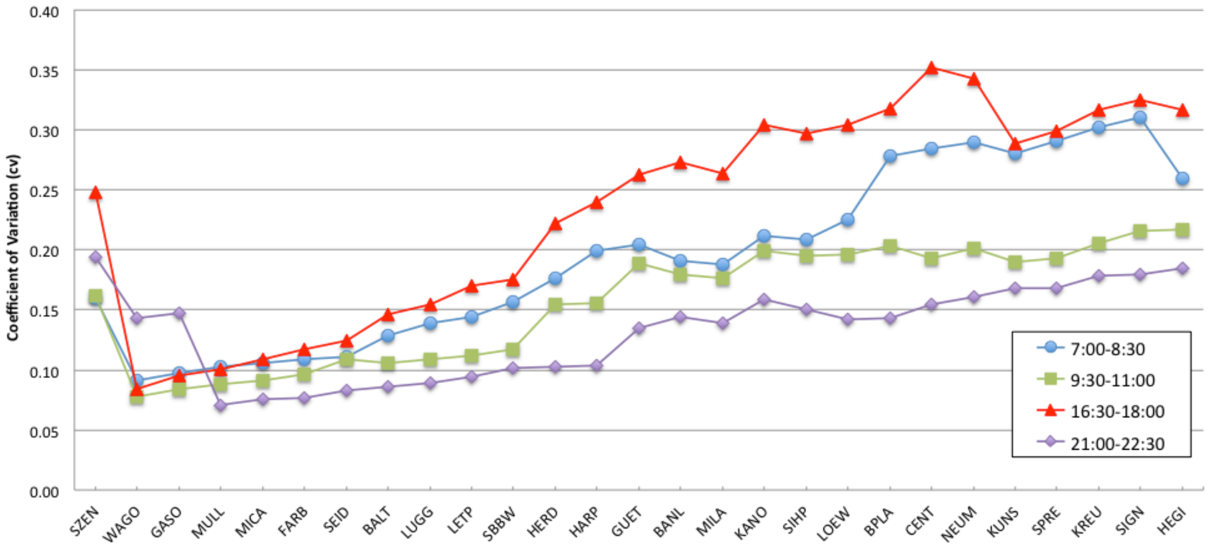
Figure 43 Two different points at stop Schlieren Zentrum

Source: Google maps

Figure 44 depicts the coefficient of variation (cv) of headways at the stop level for all time profiles. The cv is a normalized measure of dispersion, i.e. it normalizes the effect of standard deviation relative to the mean, which allows for meaningful comparisons, as it is a dimensionless amount. The late evening time profile exhibits the lowest variation and the PM peak services are the most variable, which is consistent with the route-lever summary in Table 25. Just as with the standard deviation, a considerable decrease in the cv for the PM peak is observed along the exclusive tram/bus lane between Central and Kunsthaus.

In the public transport industry, the headway cv is a typical measure of operational quality. However, it is purely operator-oriented and its improvement is not easy to understand by or communicate to the users. After all, what is the difference for passengers between services with headway cv values of 0.1 and 0.2?

Figure 44 Observed headway coefficient of variation (cv) at stop level



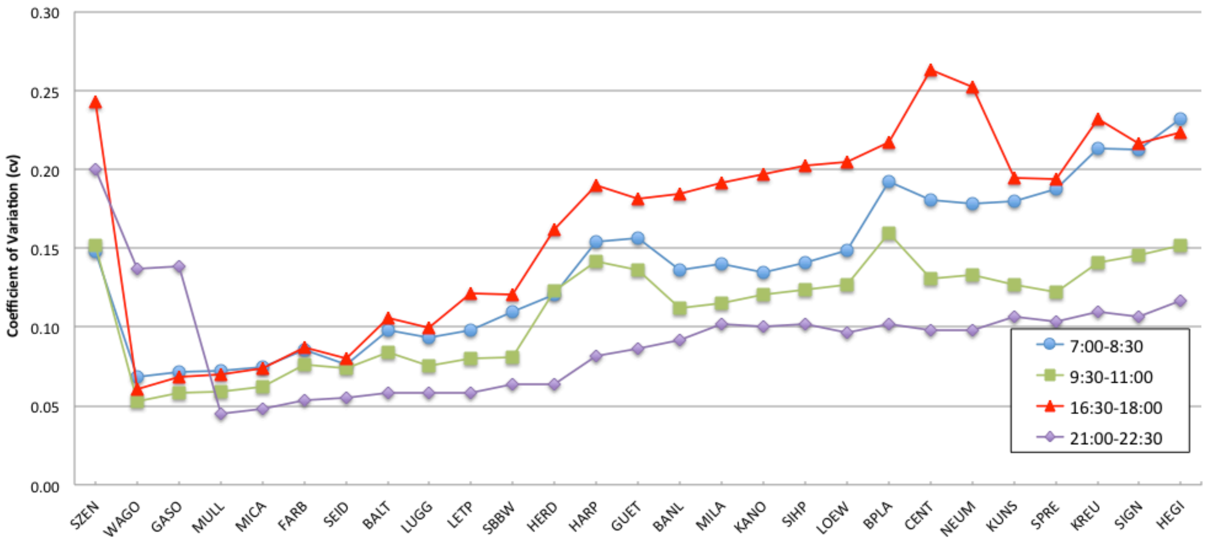
The TCQSM assigns levels of service for service reliability based on values of headway cv$_h$, as seen in Table 26. This classification applies to routes with headways of 10 minutes or less. However, their methodology for calculating the headway cv$_h$ varies slightly, as the standard deviation of headway deviations by the mean scheduled headway. Their methodology applied to Zurich is shown in Figure 45.

Table 26 Fixed-route headway adherence LOS

| **LOS** | **cv$_h$** | **P ($h_i$ > 0.5 h)** | **Comments** |
|---|---|---|---|
| **A** | 0.00 – 0.21 | ≤ 1% | Service provided like clockwork |
| **B** | 0.22 – 0.30 | ≤ 10% | Vehicles slightly off headway |
| **C** | 0.31 – 0.39 | ≤ 20% | Vehicles often off headway |
| **D** | 0.40 – 0.52 | ≤ 33% | Irregular headways, with some bunching |
| **E** | 0.53 – 0.74 | ≤ 50% | Frequent bunching |
| **F** | ≥ 0.75 | > 50% | Most vehicles bunched |

Source: TCQSM (2003)

Figure 45 Headway coefficient of variation. TCQSM methodology applied to Zurich



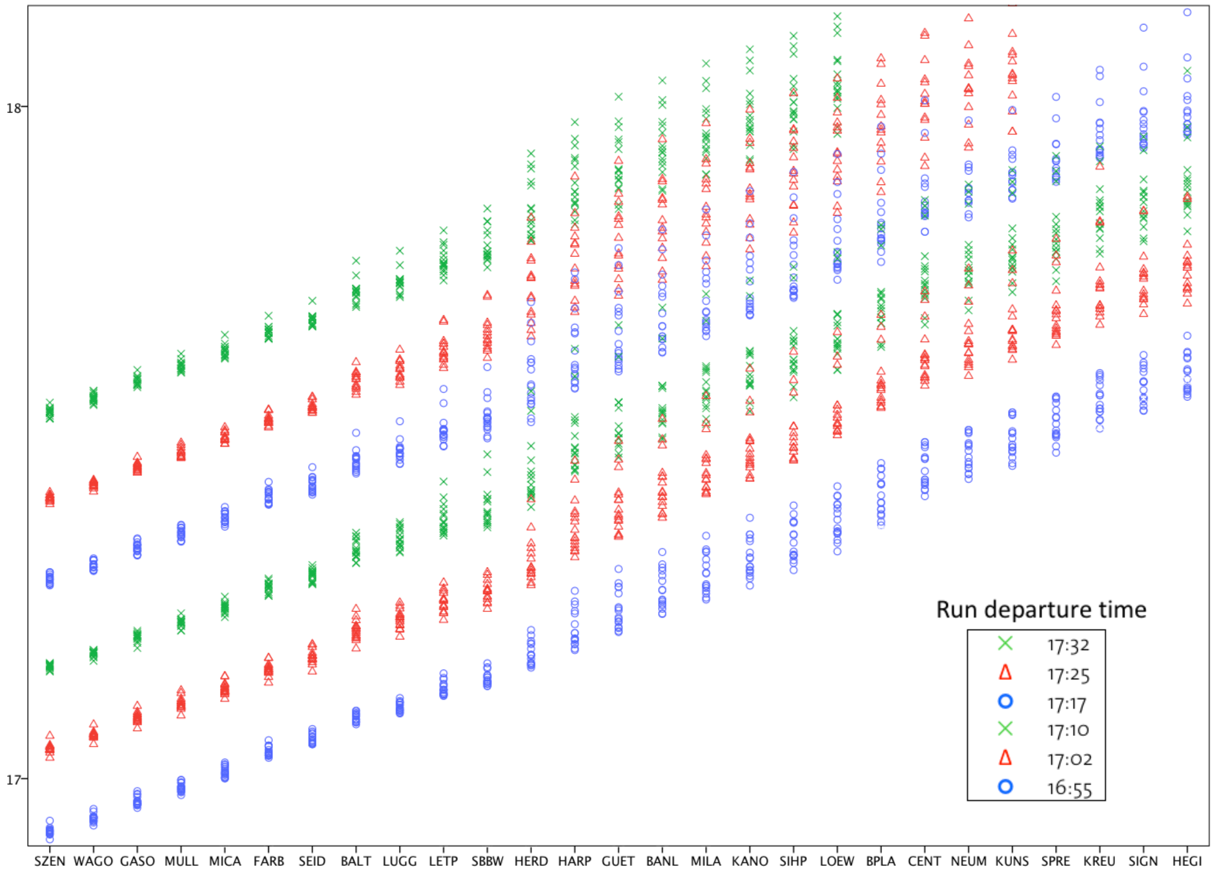
Applying the TCQSM-based LOS classification in Zurich would imply that most services are provided like clockwork (LOS level A). Only a few sections between the last stops during peak hours would classify as B, or “vehicles slightly off-headway”. Naturally, service in Zurich is relatively punctual, but it also has to its side many advantages over conventional services provided in other parts of the world. Some examples are: priority at traffic lights, fleet management practices, low-floor vehicles, off-vehicle payment and higher-capacity vehicles.

### *Insights into bus bunching*

An analysis tool available with AVL data is a plot of successive trajectories on a route. The classical use of this tool is restricted to one day, where the planned trajectory is plotted against the actual trajectory (a generic example is shown in Figure 8). Such a plot allows identifying vehicles (and their drivers) running slow, and directly shows the bunching of vehicles, and where it takes place. However, it is restricted to single day and route, which is impractical for an analyst searching for trends, or to systematically identify triggering events leading to bus bunching, which take place at particular locations.

Another application of the trajectory-plotting tool is shown in Figure 46. It displays the actual departure times of all trips departing at the same time from the first stop during February 2011, for a few consecutive runs during the PM peak. This figure plots the departure distribution at the stop level for consecutive runs. It is a useful tool that provides an insight into vehicle bunching.

