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Definition and valuation

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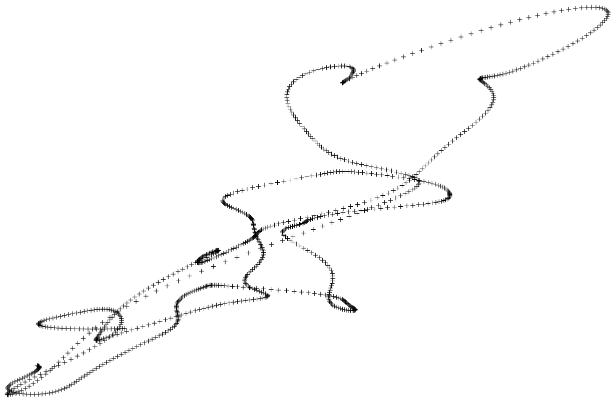

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August 2008

DTU Transport
Department of Transport

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Preface

Increasing traffic leads to increasing severity, spatial extension and duration of congestion. Congestion has two immediate consequences. One is that travel times increase on average. Another is that travel times become increasingly variable and unpredictable. When performing economic appraisal of transport policies it is important to account for both. This is fast becoming widely acknowledged in many countries around the world. The subject is, however, quite difficult for several reasons and so far there is no established consensus on how to define and value travel time variability.

This report was commissioned by the Danish Ministry of Transport and its agencies Vejdirektoratet (the Road Directorate) and Trafikstyrelsen (the Rail Agency). Its purpose is to establish a definition of travel time variability and its value that is theoretically sound, possible to estimate from individual preferences, and applicable with existing or realistically foreseeable traffic models. In addition, the report provides short term recommendations for including valuation of travel time variability in Danish practice for economic appraisal of transport projects and outlines a future Danish study of the valuation of travel time variability.

Kgs. Lyngby, August 2008

Niels Buus Kristensen
Head of department

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Summary

Increasing traffic leads to increasing severity, spatial extension and duration of congestion. Congestion has two immediate consequences. One is that travel times increase on average. Another is that travel times become increasingly variable and unpredictable. When performing economic appraisal of transport policies it is important to account for both.

There is a well-established practice of accounting for changes in average travel time. The concept is clear, average travel time is comparatively easy to measure and predict and the underlying economic principles are widely accepted. We are well able to account for the economic consequences of congestion as far as the effect on average travel is concerned.

At present, there is no similarly well-established practice of accounting for changes in the variability of travel times. This is a major short-coming of current economic appraisal methodology, since the economic costs of variability are likely to be large. The objective of this study is to remedy this situation by doing three things.

- Establish a definition of travel time variability and its value that is
  - theoretically sound
  - possible to estimate from individual preferences
  - applicable with existing or realistically foreseeable traffic models
- Provide short term recommendation for including valuation of travel time variability in Danish practice for economic appraisal of transport projects
- Outline a Danish study of the valuation of travel time variability

The first task is motivated simply by the fact that so far a definition of travel time variability and its associated value has not existed that satisfies the above criteria. Various approaches have been proposed but all have serious short-comings relative to one of the criteria.

This report proposes a theoretical economic model as the basis for defining and valuing travel time variability. The model says that the value of travel time variability, generally known as the value of reliability, can be defined in terms of scheduling preferences of individuals, the costs of being early or late and the value of time per se, and the travel time distribution summarised by its standard deviation.

The economic model is sound in the sense that it takes preferences over actual outcomes, being early or late, as its starting point. It does not introduce elements into the definition of utility, such as standard deviation or other characteristics of travel time distributions that do not correspond directly to outcomes.

This also implies that the estimation of parameters in the model from individual responses is comparatively easy, as it is not necessarily required to try to convey “variability” to survey respondents. This has proved difficult in a number of studies seeking to measure the value of travel time variability.

Finally, the standard deviation is comparatively simple to measure and predict. It is hard to conceive of a simpler and more straight-forward measure of travel time variability. It is hence the easiest measure to compute from traffic models.