Figure 46 Departure time of successive runs at the stop level. All trips of 02.2011



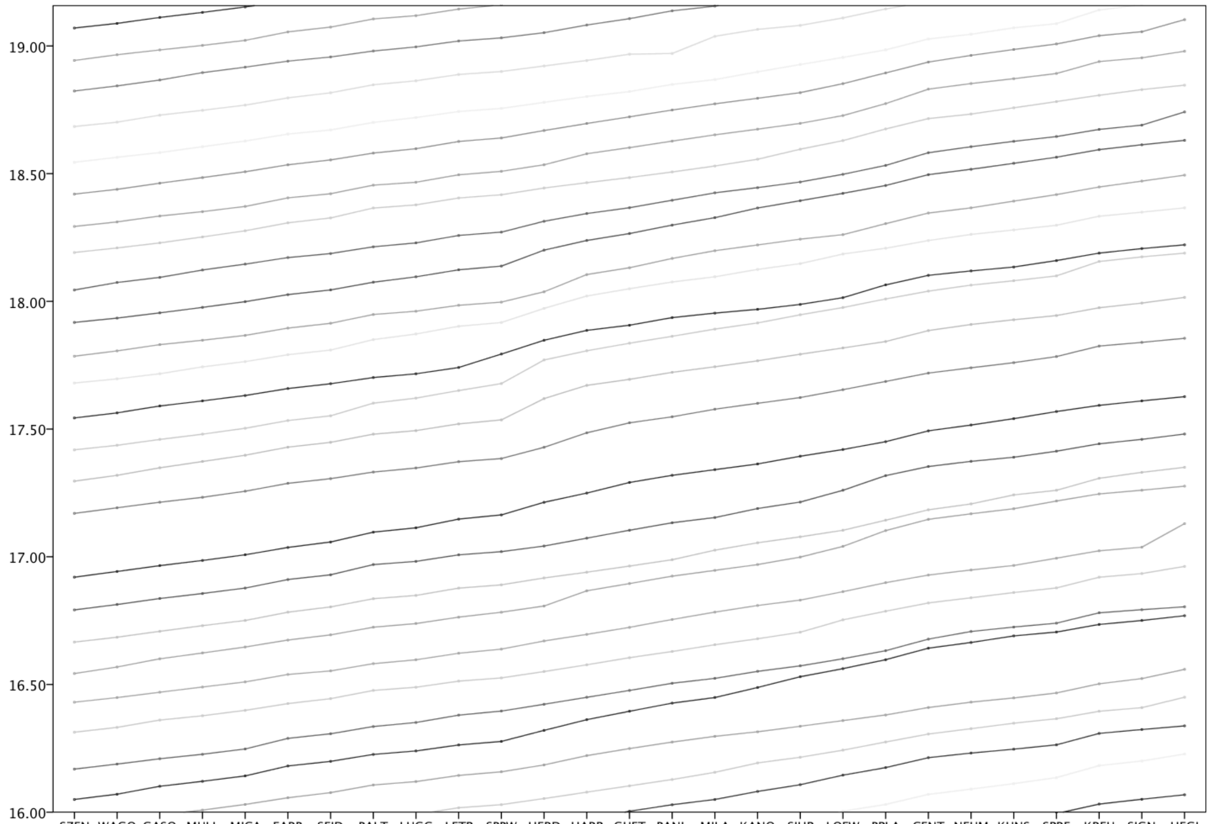
Even though only six consecutive runs are plotted, with a planned departure from the first stop (Schlieren Zentrum) between 16:55 and 17:32, it is clear how vehicles depart at consistent times in the first part of the route. As vehicles travel along the line, their departure times start to vary, and consequently deviate from the planned departure time along the route (not shown). Key stops where deviation is triggered are Bahnhof Altstetten and Herdernstrasse.

Bus bunching is not directly visible in this figure (because individual observations mixing with others are not necessarily bunched if consecutive runs in a particular day are all e.g., 10 minutes late), however, some patterns can be identified for particular runs. The run departing at 16:55 is quite consistent until Herdernstrasse, where dispersion starts and continues until Central, where dispersion decreases slightly and then remains constant until the end of the run.

Following runs (departing at 17:02 and after) display different departure patterns, with between 2 and 5 vehicles per run apparently being late enough to be caught up by the next run, (of a total of 22 runs in working days of February 2011). The largest triggering effect, which is consistent with all other previous analysis, takes place in Herdernstrasse. Particularly for the runs departing from Schlieren Zentrum at 17:17 and 17:25 delays after Herndernstrasse seem to have an effect on the following runs, where departure times deviate towards earlier departures. Most likely, the restriction policy to avoid early departures decreases the bunching effect by slowing down the following vehicle. However some vehicles show a tendency to depart earlier than planned.

In order to identify bunching vehicles, individual trajectories must be plotted for each day, as mentioned previously. In Figure 47 this was done for the runs during the PM peak in February 7th, 2011. No direct bunching is observed, nevertheless it can be clearly seen how the time between vehicles (frequency) varies along the route, almost to the point where vehicles catch up to each other. This shows that even though previous performance measures display good results, operation is not perfect, and there may be potential for improvements. Note: Y-axis scale is decimal, not sexagesimal.

Figure 47 Recorded departure time of successive runs. All trips of 7.2.2011



### 5.4.5 Passenger waiting time

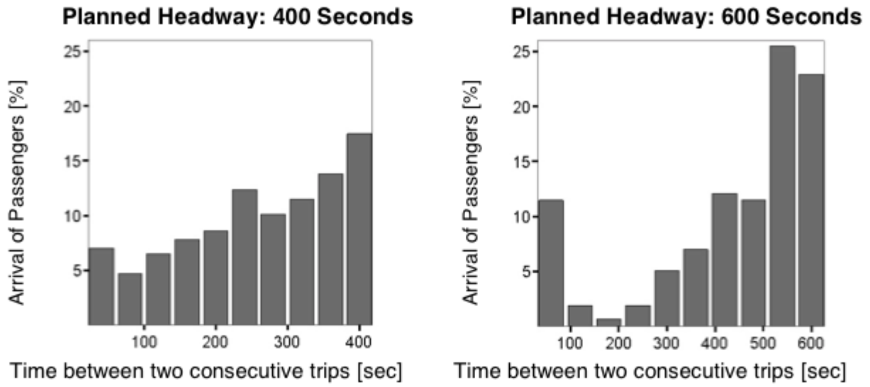
Conventional service performance measures such as the ones discussed until now, focus on reliability from the operator's perspective. These "traditional" performance measures do not relate passenger waiting time (or crowding) with service reliability. Thus, they underestimate the real cost of waiting and at the same time fail to evaluate the impact of unreliable public transport services on passengers.

This section employs the methodology developed by Furth and Muller (2006) to analyse waiting time using AVL data. Specifically, it uses headway distribution data to determine and analyse passenger waiting times at the route level for each of the time profiles previously used in the analysis. Crowding was not part of the analysis.

On routes with short headways (10 minutes or less) the literature generally agrees that random passenger arrival at stops can be assumed. This assumption will be held in the present work. In Zurich however, research by Luethi, Weidmann et al. (2006) found that even at 5-minute headways, some passengers consulted schedules and did not arrive randomly at the station, as shown in the temporal density of passenger arrivals at stops in Zurich, between the scheduled departure times for successive (AM peak hour) trips of Figure 48. This is interesting because the threshold is much lower than many models assume.

Their research also found that time of day and reliability had an important influence on passenger arrival rates, because when passengers believed the OTP of the service was good, they arrived closer to the scheduled departure time.

Figure 48 Temporal density of passenger arrivals at stops in Zurich. AM peak hour



Source: Luethi, Weidmann et al. (2006)

### *Passenger waiting time analysis framework*

The framework developed accounts for how uncertainty in headway and schedule deviation impacts not only the time that passengers have to wait on the platform, but also the amount of time they have to budget for waiting. The framework is described in detail in Furth (2006), and the mathematical justification can be found in Furth and Muller (2006). In this work, only a short description will be included for the methodology dealing with short headway services.

Using AVL records vehicle departures (from which it is possible to calculate headways) and assuming that passengers arrive uniformly and can board the first vehicle arriving at the station, mean waiting time and the distribution of waiting time can be determined. **Platform waiting time** is the time passengers spend waiting at a stop for a public transport vehicle to arrive.

With AVL data it is also possible to estimate the time passengers have to budget for waiting. To reduce the probability of arriving late at their destination, passengers have to plan an additional time to the mean waiting time. An assumption is that 5% of the passengers will accept the risk of arriving late. Therefore, the 95th percentile waiting time can be translated to the **Budgeted waiting time.**

$$W_{budgeted} = W_{0.95}$$

At the same time, budgeted waiting time can be divided in two parts: the actual waiting time (platform waiting time), and the rest, which is the case when a passenger budgets 10 minutes to wait, but the bus arrives after 4 minutes. The 6 remaining minutes are the **Potential waiting time**. Potential waiting time is not spent waiting at the platform, but at the destination. However it represents a cost for the passenger, as he or she could have potentially used this time doing something else, therefore it is a hidden cost associated with waiting, and dependent on service reliability, or uncertainty.

**Equivalent waiting time** is the weighted sum of platform and potential waiting time, which expresses the passengers' waiting cost in equivalent minutes of platform waiting time. If the weight given to potential waiting time is 0.5, the equivalent waiting time is given by the equation below:

$$W_{equivalent} = W_{platform} + 0.5 \times W_{potential}$$

The coefficient 0.5 expresses the cost of a minute of potential waiting time in terms of platform waiting time. It is an assumption, however consistent with travel demand research. When this value is 0.5, average equivalent waiting time can also be expressed as the average of mean platform time and budgeted waiting time, as follows:

$$W_{equivalent} = 0.5\ (W_{platform} + W_{0.95})$$

Moreover, passenger waiting time can be divided in two parts, ideal and excess waiting time. **Ideal waiting time** is the average waiting time resulting if service would follow the schedule exactly. **Excess waiting time** is the difference between actual and ideal waiting time. Therefore, excess waiting time is the component that can be attributed to operational issues. Following the work by Wilson, Nelson et al. (1992), mean waiting time can be partitioned as shown:

$$W_{ideal} = 0.5\ E\ [H_{schedule}]\left(1 + cv_{H,schedule}^2\right)$$

$$W_{excess} = E[W] - W_{ideal}$$

where $cv_{H,schedule}$ is the coefficient of variation of scheduled headways. The idea behind separating excess from ideal waiting time is to provide an idea of the quality of operations and the extent to which service could be improved (from the passengers' perspective) by improving service reliability. The concept of ideal and excess waiting time can be applied not only to mean waiting time, but also to budgeted and equivalent waiting time.