The economic model entails certain requirements for actual travel time distributions. We have examined some large datasets containing high-frequency measurements of travel times several places in the Danish road and rail networks. It turns out that the requirements of the economic model are met with a reasonable degree of precision. This implies that the economic model is also relevant in this perspective.

Our recommendation is then that our economic model should be used to define and value travel time variability. We use estimates of scheduling preferences gathered from the scientific literature and actual Danish travel time distributions for road and rail to establish our recommendation for the value of one minute of standard deviation of travel time relative to the value of travel time in each of these two networks. This study has thus resulted in values of travel time variability that are immediately applicable in the Danish context.

For the longer term we have two general recommendations. The first concerns the design of a Danish valuation study to replace with Danish values the estimates of scheduling preferences that we have gathered from the international scientific literature. We feel that it is still premature to undertake a full-blown valuation study seeking to be comprehensive and representative for Denmark. We propose instead to carry out a limited, more focused study, where the main point is to measure scheduling preferences and uncertainty introduced in a very controlled way.

Our second general recommendation for the longer term is to systematically collect and analyse travel time data. The systems for recording travel times are already there in some places (TRIM and RDS), but the potential of the data has so far not been realised. Systematic use of such data would allow monitoring, modelling and prediction of travel times, which in turn could end up having a large impact on transport policy.

Dansk resume

Mere trafik på vejene giver mere udbredt trængsel, geografisk såvel som tidsmæssigt. Trængsel har to umiddelbare effekter, idet de gennemsnitlige rejsetider stiger og de enkelte rejsetider i stigende grad bliver variable og uforudsigelige. I samfundsøkonomiske vurderinger af transportprojekter er det vigtigt at tage højde for begge effekter.

Der findes en veletableret praksis for værdisætning af ændringer i den gennemsnitlige rejsetid. Værdien af rejsetid er et veldefineret koncept, gennemsnitlige rejsetider kan relativt let måles og forudsiges, og der er generel enighed om de underliggende økonomiske principper. Vi er således i stand til at redegøre for de samfundsøkonomiske konsekvenser af trængsel mht. gennemsnitlig rejsetid.

På nuværende tidspunkt er der til gengæld ikke en tilsvarende veletableret praksis, hvad angår værdisætning af ændringer i variabiliteten af rejsetid. Det er en væsentlig mangel i den samfundsøkonomiske metode, der anvendes i dag, idet de samfundsøkonomiske omkostninger af variabilitet sandsynligvis er betragtelige. Formålet med dette forskningsprojekt er at forbedre metoden ved tre aktiviteter:

- Etablere en definition af rejsetidsvariabilitet og dens værdi, der er
    - teoretisk velfunderet
    - mulig at estimere fra individuelle præferencer
    - anvendelig givet allerede eksisterende trafikmodeller eller modeller, der realistisk kan forventes indenfor den nærmeste fremtid
- Give anbefalinger for, hvordan rejsetidsvariabilitet på kort sigt kan inkluderes i dansk praksis for samfundsøkonomisk analyse af transportprojekter
- Skitsere et dansk værdisætningsstudie.

Motivationen for den førstnævnte aktivitet er, at der på nuværende tidspunkt ikke findes en definition af rejsetidsvariabilitet, der opfylder de tre nævnte kriterier. Flere forskellige metoder har været foreslået, men alle har væsentlige mangler på mindst ét af de tre punkter.

Denne rapport forelægger en teoretisk økonomisk model som grundlag for definition og værdisætning af rejsetidsvariabilitet. Modellen angiver, at værdien af rejsetidsvariabilitet, ofte kaldet værdien af regularitet, kan defineres som funktion af fordelingen af rejsetid, opgjort ved dens standardafvigelse, og af individernes planlægningspræferencer, dvs. omkostningerne ved at komme for tidligt eller for sent samt værdien af tid.