### *Short-headway waiting time analysis*

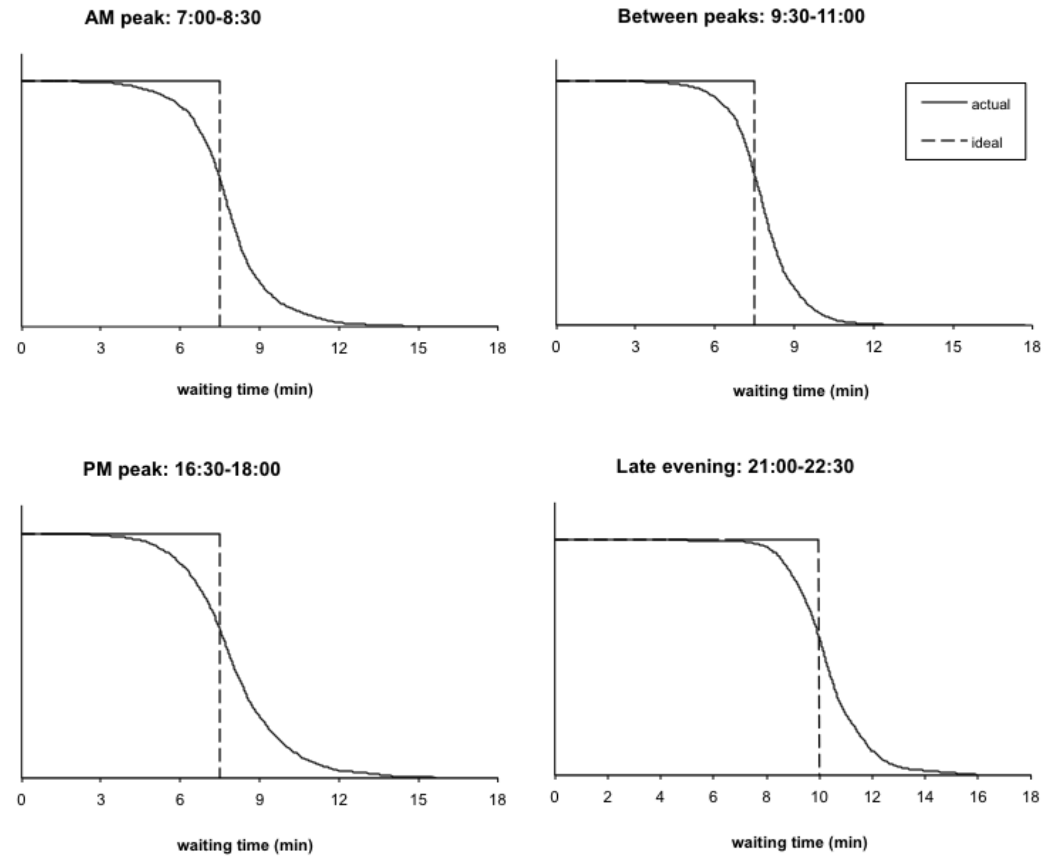
Given the assumptions of random (uniform) passenger arrivals, and passenger departing in the first vehicle arriving to the stop, the complete distribution of waiting time can be determined from the set of recorded (observed) headways in the AVL data. This determination in the proposed methodology is a step beyond the well know, and commonly used mean waiting time formula:

$$E[W] = 0.5\ E\ [H](1 + cv_H^2)$$

where E[W] is the mean waiting time, E[H] the mean headway, and $cv_H$ is the coefficient of variation of headway (standard deviation of headway divided by the mean). A simple example explaining the methodology can be found in Furth (2006).

For the case of Line 31 in Zurich, the waiting time distribution was calculated following the methodology for each of the four time profiles at the route level. Spread sheets developed within the methodology were adapted for the Zurich headways data, which is a much larger data set than the original document included. The results are shown in Figure 49.

Figure 49 Cumulative passenger waiting time distribution. All time profiles



The cumulative distributions of waiting times shown above illustrate the relationship between headways and waiting time, however, this it is not a useful format to report to management or service quality monitoring. The Y-axis corresponds to the total observations for the period, which were different for each time profile.

For this reason, two formats are suggested within the developed methodology. The first is a summary of platform, budgeted and equivalent waiting time that condenses passengers' waiting time experience, where it is possible to show waiting time breaking out between ideal and excess waiting time.

The second format shows the share of passengers in various waiting time ranges or "bins". This format supports company policy such as: "no more than x% of passengers should have to wait longer than (headway + y) amount of minutes." Public transport agencies in places like Paris, Brussels and Lyon are among those that (at least partially) use such a standard.

### *Performance measures*

Table 27 and Figure 50 summarize the route-level passenger waiting time service performance measures. They correspond to the first reporting format proposed by the developed methodology, expanded for all time profiles. Included are all recorded eastbound services during working days of February 2011 for Line 31.

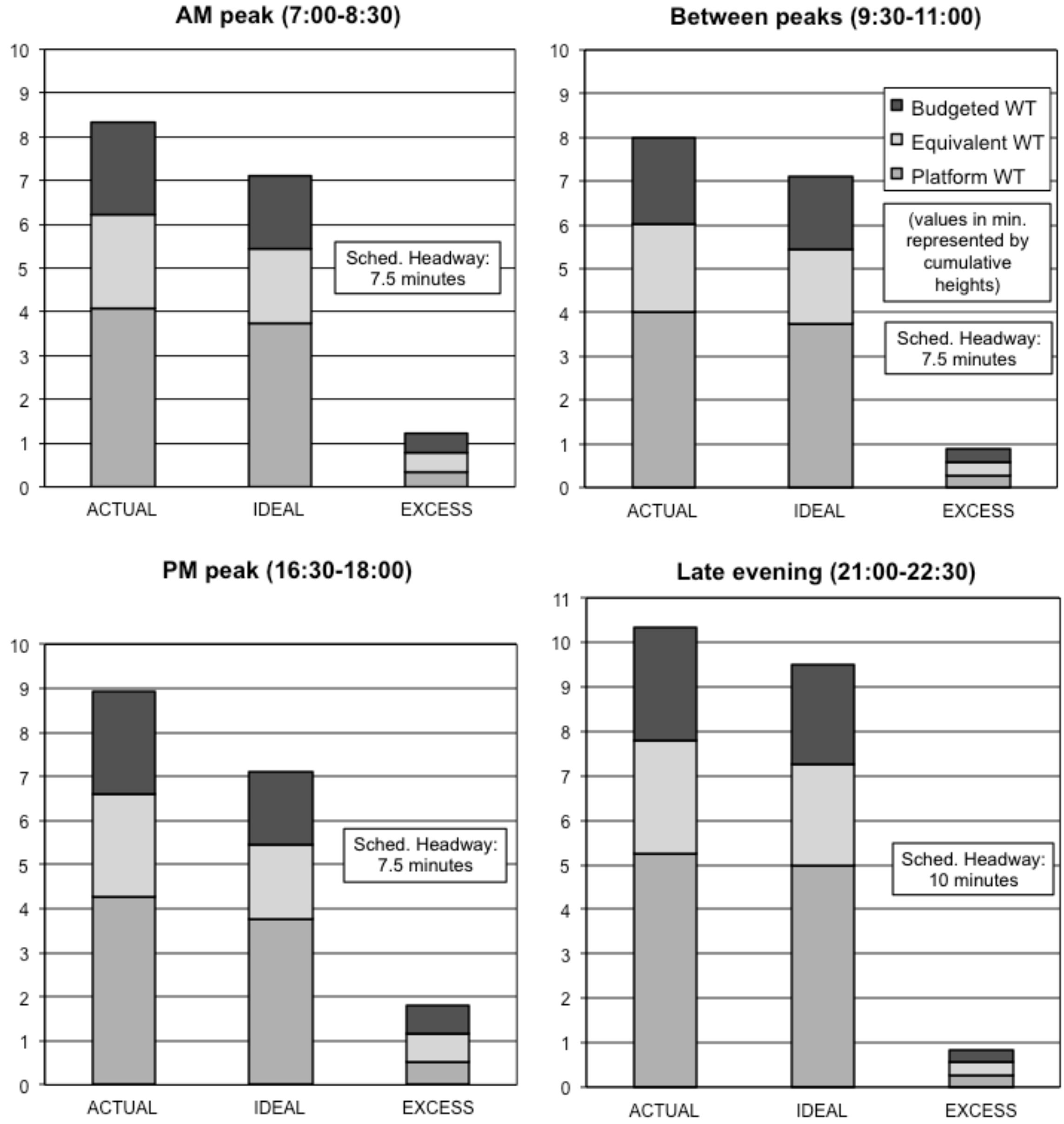
Table 27 Passenger waiting time performance measures at route level

| Time of day | Waiting time | Observed | Ideal | Excess |
|---|---|---|---|---|
| **$7^{00}$–$8^{30}$** | Mean Platform | 4.10 | 3.75 | 0.35 |
| | Equivalent | 6.22 | 5.44 | 0.78 |
| | Budgeted | 8.35 | 7.13 | 1.22 |
| **$9^{30}$–$11^{00}$** | Mean Platform | 4.02 | 3.75 | 0.27 |
| | Equivalent | 6.01 | 5.44 | 0.57 |
| | Budgeted | 8.01 | 7.13 | 0.88 |
| **$16^{30}$–$18^{00}$** | Mean Platform | 4.25 | 3.75 | 0.50 |
| | Equivalent | 6.59 | 5.44 | 1.15 |
| | Budgeted | 8.93 | 7.13 | 1.80 |
| **$21^{00}$–$22^{30}$** | Mean Platform | 5.26 | 5.00 | 0.26 |
| | Equivalent | 7.80 | 7.25 | 0.55 |
| | Budgeted | 10.35 | 9.50 | 0.85 |

The calculated passenger waiting times are in fact performance metrics that relate service reliability to the real cost that waiting time represents to public transport users. This is because the cost of waiting involves not only the cost of waiting at the stop, but also potential waiting time (the additional time passengers have to budget for waiting, but is not used waiting). Budgeted waiting time is related to extreme values of the waiting time distribution, which are very sensitive to service reliability.

Measures of equivalent waiting time (derived from the weighting of actual and potential waiting time) as well as excess waiting time were calculated. Results indicate that irregularity on this route costs passengers a different amount of equivalent excess waiting time during the day, from an average of 33 seconds during the most regular period (21:00 – 22:30) to an average of 70 seconds during the PM peak, or 115% larger.

Figure 50 Passenger waiting time summary. All time profiles at the route level



The second reporting format proposed by Furth and Muller (2006) is the percentage of passengers with excessive waiting times. This is a convenient way of presenting the passenger waiting-time distribution. Because every minute of headway represents the number of passengers arriving during that time, the minutes belonging to each headway are distributed into bins, with low-waiting time bins being filled first .The thresholds of the bins correspond to those defined in Table 14. The bin frequencies can be calculated from the cumulative distribution, but also directly.

In order to illustrate the concept, an example is taken from Furth and Muller (2006). Given the following headways for a given bus service: 4, 5, 7, 9, 10, and 13 minutes, the bins are calculated directly in Table 28.

Table 28 Passenger waiting time bin frequencies. By Furth and Muller (2006)

| **Headway (m)** | **Min in bin 0-8** | **Min in bin 8-10** | **Min in bin 10-12** | **Min in bin 12+** |
|---|---|---|---|---|
| 4 | 4 | | | |
| 5 | 5 | | | |
| 7 | 7 | | | |
| 9 | 8 | 1 | | |
| 10 | 8 | 2 | | |
| 13 | 8 | 2 | 2 | 1 |
| T=48 | 40 | 5 | 2 | 1 |
| Mean=8 | 83.3 % | 10.4 % | 4.2 % | 2.1 % |

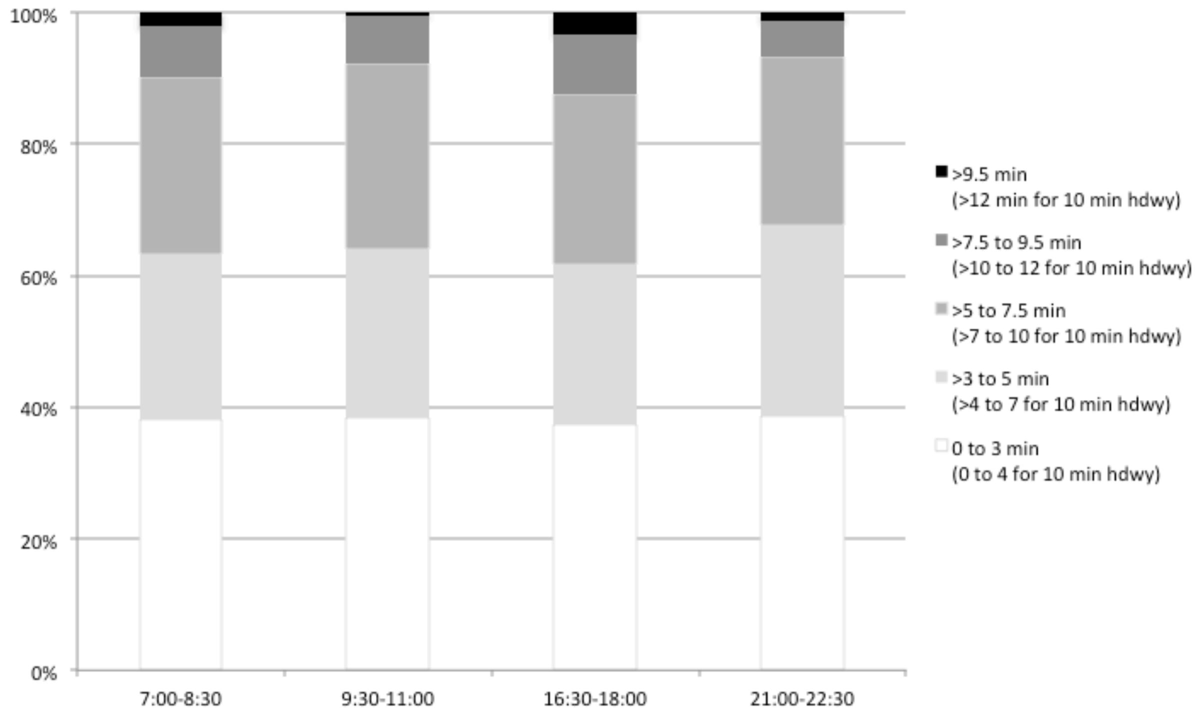
The bin time frequencies for bus Line 31 were calculated for each time profile and are presented in the table below.

Table 29 Percentage of passengers in waiting time bins. Line 31 eastbound

| **Time of day** | **0-3 min (7.5)**<br>0-4 min (10) | **>3-5 min (7.5)**<br>>4-7 min (10) | **>5-7.5 min (7.5)**<br>>7-10 min (10) | **>7.5-9.5 min (7.5)**<br>>10-12 min (10) | **>9.5 min (7.5)**<br>>12 min (10) |
|---|---|---|---|---|---|
| **$7^{00}$–$8^{30}$ (7.5)** | 38.2 % | 25.0 % | 26.9 % | 7.8 % | 2.1 % |
| **$9^{30}$–$11^{00}$ (7.5)** | 38.5 % | 25.5 % | 28.2 % | 7.4 % | 0.4 % |
| **$16^{30}$–$18^{00}$ (7.5)** | 37.4 % | 24.4 % | 25.8 % | 9.0 % | 3.4 % |
| **$21^{00}$–$22^{30}$** (10) | 38.8 % | 29.0 % | 25.5 % | 5.6 % | 1.1 % |

The graphical representation of Table 29 is shown in the Figure below.

Figure 51 Percentage of passengers in waiting time bins. All time profiles



The results draw a picture on the impact that service reliability has for the share of passengers that wait a given amount of time assuming a uniform (random) passenger arrival at the stops. From the thresholds defined in Table 14, the percentage of passengers that fall into each of the gradation bins is included in the Table below:

Table 30 Passenger waiting time bins. Evaluation threshold values per time profile

| | **Relative to headway** | **$7^{00}$–$8^{30}$** | **$9^{30}$–$11^{00}$** | **$16^{30}$–$18^{00}$** | **$21^{00}$–$22^{30}$** |
|---|---|---|---|---|---|
| Good | 0 – Headway | 90.1 % | 92.2 % | 87.6 % | 93.3 % |
| Marginal | Headway + 2 | 7.8 % | 7.4 % | 9.0 % | 5.6 % |
| Poor | > (Headway + 2) | 2.1 % | 0.4 % | 3.4 % | 1.1 % |

Consistent with previous analyses, the PM peak time profile performs the worst, during which a higher percentage of passengers wait a longer time at stops. During late night services, less than 7% of passengers have to wait more than a full headway. This value increases to over 12% during the PM peak period.

Given that random passenger arrivals are assumed, it is expected that the actual times that passengers wait for a vehicle are lower in Zurich, because the distribution of their arrival is in reality not random, but as can be seen in Figure 48, tends to be skewed towards the arrival of the next vehicle. It is possible that current reliability levels, high quality passenger information, or other causes lead to this happening, however it is not possible to make any conclusive statement in the framework of this project.

## 5.5 Summary

This section addressed the analysis and evaluation of the available AVL data to calculate performance measures that characterize reliability from the perspective of public transport operators but also from the passengers' point of view.

Operator-oriented measures include travel time, speed, punctuality and regularity evaluations at the route and stop level for four different time profiles. For the passenger perspective, a methodology was applied to calculate several measures of passenger waiting time as well as the share of passengers waiting a given amount of time relative to service headway. Only route-level analyses were done for the passenger waiting analysis.

The results show that the PM peak time profile has the lowest values of service reliability for all the observed attributes, for the selected operator- and passenger-oriented measures.

# 6 Comparison of planning and operations at the VBZ

## 6.1 Chapter overview

Chapter 4 provided an insight into the service planning process at the VBZ, while chapter 5 described the performance analyses at the different levels done for the case study of Line 31. In this chapter, the planning of the service is contrasted to the actual service delivery to identify potential for improving service reliability, as depicted in the conceptual model found in Figure 7. In the first section of this chapter, the operational level is studied and related to the different planning levels in public transport. Subsequently, the results of the qualitative comparison in this chapter, together with the analyses of Chapter 5 are used to identify potential gaps either in planning or operation. These gaps represent locations or situations where reliability decreases, and where measures could be implemented to overcome the current situation and ultimately improve the service for customers.

## 6.2 Qualitative comparison

The planning process at the strategic and tactical level, together with the policies and technology in place to prioritize public transport vehicles, provide the operational framework in which a system delivers its service. In Zurich, long-term network development strategies that take into account the city's mobility objectives and articulate them with current and future land uses, are the result of the strategic planning process in public transport.

A number of precisely constructed timetables that rely on software tools, but mostly on the experience of schedulers at the VBZ, are the main product of a tactical planning process. These timetables are the promise made by the VBZ to their customers, as they provide detailed information on when a vehicle serving a particular line, will depart from each and every station in the network throughout the day.

The level to which the operational department at the VBZ can hold this promise, in light of the many possibilities for disturbances and delays inherent of a system that is not completely segregated from external influences, provide an idea of the reliability of their service.

In the following section, the operational level is described from two perspectives: the planning activities designed to prepare for incidents that take place with different degrees of frequency; and the reaction to incidents once they happen. These two perspectives relate to the strategic and tactical planning levels throughout, and serve as a way of comparing service planning to operations, or service delivery. This section is mostly based on an interview done at the VBZ with the head of the control center, Mr. Peter Flury in March of 2010, and is complemented by a number of meetings and visits that took place at the VBZ in the framework of this project.

Subsequently, the performance analysis found in Chapter 5 is related to possible reliability gaps, derived from the operational data analysis.

### 6.2.1 The control centre: eyes and ears of the system

Zurich's public transport control center is located at the offices and main depot (and maintenance workshop) in Altstetten. It started operations in 1971, being the first of its kind worldwide. It has evolved from just knowing the location of the vehicles to managing a precise operation with high punctuality rates and connection assurance. The Intelligent Transportation Systems (ITS) currently in operation corresponds to the 4th generation, focusing on high quality passenger information and providing an integral travel throughout the network.

The actual control centre consists of 5 workstations, 4 of which are used for regular operations while the other one is available for incident management and training. Each dispatcher manages between 10 and 15 lines, independent of the mode. In peak hours, each dispatcher is responsible for about 120 vehicles.

The tasks and responsibilities of the control centre can be summarized as follows:

- Supervision of line operation while adhering as much as possible to the schedule.
- Managing of events according to their level of impact on operations, from delays of a few minutes, to collisions, accidents, emergencies and major incidents such as breakdowns or blockages.
- Processing information and delivering it to the public by different channels.

Under deterministic operating conditions, it could be argued that a control centre would not be needed, as timetables are designed to provide instructions to the drivers when to depart from any given station. However, the reality of operations involves a stochastic system behaviour that leads to situations, states and events that cannot be planned in advance. The task of the control centre is then to identify these situations, solve them and minimize their impact on operations, in order to bring the system back to a regular operational state as fast as possible.

### 6.2.2 The operational level: planning reactions to incidents

Parallel to day-to-day supervision and management tasks, the control centre has developed a series of processes to be implemented when particular incidents beyond normal delays occur. The main focus are incidents or situations that affect tram operations, given that it is impossible for a tram to overtake a blockage in the way sometimes is possible with a bus. These processes have been developed over a long period of time (sometimes over decades), and represent a tool to which dispatchers can recourse to once an incident has been reported and identified (e.g. a collision with injured person).

These planned responses to incidents are a standardized tool that aims at reducing both the time needed to deal with situations, and the impact that certain events might have in operations. The general objective is to keep vehicles moving despite blockages or disruptions, through the implementation of pre-defined processes. These processes are related to the available infrastructure and list, step by step, the different tasks needed to overcome any kind of disruption. Particularly important is the redundancy of infrastructure (e.g. switches, tracks and catenaries for trams) at key points of the network (strategic planning level), which physically provide ways for dispatchers to implement deviation strategies planned around that infrastructure availability while a given disruption is overcome.

The control center at VBZ considers that good (i.e. realistic and achievable) schedules, regular operation and quick reaction to incidents, supported by the previously mentioned processes, represent the main tools to provide a high quality public transport service for their customers. From their point of view and experience, the network in Zurich is already so dense that increasing vehicle frequency in many lines (reducing headway) brings no additional benefit due to the disruptions caused among public transport vehicles themselves. Critical points are Central, Bellevue, Hauptbahnhof and Stauffacher, which have no capacity for additional vehicles without compromising the quality of operations. In fact, a project was implemented in 2008 to harmonize the vehicle frequencies, reducing them from 9 to 8 vehicles per hour. The results were positive, as own disruptions decreased and the stability of operations increased, without compromising the level of service. Courses spared during rush hours were distributed throughout the day, further improving service for the users. Additional capacity in the future will consequently need to be added via larger vehicles, not additional courses.