Den økonomiske model er velfunderet, da den tager udgangspunkt i præferencer over faktiske udfald: For tidlig eller for sen ankomst. Den antager således ikke, at individernes nyttefunktioner afhænger af standardafvigelsen eller andre kendetegn ved rejsetidsfordelingen, som ikke direkte kan forbindes med faktiske udfald.

Denne egenskab medfører, at det vil være relativt let at estimere modellens parametre ud fra individuelle svar på spørgeskemaundersøgelser, idet det ikke er nødvendigt at forklare begrebet "variabilitet" for deltagerne. Dette har vist sig at være problematisk i flere gennemførte forskningsprojekter, der forsøger at måle værdien af rejsetidsvariabilitet.

Desuden er standardafvigelsen relativt simpel at måle og forudsige. Det er derfor svært at definere et mere simpelt og ligefremt mål for rejsetidsvariabilitet, der samtidig er let at beregne fra trafikmodeller.

Den økonomiske model stiller nogle krav til de faktiske rejsetidsfordelinger. Vi har undersøgt nogle store datasæt med højfrekvente observationer af rejsetid flere steder på det danske vej- og banenet. Det viser sig, at modellens krav til data er opfyldt med en acceptabel grad af præcision. Modellen er således også relevant i dette perspektiv.

Vores anbefaling er derfor at anvende vores økonomiske model til definition og beregning af værdien af rejsetidsvariabilitet. Den anbefalede værdisætning baseres på internationale estimater af planlægningspræferencer taget fra den videnskabelige litteratur samt faktiske danske rejsetidsfordelinger for vej og bane. Projektet leverer således værdier af rejsetidsvariabilitet, som er umiddelbart anvendelige i dansk sammenhæng.

På længere sigt har vi to generelle anbefalinger. Den første vedrører designet af et dansk værdisætningsstudie så ovenstående værdisætning fra den internationale videnskabelige litteratur kan erstattes med tilsvarende danske værdier. Vi mener, det er for tidligt at foretage et regulært dansk værdisætningsstudie, som i sagens natur er meget omfattende og bør repræsentere hele befolkningen. I stedet foreslår vi at foretage et mere begrænset og fokuseret studie med fokus på måling af planlægningspræferencer og rejsetidsusikkerhed på en kontrolleret måde.

På længere sigt er den anden generelle anbefaling at indsamle og analysere rejsetidsdata systematisk. Systemer til at måle rejsetider findes allerede på visse vej- og banestrækninger (TRIM og RDS), men datapotentialet er indtil videre ikke udnyttet. En systematisk anvendelse af sådanne data vil gøre det muligt at monitorere, modellere og forudsige rejsetider, hvilket meget vel kunne have stor betydning for dansk transportpolitik.

1 Introduction

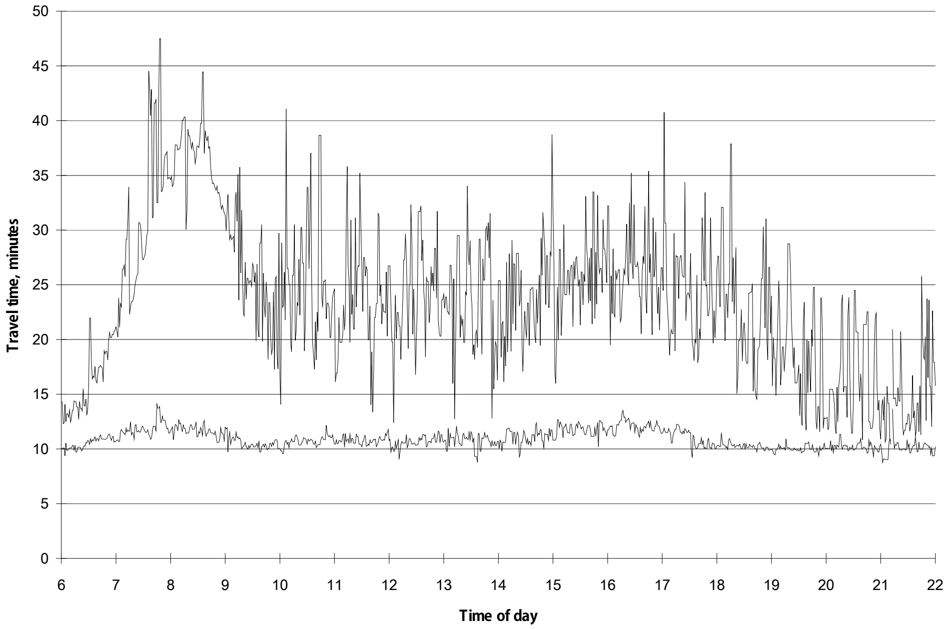
The level and spatial extension of congestion is increasing all over the world. In Denmark it is not only widespread in the Copenhagen area but is fast becoming a national issue.

Congestion leads to increased travel times. This represents a significant cost to society and a main motivation for expanding infrastructure or regulating its use. Changes in travel times are routinely handled in economic evaluations of transport policy through application of values of time. It is thus possible to compare the gains from reducing travel times to the costs of policies.

Congestion not only increases travel times, travel times also become more variable and unpredictable as congestion increases. From the point of view of the traveller, it becomes hard to predict for instance how long the commute to work will take. This uncertainty entails additional costs to travellers and hence to society. It is relevant and necessary to include these costs in the economic evaluations of transport policies, especially those policies that are directed against reduction of travel time variability.

As an illustration of the extent of uncertainty, Figure 1 shows the minimal and maximal travel time on 11.3 km of Frederikssundsvej towards Copenhagen, observed over a period of about three months. The figure includes only weekdays. Where the minimum travel time, the free flow travel time, is around 10 minutes, the maximum varies up to about 40 minutes in the morning peak. The difference between the minimum and maximum is about 15 minutes most of the day. A traveller in the middle of the morning peak has at least a one percent chance of experiencing a travel time that is more than three times the free flow travel time.

Figure 1. Minimum and maximum travel time in minutes over the day on Frederikssundsvej towards Copenhagen



So far there has been no accepted approach to evaluate travel time variability in economic appraisal in Denmark. Different measures of travel time and relations to congestion have been formulated for road and rail respectively, but these have often had a performance approach from the perspective of the infrastructure. In order to define measures for use in economic appraisal it is necessary to take the perspective of the traveller.

The main purposes of the present study are to:

- Establish a definition of travel time variability and its value that is
    - theoretically sound
    - possible to estimate from individual preferences
    - applicable with existing or realistically foreseeable traffic models
- Provide short term recommendation for including valuation of travel time variability in Danish practice for economic appraisal of transport projects
- Outline a Danish study of the valuation of travel time variability

1.1 Acknowledgements

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Daisuke Fukuda's stay at DTU Transport is financed by the Kajima Foundation. We thank Tokyo Institute of Technology for giving access to their supercomputer "Tsubame Grid Cluster"[1], which has been used for part of the nonparametric treatment of travel time data.

[1] http://www.gsic.titech.ac.jp/index.html.en

2 Travel time variability

The terms travel time variability, reliability and regularity are often used interchangeably. However, in this study we will use the term travel time variability as a generic term across modes. The terms reliability and regularity are used for measuring variability relative to given timetables, where reliability is used when departure times are specified and regularity is used when headways are specified.

We use the term "value of travel time" (VTT) as a more precise term than the widely used term "value of time". In this report, we shall refer to the "value of travel time variability" (VTTV). It is one of the objectives of this study to seek a definition of what the term should mean.