In cases where temporal disruptions take place (e.g. construction sites), tactical planning tries to avoid changes in running times for existing timetables, and the strategy followed is to have an additional vehicle for the same timetable. In this way, all vehicles have a larger recovery time buffer at terminal stations, so even if they are allowed to run late, they can recover after each course. This is a compromise for such cases where disruptions can occur with a given frequency, but do not always happen. If running times were increased in the timetable, vehicles would systematically run early and holding would take place often, increasing travel time for passengers even when this would not be necessary. In the event that the situation results in less delay than expected, the additional vehicle can simply be taken out of service and customers would not be affected. This flexible interaction between planning and operations is quite passenger oriented, as the waiting time for the users is considered, and the additional delay is absorbed when it takes place, not for every single trip, as the case would be if timetables were adjusted.

### 6.2.3 The operational level: dealing with incidents

As previously mentioned, dozens of processes have been developed for all sections in the (tram) network where a disruption can take place, for any given reason. These are clearly identified and include precise instructions on how to react to a variety of incidents, such general disruptions, derailments, catenary damages, collisions, blockages, power outings, fire or explosion in a vehicle or a stop, fire alarms, police and/or ambulance requirements, weather related events, and many more. The idea is to identify the location, most probable cause (and possible duration) of a problem very quickly, and immediately implement a set of standardized instructions that include all the things that need to be done to overcome that particular disruption. These may include communication with drivers, police, emergency services, technical services; providing instructions; informing the public; and do everything possible to avoid vehicles behind the blockage to be affected and stop delivering passengers. These processes have been developed and refined throughout many years, and are the result of the know-how of the control centre at the VBZ.

Once an incident has been reported, depending on the severity (emergency, or not), a dispatcher receives the call and remains in contact with the driver, other dispatchers can listen to the communication, take over the supervision of the lines assigned to the first dispatcher, and communicate with emergency offices as needed. Dispatchers are trained to take independent decisions and act as a team when required, following the previously mentioned standardized processes. Depending on the severity of the disruption, operation may be affected partially (continue operating on one direction, or via a detour), or totally. In the latter case, and depending on the time of day, spare vehicles (normally diesel buses) are deployed to temporarily replace trams.

A pre-requirement for these standardized processes to be highly effective is the rapid response of the control centre to incidents or disruptions, as delays propagate very quickly in a network as dense as Zurich.

Changes in operating conditions, resulting from financial saving efforts, have also required new approaches to react to a reduced number of available (reserve) vehicles. Previously 3 to 4 vehicles were accessible, today, only one tram and one bus are available as a spare during rush hours. A solution to this issue has been the implementation of early turn policies, whenever a vehicle exceeds the time required to depart from a terminal station on time for the following course. However, a handicapped-oriented policy to have every second course be a low-floor vehicle complicates the implementation of early turns, as the sequence of low and high vehicles is disrupted. An increased tolerance for exceptions to the policy (only when required) might prove beneficial for operations, as the vast majority of passengers can use a high floor vehicle. In the future, as new vehicles are acquired and put into service to replace older vehicles, this restriction should be overcome.

## 6.3 Reliability improvement potential identification

The infrastructure and priority conditions deployed in the strategic level, summed with the operational "instructions" designed at the tactical planning level, provide the framework in which a public transport system delivers its service to the users. The discrepancies between the planning and the actual delivery of service can be interpreted as the unreliability of the system.

In order to identify the potential for improving reliability, in the following, the multi-level performance analyses of Chapter 5 are related first, to the operational processes described in section 2.4, and second, to the different elements that influence reliability, described and classified in section 3.3.

### 6.3.1 Within operational processes

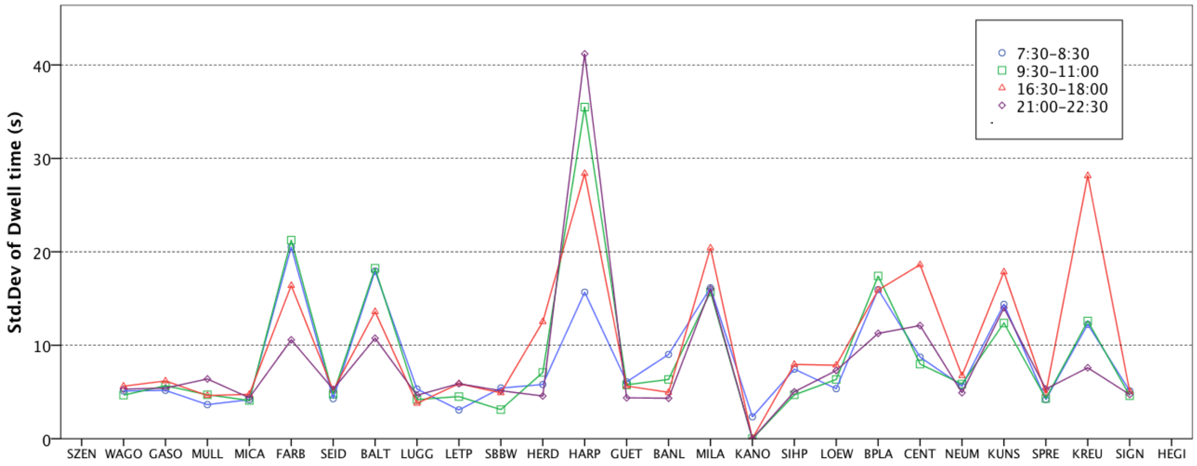
The two main components of the total travel time between terminal stops are the time spent at each stop, and the time required getting from one stop to the next (driving time). An additional classification of driving time is the productive driving time where vehicle movement takes place, and the time that is "wasted" due to congestion, an obstacle of any kind, or due to a traffic light; any of which considerably reduces the speed of a vehicle or brings it to a halt. No clear differences were determined between productive and unproductive travel time for vehicles.

#### *Time spent at stops*

Not considering the terminal stops (as this is where trips begin and end, and no actual passenger dwell time takes place, but a turning, recovery and driver rest time), all stops of a public transport line follow the same generic dwell process, depicted in Figure 5. A number of fixed time processes take place, as well as processes that vary according to parameters defined in Table 5. One of the parameters (not considered in this study) is the passenger volume at a given stop, and most importantly, the time needed by each passenger to board/alight a vehicle, or passenger exchange rate. This is especially critical when a vehicle is travelling close to its capacity, as passenger movement is heavily restricted (slowed down) and passenger exchange times are extended. Vehicle design, layout, number and width of doors, speed of door opening and closing, are all variables influencing passenger exchange times. From the infrastructure perspective, grade access, stop layout and passenger distribution at a stop also influence time spent at a stop.

In this study, no detailed dwell analysis was done, in part because no passenger volume data was available. However, a figure of the variation in dwell time (difference between actual departure and actual arrival time) for each of the used profiles at each of the stops (excluding terminals) is found in the following page.

Figure 52 Dwell time variation at the stop level for all time profiles



The figure above shows the standard deviation (in seconds) at each stop for the given time period. The causes for these variations cannot be directly inferred from the available data. Considerable dwell time variations can be seen at Farbhof, Bahnhof Altstetten, Hardplatz in particular, Militär-/ Langstrasse, Bahnhofplatz, Kunsthaus and Kreuzplatz. For the first two cases, most variation is taking place in the morning peak and between peaks, followed by the evening peak and lastly by the late evening period. It is possible that the direction of travel (towards the city centre) impacts variation in the dwelling time due to passenger volumes.

In Hardplatz, variation is highest during the late evening, but less than half of that during the AM peak period. It is possible that this variation is induced by the driver exchanges, which are most likely not taking place during the AM peak. During the PM peak, most variation in dwell time is observed in the second half of the line, particularly in Central, and Kreuzplatz. Some of the variation in dwell time observed at each of the stops should be attributable to planned connections in the schedule, particularly at Farbhof, Bahnhof Altstetten, Hardplatz, and Central. It is not clear if Militär-/ Langstrasse is a stop with a planned connection with Line 32. In Kunsthaus, dwell time variation is considerable, but consistent throughout the day. This is due to the traffic flows taking place at that particular stop: four tramlines and a street with high volumes of private traffic bring the intersection close to its capacity. Vehicles of Line 31 must wait for a slot in the traffic light cycle, which according to the VBZ is the reason for longer dwell times at that particular stop.

Finally, at Kreuzplatz, almost 3 times more variation is observed during the PM peak period as during late night services. It is possible that the different lines (11, 15 and S18) also serving at the station, and the limited infrastructure (buses share stop with trams and the S18) have a negative impact on the consistency of dwelling times at that particular stop. Possibly dwell times of Line 31 need to be very quick to avoid disrupting tram services, and eventually buses may have to wait for rail-based vehicles to depart and clear the stop.

A practical tool to implement at stops are time holding practices, which are normally used to avoid vehicles running early, and reduce delay by adding buffer time to a schedule along the line instead of only at the terminal station. Drivers can see (or are informed of) their deviation from the schedule, wait at particular (holding) points when running early (normally where the required infrastructure is available) and return back to schedule.

At the VBZ, planned transfers at particular stops with high passenger exchanges, as mentioned in section 4.4.2, are a way of providing both a holding point, and including some buffer time into the schedule. The coordination of the lines (and its optimization) at the schedule level is an advantage for the passengers, as waiting times due to transfers are then considered, and where possible, reduced. However, the amount of additional buffer time inserted in the schedule is purely based on experience.

To the knowledge of these authors, there is no systematic practice to optimize the allocation of buffer time in the schedule. Naturally, restrictions such as vehicle number, union agreements on resting time, vehicle travel time, etc., play a role in the amount of buffer time that can be assigned at any given point, and the experience of a scheduler is no doubt essential. A possibility would be to implement optimization functions that include these restrictions and systematically optimize the buffer time allocation in the schedule. This is out of the scope of this work and remains as potential for the implementation of existing or future research.

### *Time spent between stops*

Most of the analyses done in chapter 5 dealt with measures that reflect the impact of external elements on the vehicle travel time between stops, i.e. the driving time. Variations in travel time influence punctuality, regularity and consequently, passenger waiting time. Statistical measures reflecting variation of the previous metrics give an idea on how much a particular measurement changes between locations and/or time of day.

For the travel time analysis, it is clear that during the PM peak hour, more than 50% of the vehicles systematically require between 1 and 2 minutes more than the planned travel time, as reflected in Figure 24. Possible measures to increase reliability during these periods, would be to increase the planned travel time between 1 and 2 minutes during both the AM and the PM peak. The potential increases in resources needed to accomplish this are not part of this study.

From the normalized travel time distribution in Figure 26, very strong variations in travel time are observed just before Herdernstrasse and Hardplatz, when comparing the PM peak period with the period between peak hours. For the first case, the most likely cause for this variation is the sheer traffic volume at the crossing of Herdernstrasse and Holhstrasse with the subsequent queue build up. Potential for decreasing variation (and increasing reliability) rests in the possibility for the buses of Line 31 to jump ahead of the private vehicle queue and cross the traffic light with priority. No other public transport lines are present at the crossing, and the headway of 7.5 minutes should have no significant impact on the capacity of the intersection.

Travel time distributions just before Hardplatz are also much larger during PM peak periods than between peaks (when dwell time deviations are particularly high), see Figure 26. Even though a bus lane is present at the crossing, it is possible that the vehicles of Line 31 are still losing time behind a queue. In this case, if the street geometry permits it, an extension of the bus lane would be a possibility to reduce variation. Another possibility would be to extend the green time in the traffic light cycle to reduce the length of the queue and allow the vehicles of Line 31 to get into the bus lane faster.