2.1 Terminology

In our discussion of travel time variability we decompose travel time into free flow travel time (the minimal travel time without congestion) and delay. Some delay can be anticipated and therefore does not cause uncertainty, e.g. the systematic variation with time of day (peak versus off-peak) or day of week (weekday versus weekend). Therefore, delay is further decomposed into systematic delay, which can be explained by observed characteristics of the trip, and unexplained delay[2], which cannot be foreseen and taken into account:

Travel time = free flow time + systematic delay + unexplained delay

While the distinction between free flow time and delay is straightforward, the distinction between systematic and unexplained delay is somewhat ambiguous: It depends on how much is known about the trip, and hence is a matter of perspective. From the traveller's point of view, unexplained delay is everything he cannot foresee; such as additional travel time caused by random demand fluctuations or capacity reductions due to accidents, unannounced road works etc. However, travellers may differ in their perspective depending on how well they know the trip, as experienced travellers may be able to foresee a greater part of the demand variation or have knowledge about the likelihood of delays due to accidents etc.

[2] We use the term unexplained delay instead of unexpected, since the mean of the unexplained delay may be different from 0.

In the literature, systematic and unexplained delays are often referred to as recurrent and non-recurrent delays, respectively (Bates et al., 2001, Noland and Polak, 2002). Transek (2006) further decomposes non-recurrent delay into "usual" variability (random day-to-day variation, which causes travellers to use safety margins to reduce the risk of being late), and unpredictable long delays that are so long and infrequent that applying extra time margins to allow for them is unreasonable.[3] We shall not apply this distinction here as it is not very clear cut and as it is not apparent that it is meaningful from the point of view of the traveller.

In modelling, the unexplained delay is represented by a random variable with a probability distribution, such that travel time varies randomly. However, there are different ways to interpret the above decomposition. In some cases in the literature, all three components are defined to be positive, implying a positive mean value of unexplained delay. In other cases, it may be convenient to define unexplained delay as random with zero mean, such that mean travel time is given by free flow time and systematic delay, and unexplained delay is simply the variation around the mean delay. The shape of the distribution of unexplained delay is the same in both cases; the only difference of the formulations being a shift in location.

We define *travel time variability* as the random variation in travel time, i.e. the variation in unexplained delay. The variation in free flow time and systematic delay is termed *systematic variation*.

Table 13 in the Appendix summarises the applied terminology and contains translations between Danish and English terms.

2.2 Determinants of the travel time distribution

The factors affecting the systematic part of the travel time distribution include:

- the general (average) demand level
- the physical road characteristics, i.e. the general capacity level
- the speed-flow relationship

Clearly, demand variation over the day is a major source of systematic variation: On congested roads, travel times are often higher during morning and afternoon peak hours, when traffic is denser. Transek (2006) analyses travel time data from Swedish roads and finds that not only the mean travel time, but also travel time variability varies by time of day. The same is found for Danish data (section 5.3).

[3] See also the English paper by Eliasson (2004).

Variability may arise from fluctuations in demand or from unforeseen incidents affecting the flow capacity, such as accidents blocking part of the road or weather conditions. Another important source of variability is small random perturbations to traffic flow, which may lead to large variations in travel time under congested conditions. Generally, not only the mean travel time but also its variability, however defined, increases with the demand.

In this study we are concerned with the value of variability (VTTV). The idea is that we can compare two situations by computing a generalised travel cost for each situation. Travel time variability, measured in some way, and an associated value of reliability constitute a part of the generalised travel cost.

It must be recognised that the relationship between the travel time distribution and the time of day is not exogenous. When the mean and standard deviation of travel time start rising at a certain time in the morning, reaches a peak at a certain time and decline again until a certain time, the whole shape of the peak is a consequence of individual scheduling decisions, where travellers trade off departures from their preferred schedule against travel time. In this way, some travellers choose to arrive at work earlier than they would ideally like in order to avoid the worst congestion.

If we then consider a policy that changes capacity, then we need to account for the effect on scheduling, before applying a VTTV. It is not a part of the present study to describe such scheduling choices. It is presumed that these issues are handled in a traffic model. It should be noted that this is not easy and requires some development of current modelling practice.

We expect the distribution of travel time for a scheduled transport service to differ from the distribution for car traffic, as a scheduled service does not accumulate "earliness": If the bus arrives early at a stop, it will have to wait there for the timetable to catch up before it continues. Rail traffic differs even more from car traffic, as rail operates on a network that is separated from other traffic. This implies on the one hand that traffic flow is regulated such that it is more efficiently distributed; on the other hand the system is likely to be much more sensitive to incidents, as it is relatively inflexible.