In Bahnhof Altstetten, the difference between PM peak and between peaks is not as drastic as for the other two locations. The causes are probably the reduced infrastructure (only two lanes) with mixed traffic; the number of bus lines converging during peak hour (six); and the large number of pedestrians crossing the street and transferring between bus lines and the trains serving the railway station.

Two possibilities for improving the performance of Line 31 (and other bus lines) at this station would be first to reduce (or restrict) the private vehicle traffic just in front of Bahnhof Altstetten (at least during peak hours); and second, to improve the flow of vehicles and pedestrians either with collaboration of the police (as it already happens in Central), or with temporary pedestrian traffic lights. This last measure is to be studied carefully, as waiting times for pedestrians should be kept to a minimum to avoid people crossing in red to reach a connection at the train station, which might lead to potentially dangerous situations.

A very good performance metric that compares planning with operations is the run time ratio (RTR), shown in Figure 27. A value of 1 indicates that actual running time matches the planned running time. Larger values mean actual running time is exceeding planned time. After talking to the VBZ, the large peak in Kanonengasse was due to road works. Other points where actual running time systematically exceeds the planned running time are the section between Farbhof and Seidelhof (1), between Herdernstrasse and Hardplatz (2), between Central and Neumarkt (3), between Kunsthaus and Sprecherstrasse (4), and between Kreuzplatz and Signaustrasse (5). Possibilities for improving this situation could be either increasing the travel time between sections in the planning stage (schedule), or accelerating vehicles by reducing the influence of external elements.

It is interesting that in (1), the highest RTR is for the late night profile. It is possible that the drivers are running slow systematically, to avoid being early, i.e. it would be required to see if there is excess slack in the timetable for this section. For (2), potential improvements have already been discussed for the access to Hardplatz. In the case of (3), the scheduled arrival of a tram of Line 3 just one minute before Line 31 might negatively impact the travel time, as buses may have to systematically wait for the stop to be free. Case (4) is actually less critical during the PM peak, however, the traffic light just after Kunsthaus seems to cause delay. Furthermore, the road section until Sprecherstrasse is shared with traffic along a narrow street with several pedestrian crossings and potential for parked vehicles. Besides improvements at the traffic light, no further potential is found for this section. Finally, for (5), leaving the stop, and getting through the intersection seems to be the problem, as the stop is shared with 2 tram lines plus the S18. Moreover, several streets converge at this busy intersection. Only minimal potential for improvement is observed here, besides a slight increase in the planned travel time. After the intersection, vehicles run into a shared tram/bus lane, so private vehicle traffic is not an issue.

Most variation in travel time is observed after Bahnhof Altstetten during the AM peak, at Hardplatz between peaks, and the road section leading to Herdernstrasse, as well as between Kreuzplatz and Signaustrasse during the PM peak (see Figure 28). Only comparatively small variations are observed during the PM peak. Potential measures to reduce this variation have already been discussed.

Sharp variations in median speed throughout the day (Figure 30) are clearly observed before Bahnhof Altstetten, Herdernstrasse, and Hardplatz. These might be attributed to traffic volumes and potential for improvement has already been discussed.

Punctuality and regularity analysis point at the same key places for decreases in performance along Line 31. Buffer in the schedule, tram lanes used by buses, and control strategies, most likely contribute to a partial (systematic) recovery after Central, especially in punctuality metrics. In the case of regularity metrics, Herdernstrasse has a triggering effect on headway deviation, with the difference (in comparison to punctuality) that irregularity tends to spread and after Central the spreading of the headway distribution stops, but hardly decreases. Even though it is not very clear, this triggering effect in Herdernstrasse can also be seen in Figure 46, where actual departure times start to vary and spread out.

Passenger waiting time, particularly at the route level, provides little information on where problems are taking place along the route. A disaggregate measure would most likely point out the same stops already identified, as waiting time increases with headway variation. It is nevertheless a useful measure from the customer’s point of view. Passenger volume data would enhance the calculated metrics, as service reliability could be weighted by the number of people using the stop. This would point to the locations where most people would benefit from service reliability improvements.

### 6.3.2 Within delay influencing elements

From the classification and categorization of the elements that have an influence on delay (section 3.3.2) summarized in Table 9, the analyses of chapter 5 provide only a partial insight into the relationship between travel time and the different states, properties and events taking place with different levels of frequency.

The most clear states reflected in the performance metrics are the level of traffic in the form of congestion (increased travel time, reduced speed), and the variability of travel demand, reflected in dwell time, as a proxy of passenger volumes. No clear statements can be made on the impact that traffic compositions, passenger composition or curb parking have on performance at any level of this study.

From the perspective of the properties influencing delay, stop layout and the provision of bus lanes are clearly reflected on the changes in performance. Reduced infrastructure at stops served by several lines can be problematic, such as the case of Neumarkt and Kreuzplatz. But having the infrastructure alone does not guarantee better performance, as is the case in Hardplatz. Bus lane availability (or the possibility to use a tram lane) greatly benefit performance, as can be clearly seen in punctuality metrics after Central.

For the case of regularity, its spreading is systematically slowed down in the presence of bus lanes. Travel time however does not seem to improve, as seen with the RTR metric, however schedules can always be refined to reflect better planned travel times. Other properties influencing delay were not studied in detail or observed as to having a large impact on performance.

Finally, for the events influencing delay, a clear example was Kanonengasse in this study, where most metrics were off due to the delay that the construction work caused. RTR was about 2.5, throughout the day, median speed was reduced to about 50 %, and a decline in punctuality was observed. Regularity on the other hand, was not impacted by this event. Other events might have taken place, but given the resulting outliers in the data, were not included in the analysis, and in practice are normally dealt with by the control centre.

## 6.4 Summary

The objective of this chapter was to relate the operational processes and different effects influencing delay to the multiple performance analyses done in chapter 5, in order to pinpoint locations where reliability problems exist. The most useful analyses to identify reliability problems are those focused on variations of metrics between times of day as well as along the line. Particularly useful was the travel time analysis, specially the run time ratio (RTR) metric. The RTR allows a direct comparison between planned and actual travel time, and identifies locations that either require either and adjustment of the planned travel time, or where improvements of other nature should be looked into.

Changes in speed were mostly related to changes in traffic volume, and dwell time was used as a proxy for passenger activity, as passenger counts were not available for this study.

Punctuality and regularity measures are mostly affected by the variations in travel time, and it was seen that bus lanes and stop layout have a clear impact on these performance metrics.

Critical points in Line 31 were identified at the road section before Herdernstrasse and Hardplatz, and large variations (soaring standard variation and coefficient of variation values) were also identified at these particular stops. Some possibilities for improvement were already discussed at the general level. They are expanded in the following chapter.

# 7 Improving service reliability

## 7.1 Chapter overview

This chapter condenses the findings of chapters 4 to 6 and relates them to ways of improving service reliability in Line 31. In the first part of the chapter, a literature review on the possibilities for reducing unreliability at different levels is contrasted to the strategies already in place in Zurich. Subsequently, the statistical analyses of chapter 5 are related to specific stops, locations and situations along line 31 that contribute to reductions in the quality of service. These situations are identified as potential for improving service reliability in the line. Finally, possibilities for reducing the impact caused by these situations are discussed and evaluated in a qualitative manner.

## 7.2 Strategies to reduce unreliability

It is well known that public transport services are influenced by both internal and external factors (see 3.3.2), a consequence of the dynamic nature of the operating environment. Variations in private vehicle traffic and passenger volumes (among many others) induce variability in the duration of one or more of the processes described in section 2.4.

Much has been done to increase our understanding of the causes for unreliable services and to develop strategies to improve public transport reliability. Early work in this area includes Abkowitz (1978) Turnquist (1981), Abkowitz and Engelstein (1984) and Levinson (1991), who identify the main causes for unreliability, and propose a number of strategies to improve it. In Abkowitz (1978), the authors propose three basic techniques: priority, control (dynamic changes in bus operations from original schedule), and operational (dealing with route, schedule and resource allocation changes). Work by Turnquist (1981) identifies four major classes of strategies for improving reliability in bus services: vehicle holding strategies (for schedule- and headway-based services), reducing the number of stops along a route, signal pre-emption and provision of improved ROW. Results indicate that such strategies can have substantial improvements in travel- and waiting time, and that the level of improvement depends on the particular situation, but mostly on the frequency of the service.

In Zurich, most of these strategies are already in place: holding strategies in the form of planned connections and additional buffer time. The distance between stops is dictated by an accessibility policy, which requires a stop to be accessible within 300 meters of an urbanized area. Signal pre-emption is in place for most, if not all, tram and bus lines. Finally, segregation from other traffic is limited given the scarcity of space and the multiple actors (pedestrians, cyclists, public transport, private vehicles, etc.) wanting to use it. A particularity is the clear preference for implementing tramlines, but not for bus lines in Zurich. Given that measures are either in place and fairly well extended, or restricted by policy, it is quite a challenge to propose ways to improve quality of service and reliability for public transport in an environment such as Zurich, where it may seem that most of what is possible is already in place, and with an operator such as the VBZ, keen on details and precision.

Regarding other ways to improve service reliability, Abkowitz and Engelstein (1984) propose a methodology to maintain service regularity through improved scheduling and real-time control based on models developed and validated from empirical data. Their findings suggest that mean running is chiefly influenced by trip distance, passengers boarding/alighting, and the number of signalized intersections. Work by Levinson (1991) acknowledges the development in technology taking place at the time and focuses on its role in service supervision. It describes the change that would later take place in industry practice, from controllers on the road, to automatic supervision of the entire fleet in control centres. Finally, a number of guidelines are suggested to improve supervision strategies, given the particular situation to improve. These are: service restoration-, schedule control-, headway control-, load control-, and extra board management strategies.

Scheduling and control practices in Zurich, described in sections 4.4.2 and 6.2.3, follow an approach largely based on experience. Currently, a number of software tools and IT support are in place for scheduling and are ubiquitous for operation management. However, in scheduling, software tools are seen as a way to reduce the burden on repetitive tasks. The experience of a scheduler is highly regarded, and applied throughout the process. Tasks such as schedule smoothing and vehicle pull in and outs are done by hand for every schedule of every route.

In the scope of this work, route length was not assumed to be a source of delay, as the aim was not to change the route configuration in any way, but rather to understand where reliability problems take place, and search for ways to improve the situation. Passenger count data were not available for analysis; however, dwell time was used as a proxy for passenger volume.

From the operational control practices mentioned in the literature, most are applied in Zurich (i.e. schedule and headway control). Strategies dealing with load control are not in place in Zurich and for such cases, the driver contacts the control centre for advice and instructions. The control centre is proactive in dealing with all kinds of problems and disruptions, and short reaction times from dispatchers together with an immediately available course of action (planned in advance) are considered essential for providing a high quality service for their customers.

From the literature, work by Ding and Chien (2001) deals with the specific problem of headway regularity. Making use of real time control technology in an “advanced public transportation system environment”, i.e. Automatic Vehicle Location (AVL) Systems, a real-time headway control model is developed to maintain desired headways. Their work demonstrates that control strategies can be used to regulate headways efficiently and reduce average waiting times. In the area of design and implementation of bus-holding strategies, Fu and Yang (2002) develop two models, one based on preceding vehicle headway, the other considering both the preceding and the following headway, to optimize the number and location of control points. Their work also sheds light on the value of real-time information.