It is relatively straightforward to measure the distribution of travel time for a single road section or a single public transport line (see section 5.3). Some studies have found that the pattern of variability resembles a lognormal distribution (e.g. Rietveld et al., 2001; see also the review in Noland and Polak, 2002); while Bates et al. (2001) find that the delay distribution for their train data is better described by a generalised Poisson distribution.

However, converting travel time distributions for a set of adjacent road sections into a distribution for an entire trip is more complicated. To do so, one needs to know how travel time distributions on adjacent road sections are correlated. For public transport trip-chains, there is further the problem that a small delay in the early part of the trip-chain can cause travellers to miss their connection, which causes a much larger delay. Hence, it is necessary to model the probability of missing a connecting bus/train (which depends on the joint travel time distribution of all vehicles used) as well as the additional delay incurred if missing the connection (which depends on the frequency of the connecting vehicle). See Rietveld et al. (2001) for an application.

3 Danish practice

Travel time variability is not yet included in the general Danish economic appraisal practice. However, several authorities of especially public transport use different reliability measures to evaluate travel time variability. This section summarises the handling of travel time variability by authorities for road, rail and bus transport. Note that while the main focus of this report is measures applied in economic appraisal, most of the measures mentioned in the following are performance indicators, which of course reflects the interests of the transport authorities.

3.1 Road transport – Vejdirektoratet

Vejdirektoratet (The Danish Road Directorate) which is part of the Ministry of Transport is responsible for planning, construction, operation, and maintenance of the national roads of Denmark. Besides the responsibility for the national roads, the directorate has a sector responsibility for all roads in Denmark, which means that the directorate among other things has some responsibility for collecting data on roads, traffic and accidents.

3.1.1 Measurement and valuation of indicators for travel time variability

Currently, Vejdirektoratet has no strict definition and evaluation of travel time variability. However, variation in the mean travel time due to congestion and incidents is included through speed-flow relationships, observations or micro simulation.

Vejdirektoratet uses delay as a proxy for travel time variability, for want of a better measure. The reason for using delay is that it is easy to measure on the transport network, and positively related to variability, since an increase in variability leads to a higher probability of delay. The travel time without delay is set in different ways, e.g. as the travel time in off-peak periods or based on a speed slightly lower than the permitted speed.

For appraisal of infrastructure schemes in the greater Copenhagen area, the Ørestad Transport Model (OTM) is used to evaluate changes in behaviour and the consequences for the total travel time for proposed schemes. Consequently, the definition used by the directorate is adapted from the traffic model. Here, travel time for different road segments are generated based on speed-flow relationships for a number of matrices corresponding to time periods throughout the day.

Outside the greater Copenhagen area, nationwide speed-flow relationships are used to evaluate the delay in much the same way as in the traffic model. However, the effect of congestion on demand and route choice is rarely included here.

The valuation of the delay is based on the official unit prices, i.e. that a minute delay is evaluated as 1.5 minute of travel time. This evaluation originates from results of the UK Value of Time study (DETR, 1996/1999).

3.1.2 Other indicators of travel time variability

The focus of Vejdirektoratet is mainly on the performance of the system. Consequently, the directorate has a number of measures to show the variation in level of traffic throughout the day.

For instance, the directorate has defined a measure of congestion relating the level of traffic to capacity. In this way, levels of congestion are related to densities and coloured as red, yellow, and green on maps, which are shown real time on the home page. An example is given in Figure 2.

However, focus has shifted towards the traveller, and travel time as observed by the traveller is the focus in a pilot data collection by camera detection of number plates on two road segments in Denmark. One is the radial road from north-west towards Copenhagen (Frederikssundsvej) and the other is the motorway on the western part of Fyn and northward in Jylland. Both datasets are included in this study, see e.g. section 5.3.

Figure 2: Example of real time illustration of congestion (Source: Vejdirektoratet, www.trafikken.dk)

3.2 Rail – Trafikstyrelsen and Banedanmark

Trafikstyrelsen (The National Rail Authority) which is part of the Ministry of Transport is responsible for planning, coordination, and regulation of railway traffic, including preparation of economic analyses of railway demand and infrastructure investments. The daily operation of the national railway infrastructure is the responsibility of Banedanmark (Danish National Railway Agency), an agency under the Ministry of Transport. Banedanmark is responsible for maintenance of the rail infrastructure as well as for monitoring and controlling the traffic, and allocating capacity to train operators.

3.2.1 Measurement and valuation of indicators of travel time variability

Like Vejdirektoratet, Trafikstyrelsen uses delay as a proxy for travel time variability (Trafikstyrelsen, 2005a). In economic analyses, variability is computed as the total number of passenger-delay-minutes relative to the timetable, which in itself includes some share of expected delay. The passenger delay-minutes are calculated as the average delay per train according to the timetable times the average number of passengers per train (Trafikstyrelsen, 2005b). In 2005 a unit price of 1.5 times VTT was applied to assess the value of the variability, but the official recommendation used has since been changed to 2 times VTT.

A recent example of such analysis is the cost-benefit analysis carried out in the Copenhagen-Ringsted railway project (Trafikstyrelsen 2005a, 2005b) where various infrastructure alternatives are compared. This analysis includes the estimated benefits from both travel time savings and improved reliability.

When forecasting variability, two types of delay are considered separately:

- Delay due to severe incidents[4] is estimated from the number of delayed and cancelled trains and the frequency of severe incidents, segmented according to the physical design of the railway system.
- Other delay is forecasted using a linear or quadratic relation between delay and a capacity utilization index, which depends on the timetable and the physical design of the railway. (For freight transport, no such relation is found and hence delay is assumed to depend only on physical design.)

The passengers' transport pattern is forecast with a traffic model that models behaviour (mode choice) in each of the considered infrastructure alternatives. Mode choice is assumed to depend on in-vehicle travel time, waiting time, and time used at interchanges, but not on price, comfort, or the forecasted variability. This could lead to an understatement of the benefits, as improved reliability may cause more people to switch from car to train, thereby at the same time obtaining a reliability improvement compared to the car, *and* reducing congestion on the road.

[4] A severe incident is defined as an event that necessitates the use of an emergency timetable.

3.2.2 Other indicators of travel time variability

The main source of data on variability of rail travel time is RDS[5], a data system administered by Banedanmark. The system registers the scheduled and actual arrival and departure of all trains at certain registration stations, along with details of the train. For delays exceeding 6minutes, the system further registers the event causing delays by type of event and number of affected trains.

Banedanmark uses several different variability measures based on RDS data. Some measure the level of service of Banedanmark, others the service provided by the train operators. Table 1 below provides a summary. Note that all measures are defined relative to the operational timetable and not relative to the public passenger timetable.

Table 1: Variability measures for rail traffic (Source: Banedanmark)

Measure	Definition
Product reliability	Share of on-time arrivals on certain registration stations relative to the total number of arrivals on these stations. On-time means less than 6 minutes delay in the case of regional/intercity trains, and less than 2.5 minutes delay in the case of S-trains.
Traffic reliability	One minus the share of arrivals cancelled within 72 hours of scheduled departure from the first station (note that each train has several arrivals: one for each registration station on its way).
Train path punctuality	One minus the share of planned arrivals that are *affected* due to circumstances for which Banedanmark is responsible. Here *affected* means delayed at least 6 minutes or cancelled less than 72 hours before scheduled departure from the first station.

Product reliability and traffic reliability are used to measure the overall reliability of the railway service provided by train operators, regardless of who is responsible for delays and cancellations. The reliability standards, to which train operators are obliged, are defined in terms of these two measures, but corrected for the share of delays/cancellations for which the operator is not responsible.