Zurich invests considerable effort in developing precise and realistic timetables. Following the schedule is the main operational goal. When disruptions occur, the focus changes to regular operation (an even vehicle spacing) until the vehicles are brought back to schedule.

Based on work by Abkowitz (1978), Cham (2006) divides strategies to improve service reliability in two categories: preventive and corrective. The former are more related to the tactical planning level, the latter to the operational level. The tables in the following pages provide a summary of selected strategies, and the extent to which they are applied in Zurich.

Table 31 Preventive strategies to increase reliability and their use in Zurich

| **Preventive Strategy** | **Implementation in Zurich** |
|---|---|
| *Route design and Lane Priority* | |
| Exclusive bus lanes | Only partially, shared use of exclusive tram lanes where possible. |
| Route length | Part of strategic planning level. Not considered. |
| Number of stops | Stop spacing determined by accessibility policy. |
| *Signal Priority* | |
| Traffic signal priority | Yes. Widespread throughout the city. Hierarchy with preference to trams. Some intersections where several public transport lines converge with high traffic flows are problematic as they are close to their capacity. |
| *Operator related* | |
| Reserve operators and vehicles | Very restricted. Currently only one bus and one tram as reserve. |
| Standby buses | Very restricted. See above. |
| Driver training | Yes, more experienced drivers perform better (according to VBZ). |
| *Supervision* | |
| Service supervision | Very developed and network wide. Proactive approach with fast reaction times and pre-developed processes tailored to almost every possible situation that may arise. |
| *Schedule adjustment* | |
| Adjust schedules | Yes. Typically after 4 years of operations the VBZ considers that optimal travel times can be obtained for design. Small adjustments and refinements are done as required. |

Table 32 Corrective strategies to increase reliability and their use in Zurich

| **Corrective Strategy** | **Implementation in Zurich** |
|---|---|
| *Holding* | Yes. Though holding in Zurich is mostly the result of planned connections that take place at stops with many passenger transfers, rather than an isolated strategy. Buffer time is allocated at these places as well. |
| *Expressing* | Not a common practice in Zurich to the knowledge of these authors. |
| *Short-turning* | Yes. Used in cases when a vehicle has no time to recover from its delay at a terminal station. The vehicle behind turns early and takes the place of the delayed vehicle in the sequence. The late vehicle operates the schedule of the vehicle that turned short. In this way service can be kept regular. |

Most recent literature largely focuses on the use of large amount of data recently available to planners, controllers and researchers. As mentioned in section 3.6, Automated Data Collection Systems (ADCS) have changed the amount, quality and cost of available data and represent an opportunity to exploit a previously expensive and lower quality resource of information. Examples abound, where the role and potential of ADCS is discussed, as well as the use of AVL and APC data to develop more sophisticated reliability analysis, performance evaluations, supervision and control strategies, performance measures and statistical evaluations (see section 3.4). These are similar objectives to the one of this particular work.

Further ways of increasing performance, indirectly related to reliability, are mentioned by Vuchic (2005) and focus on increasing capacity, decreasing dwell time and increasing speed. They are summarized below:

- Increasing capacity: vehicle capacity, headway. For buses: multiple stopping slots for simultaneous stopping, leapfrogging, express services, platooning.
- Decreasing dwell time: vehicle floor height and platform height, number of boarding/alighting channels, fare type and fare collection.
- Increasing speed: vehicle design and performance characteristics, intersection and street design, traffic signal priorities for public transport, stops, elements of operations.

## 7.3 Possibilities for improving service reliability of Line 31

A number of situations and locations throughout this work were identified as contributing to reductions in service reliability, as pointed out in section 6.3.

From the statistical analysis, the most useful metrics to identify such locations are those describing variation and distribution spread, such as standard deviations and coefficients of variation. The latter are normalized measures of variation that allow for meaningful comparisons between time periods, or routes, as the measure itself is dimensionless.

Other metrics allowed a direct comparison between planning and operation, such as the run time ratio (Figure 27), where the share of additional time required to travel a segment (compared with the planned time for that segment) is directly observable.

The passenger-related metric of waiting time did not prove very useful for identifying reliability problems. This is because first, in the aggregated form it can only provide a route-level result; and second, because passenger waiting time is a function of headways regularity, which at the same time is dependent on trave time variability.

Performance measures can vary greatly during the day and direction, and largely depend on passenger volumes and travel direction, convergence of public transport lines at infrastructure bottlenecks, and increased private vehicle traffic. These situations bring intersection capacity to its limits, and reduce the efficiency of traffic light priority measures.

Contrasting the results at the stop and route level for different time profiles provides an idea of the changes in demand, as well as variation in the elements influencing performance, such as increased vehicle traffic. Punctuality and regularity metrics relate the travel time to the schedule, and good performance measures are a result of adequate schedules and good control practices. From the information gathered in chapter 4, it is clear that scheduling and controlling strategies and measures at the VBZ are well developed, and in some cases go beyond what is found in the literature. Examples are the emphasis on connection protection in the schedule development, and the development of processes to address particular events at specific points in the network given a large array of circumstances.

The VBZ network is mature, dense and heavily operated. The system comes close to its operational limit under the current circumstances during peak demand. Potential for improvement is hard to find given the available infrastructure, policy guidelines and operational budget. However, this study has aimed at just that. Understanding planning practices at the VBZ, comparing them to a generic planning process, and then relating them to the operational performance of Line 31, has shed some light on locations and situations that contribute to service unreliability.

In the following, suggestions for improving service reliability are presented and discussed at the tactical planning and operational levels. General and specific measures are suggested at each level. Their plausibility for implementation remains to be verified, as the variables and actors involved into the implementation of such solutions are manyfold and complex, and extend beyond the scope of this work.

### 7.3.1 Tactical level

At this level, suggestions are aimed at the planning level, particularly at scheduling practices that could eventually increase operational reliability. As previously mentioned, the applicability of these suggestions is subject to a feasibility study by the planning department at the VBZ.

#### *General measures*

- Slightly increase total travel time during the peak periods. Figure 24 clearly shows that during peak periods, the median travel time is around 1 minute higher than the planned travel time during the AM peak. In the case of the PM peak, the median is about 2 minutes above the planned travel time. Implementing this measure might require reducing the layover (recovery) time at the terminal station. It remains open to define if an additional vehicle would be needed, as the actual threshold for satisfying all union and technical restrictions is unknown.

- Increase the slack time at the terminal station for systematically delayed courses. Some specific courses seem to be systematically arriving late at the terminal station during the PM peak (see Figure 46). It would be interesting considering an increase in the recovery time of only these particular courses, however, it is possible that recovery time is already maximum possible during the whole period. Incrementing travel time (previous suggestion) would aggravate this situation.

- Increase the percentile of travel time distribution from 50%. Current VBZ practices and experience use the median of the recorded travel time distribution to plan their travel time in the timetable. Often in other places, higher percentile values are used, to increase the percentage of trips that arrive on time at the terminal station. After an inquiry at the scheduling department, they stated that the median is what has proved best in their experience, and that some trials increasing the travel time percentile mostly allowed for vehicles running early. It is possible that this is not the case for every line.

- Optimize buffer time allocation in the schedule using mathematical methods. Current practices allocate buffer time in the timetable based solely on experience. Another approach would be to use mathematical optimization for this assignment. The effort involved in implementing this idea is estimated as considerable. The added benefit of this optimization would clearly be marginal.

- Improve platform design to accelerate passenger exchange. Level boarding with the minimum vertical distance will improve vehicle accessibility for mobility-restricted people as well as for every other person. Faster passenger exchanges reduce station dwell time and total travel time. Currently, some platforms are being raised for this purpose. This is an ongoing project at the VBZ that aims mostly at increasing accessibility. Improved stop layout designs could eventually induce customers to better distribute themselves to access a vehicle. The expected impact of this measure is however reduced.

### *Specific measures*

- Implement a queue jumping strategy before Herdernstrasse. This is the single most important location for improving reliability in Line 31 on the eastbound direction. Variation of performance metrics at his point is the highest in all the line among the four time profiles. It is considered that the volume of private vehicle traffic, in particular during the PM peak, reduces reliability in two ways. First, the queue forming at the traffic light along the Hohlstrasse, and second the traffic flows along the Herdernstrasse, which reduce the capacity of the intersection. In providing a queue jumping strategy, a possibility would be to set a traffic light a given distance before the crossing, that would hold the traffic on the right lane, so that the buses of Line 31 could overtake the queue using the left lane (left turns only).

  The distance would need to be determined by the traffic office, as it would depend on the length of the queue forming on the left lane. The cost of a queue jumping traffic light is not known, but it is expected that the benefit will be high, by reducing variability in the operation of Line 31. Impact on vehicle traffic could be minimized, as the traffic light would only be active when needed, to clear the queue for the bus. The implementation of this traffic light would work best in combination with absolute traffic light priority at the intersection. This is shortly discussed below.

- Provide higher traffic light priority for buses at Herdernstrasse. Ideally in combination with a queue jumping strategy, as proposed above. It is not clear if the vehicles of Line 31 already have complete priority, given that they are the only public transport line crossing the intersection. However, it would be important that the vehicles get absolute priority as that particular intersection is adding the highest portion of variability to the route (in the eastbound direction).

- Extend the bus lane arriving to Hardplatz. Together with high dwell time variations (Figure 52), travel time variations are also comparatively high for the services arriving to Hardplatz. Even though there is already a bus lane in place, it is relatively short (barely longer than the vehicle itself). It is suspected that queue building of private vehicles unnecessarily prolongs arrival time of vehicles at Hardplatz. The proposed solution is to extend the bus lane as long as it is required to avoid losing time behind queuing traffic.

A current spatial restriction is the presence of two lanes on the opposite direction. However, changing the street layout and widening the road section could allow extending the bus lane. On the other direction, private vehicles are assigned to the right lane and public transport to the left one. By timing departures of buses ahead of private vehicles via traffic light signals, only one lane would be needed to exit the intersection for both traffic flows. This lane could then be widened to the current two lanes downstream, creating the space required for the bus lane in the opposite direction. Implementation restrictions are unknown, and costs are estimated to be low, as it would involve mostly paint (no construction), and possibly modifying the current traffic light cycle program.

### 7.3.2 Operational level

The measures here suggested are directed mostly at the control centre and the service delivery element of public transport. Again, their viability, implementation and feasibility would need to be verified by the VBZ.

#### *General measures*

- Driver training. Given that much of the vehicle travel time variation comes from the drivers, it is logical to think that harmonizing driving behaviour (to follow schedule), is a way of reducing operational variability. Given that it is possible to provide performance metrics for each driver (not done in this study, as data was anonymized), implementing a reward system for drivers with performance levels above a given threshold, even if symbolic, would raise awareness on the issue. Small reductions in variability could possibly be achieved. External causes of variability would not be reduced by this measure.

- Influence passenger behaviour when bus bunching occurs. This idea basically proposes that the control centre develop measures that inform passengers at specific stops that two vehicles are arriving close together, and that they should board the second vehicle. This could be achieved by providing audio messages one to three stops ahead of the delayed vehicle’s position. Additionally, visual messages on the front of the delayed vehicle could inform passengers at a stop to board the next vehicle. It would require an awareness campaign, as well as pilot tests. Possibly doing some market research on the issue with the public would provide valuable feedback on the feasibility of such a strategy. Currently, the operational department of the VBZ considers this is not a realistic idea, and that passengers will in any case board the first vehicle, even if it is already full.

- Increase flexibility of low-floor vehicle strategy during rush hours. The low-floor vehicle strategy is a step forward in improving service for customers with mobility restrictions, as it provides every second service with a low floor vehicle, needed especially by people in wheelchairs. However, in the peak of rush hours, sometimes it is required to turn vehicles early to return them to schedule. A flexible approach of the low-floor strategy (exceptions when absolutely necessary) could provide useful for operations.

***Specific measures***

- Optimize driver change at Hardplatz. Much variation is observed at Hardplatz, both for run time as for dwell time, particularly during the PM peak and in between peaks profiles. It is assumed that driver exchanges are taking place during these periods. Limiting the time available for this activity might bring some additional stability to the operational performance of the line. Acceptance by drivers, as well as union agreements are an open question for the implementation of this suggestion.

- Implement control strategies for optimizing public transport vehicle flow at Bahnhof Altstetten. Several public transport lines serve Bahnhof Altstetten, with only two lanes that are also used by private vehicles. Large numbers of pedestrians frequently cross the street to transfer to the trains serving the station. This convergence of different actors on the limited space has an impact on the performance of Line 31. Two suggestions are proposed: the first one is closing the street in front of the station to private vehicle, even if only during rush hours. This would reduce the demand for space, leaving it free for public transport and pedestrians. The second solution is to regulate the pedestrian flows crossing the street, be it with a policeman during rush hours, or with a traffic light, where waiting times would need to be rather short to prevent pedestrians from crossing the street, while providing priority to public transport vehicles. A combination of the two suggestions would yield the best results.

## 7.4 Summary

This chapter presented a number of strategies to reduce service unreliability in fixed public transport lines. Strategies found in the literature were contrasted with those already implemented in Zurich. Furthermore, general and specific measures to increase reliability at the tactical planning as well as the operational level were presented and discussed.

The two locations with most potential for improving reliability in the short term are the approach to Herdernstrasse, and both the approach to, and the variation of dwell time in Hardplatz. Measures suggested include queue jumping schemes, increased priority at traffic lights, and an extension of a bus lane with the appropriate change in street layout. Implementation challenges and plausibility were discussed, but remain the task of the operator and the city to define their applicability.

# 8 Conclusions and recommendations

## 8.1 Research summary

This work represents an attempt to provide insights into planning and operational processes taking place at the VBZ in Zurich, and to relate them to the actual service delivery using Line 31 as a case study. The focus throughout is service reliability, as defined in Chapter 3. Planning processes were defined and contrasted to actual operations by means of detailed statistical analyses that comprise mostly the perspective of the operator, but also include the view of the users.

Service reliability is an important characteristic of public transport associated to quality that has a great influence on a person's mode choice. One of the main goals that any city should have is to increase the share of people using public transportation, and increasing service reliability is a step in that direction.

In this work, a generic planning process described in Chapter 4 was contrasted to the actual planning process taking place at the VBZ at the tactical level. The planning process at the VBZ was reconstructed from a series of interviews with the head of the scheduling department that took place in 2010 and 2011. Differences and similarities were observed and discussed. It was found that the VBZ includes a high level of precision in their processes, and to some extent, implements more comprehensive planning practices than those described in the literature.

A system approach, highlighted by the effort in transfer coordination and protection via detailed and realistic schedules, is a key element of the high reliability levels observed in Line 31 and a valuable service characteristic for users. Planning extends into the operational level, where detailed processes have been developed through the years to provide standardized, precise, and efficient responses to all sorts of incidents by the control centre.

Experience is a valued asset at all levels, and is supported by the use of software tools and the latest dispatching technologies. One drawback is the role VBZ plays in the development of software tools and updates, as it often encounters bugs and other problems, inherent to the implementation of new technologies.

The performance analysis in Chapter 5 was done using one month of operational AVL data records from Line 31 to calculate a number of reliability metrics. These focused on travel time, speed, punctuality, regularity and passenger waiting time. Four time profiles were selected for all the analyses, to capture changes in demand and private vehicle traffic: the AM and PM peak, between peaks and late night. No passenger counts were available for this study. The most useful measures to identify problems were those focused on the variation of travel time and the spread of the distributions. Planning was directly compared to operations with one particular measure, the run time ratio, or RTR.

Insights into the bus bunching phenomena were provided. Bus bunching was not directly observed from the available data, however, during peak hours, particularly in the afternoon, headway variation is greatest and vehicles show a tendency to bunch. A clear triggering effect for bus bunching was observed to take place in Herdernstrasse. Together with Hardplatz, these two stops and the road sections leading to them show the highest variability in punctuality and regularity metrics. They represent the highest potential for improving reliability of Line 31 in the eastbound direction, given the restricted spatial availability and convergence of public transport and private vehicles at other points along the line with high variation in performance throughout the day.

In Chapter 6, the findings of Chapters 4 and 5 were compared, and related to operational practices taking place at the VBZ. These were obtained from an interview with the head of the dispatching centre. For the VBZ it is clear that in their dense network, more capacity will have to come from larger vehicles, not from a denser timetable. A good experience in Zurich was the introduction of higher capacity vehicles in Line 31 instead of higher service frequencies. Larger vehicles required some infrastructure adjustments, but increased schedule stability and operational reliability. Vehicle size increments are limited in the case of tramlines in Zurich mostly due to its urban layout.

Possibilities for improving reliability were reviewed from the literature and evaluated for their current applicability in Zurich. Most of the found preventive and corrective strategies to increase reliability are already in place in Zurich. The most effective means to increase reliability, according to the literature and reflected in the data analysis, is increasing the degree of segregation from other traffic and minimizing the time vehicles require crossing intersections.

Line 31 makes use of exclusive lanes in place for trams, but enjoys only a limited extent of bus lanes in other sections. Traffic light priority for public transport is high in Zurich, but difficult to optimize where private vehicle traffic volumes are high, such as in Kunsthaus, Herdernstrasse and Kreuzplatz.

The most important findings and suggestions regarding problematic locations and their potential for improving reliability are found in the following section.

## 8.2 Findings and conclusions

This work has provided an insight into the performance of Line 31 in Zurich by means of a detail statistical analysis of off-line operational data records.

From the planning perspective, the VBZ goes beyond the state of practice in their level of detail, precision and considerations for developing efficient and achievable timetables. These timetables are the guidelines for a precise operation, which is supervised and managed by a proactive control centre. The control centre engages in planning activities on its own, as it has developed a number of detailed processes to react to all kinds of possible events in the network. The main objective of the control centre is to keep vehicles moving, implement deviation schemes when required, inform the public, and bring service back to schedule as soon as possible.

From the perspective of performance measures, the most useful in this analysis have been those dealing with variation and spread of the distributions. Travel time analysis in particularly important, as variations in travel time impact speed, punctuality and regularity. Punctuality and regularity measures reflect the variation of travel time. Vehicles can recover (improve) punctuality metrics with buffer time along the route. However, regularity metrics can stop deteriorating but hardly recover. Management from the control centre is required, and often a vehicle must reach the terminal station to start again on time (and with a regular interval).

Headway regularity influences average passenger waiting time, however passenger waiting time is not a very revealing measure, particularly in the aggregated route-level.

From the statistical analysis of the data, congestion and passenger demand seem to have the most impact on performance. At the same time, the provision of bus lanes is directly correlated to improvements in performance metrics. In those sections where a bus lane is present, performance metrics improve, particularly punctuality.

The impact of road works is clearly visible in the data, as systematic delays are taking place along the route. Other, more infrequent events are not directly observable in the data and represent outliers, which are not considered in the planning stage.

A number of suggestions were proposed at the tactical planning and operational levels, both general for all services and specific for Line 31. The two most interesting locations with potential for improving reliability are: (1) the intersection before Herdernstrasse, where public transport vehicles systematically loose time and headway regularity becomes unstable; and (2) the approach section and dwell time at Hardplatz. It was proposed to evaluate the possibility of implementing a (private vehicle) queue-jumping scheme with the introduction of a traffic light to hold back the private vehicle traffic and create a temporary slot for public transport vehicles to overtake. Adding absolute priority to public transport vehicles in the crossing would optimize the queue-jumping strategy, in particular since no other public transport lines are going through that particular crossing.

At Hardplatz, an extension of the existing bus lane was proposed, possible with a change in street layout and traffic light cycle that must be verified by the proper authorities and the VBZ. Moreover, driver exchanges at Hardplatz during the in-between peaks and late night time profiles, add considerable variability to operations. It is suggested that these processes are looked into and if possible optimized to reduce variability. The viability and acceptance of these suggestions, as well as with the other ones included in this work remains open for discussion and analysis.

## 8.3 Limitation and further research

Some of the limitations of the study were already mentioned in the chapters when dealing with the specific topic. As overcoming limitations of current or past research often leads to interesting research findings, the limitations of the present research study will be mentioned in connection with proposed future research.

The present study revealed a number of areas with potential for future research by extending the scope of the study. The scope can be expanded in different ways. The first dimension of extension is time. In the current study, only operational data for one month was analysed. The findings could be compared to the same month in different years or the assessment period could be simply prolonged. Another dimension extension for future research is space. Space can be considered in different ways. In the present study only one bus line was considered. Therefore, additional bus lines could be included in the study. Furthermore, also tramlines could be integrated in the analyses. The holistic approach would be to analyse the reliability of the entire VBZ network. In this approach, also the interdependencies between different tram and bus lines could be considered and evaluated. A different viewpoint on the dimension space is to adopt the findings of the study and the best practice approaches to other public transportation networks in other cities or countries.

Furthermore, additional variables could be included in the analyses. As already mentioned in the report, passenger counts and load factor evaluations with their impact on reliability could be included. This is particularly required for evaluating passenger-related reliability measures, such as waiting time indicators.

Besides including additional variables, it is possible to increase the level of detail of the evaluations. In this matter, more precise passenger waiting time distribution functions in the calculation of passenger waiting time performance metrics could be implemented.

Additionally, it is possible to expand the scope of the study in terms of content and further research questions. The efficiency evaluation of line coordination could be included in the analysis.

An additional dimension for extending the research is systematology. As it was already pointed out, some of the crucial planning procedures, such as ensuring connections at defined stops, are predominantly performed manually and are based on experience. So it would be beneficial to systematize this process and to develop models that optimize the allocation of waiting time for transfer protection, holding, and buffer in the schedule. This could be included in a holistic optimization approach for timetable scheduling.

In the current study the impacts of causes of unreliability were only classified and used subsequently in a qualitative way. For further research, the impacts of single elements influencing reliability could be quantified, and prediction models based on the quantitative contributions could be developed. Additionally, delay propagation phenomena and delay recovery with their influencing factors could be studied and explained quantitatively.

In this work, the reliability improvement strategies have been evaluated in a qualitative way. The next step of further research could be the integration of quantitative evaluations of the proposed reliability improvement strategies. It is essential to model the benefit evaluation. This is linked to behavioural surveys on the value of time and reliability.

In this study reliability and stability measures were derived from the literature and applied to the case study. A further approach is to propose an extended balanced scorecard for reliability and stability, which can be used to standardize the evaluation of reliability gaps and to facilitate deriving measures to increase reliability.

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