[5] Regularitets- og DriftsStatistik.

Train punctuality measures the performance of Banedanmark, which is also obliged to meet certain standards for this measure.

3.3 Bus – Movia

Movia is the regional transport authority in the capital and Zealand regions. It administers all public bus services, as well as the local railways owned by the two regions.

3.3.1 Measurement and valuation of indicators of travel time variability

Since Movia is primarily organising bus operations their focus has not been much on measuring and valuing variability for use in economic appraisal. However, many measures of variability are used and an implicit valuation of delay may be found from the approach producing timetables.

When planning timetables Movia applies travel times corresponding to the 70^{th} quantile of the observed distribution of travel times for the specific section. This corresponds well to empirical measurements of scheduling parameters (section 4.3) and the model presented in section 5.2, which leads to an optimal risk of being late of around 0.3.

3.3.2 Other indicators of travel time variability

In general, bus operators are obliged to meet certain reliability standards: Buses are not allowed to depart early or depart more than two minutes late from the initial station, and change of driver along the route must not take more than two minutes. Further, it is required that a certain proportion of the scheduled bus hours is actually carried out. Violations of these standards imply economic sanctions (c.f. Movia’s invitation to tenders, e.g. Movia, 2007).

Table 2 below provides a summary of the reliability measures employed by Movia to evaluate the performance of bus operators.

The last two measures in the table, “Regularity” and “Reliability”, are used to evaluate the performance of some of the A-buses[6], whose passenger timetable in certain periods of the day is defined in terms of a given headway rather than fixed departure times (c.f. HUR, 2006).

[6] A-buses are high frequency city buses in central Copenhagen.

Table 2: Reliability measures for bus traffic (Source: Movia)

Measure	Definition
Share of realised bus hours	Share of scheduled bus hours actually carried out.
Quality flaw	Incidents such as: • Bus departing initial station early or more than two minutes late • Change of bus driver along the route exceeds two minutes.
Reliability	Share of registration points with the bus departing less than 15 seconds early and arriving less than 120 seconds late according to the timetable
Regularity	Share of registration points with the headway between two buses (same line) deviating less than 90 seconds from the scheduled headway

In a sense, Movia does operate with a value of reliability in economic analyses of tenders (Movia, 2007): Tenders must include budgeted number of quality flaws. This figure is converted to monetary values to enable comparison of different tenders. The applied “conversion rates” represent Movia’s willingness to pay for service reliability. These rates are also applied in the computation of economic sanctions. However, the rates are not necessarily based on travellers’ or society’s valuation of reliability – they are set by Movia with the purpose of ensuring that operators have suitable motivation to meet the quality standards.

The basis for this is an extensive data collection where Movia defines the following measures of variability of bus travel time:

1. **Counting buses**. Approx. 5% of all bus trips are run by a so called “counting bus”, which records number of passengers, time of day and GPS location at each bus stop. The sample of bus trips is weighted to represent the entire pattern of bus trips. The data are used to compute the passenger level and to monitor the quality of the bus service.

2. **Abit**. In A-buses position and time of day is recorded every 10 seconds and at all bus stops. These data are used to monitor the quality of the bus service, and to provide input to the dynamic sign system at the bus stops.

3. **Radio system**. New radio system in all buses in the former HUR area[7], which records the time of day and position once a minute. Also to be implemented in remaining Movia buses. When fully implemented, the system will provide data to monitor the quality of the bus service.

4. **Interviews**. Movia conducts on-board interviews with bus passengers to evaluate their perception of the quality of the bus service. Quality is measured by a customer satisfaction index comprising nine points, of which one is adherence to schedule.

[7] The greater Copenhagen area and North Zealand.

4 Literature review

This section summarises the evidence from the international literature on travel time variability. Section 4.1 describes how uncertain travel times are included in transport demand models. In the models, travellers are assumed to trade off money or mean travel time for variability, which means that a value of travel time variability (VTTV) appear in terms of travel time or money as the relative weight assigned to TTV compared to the weights of mean travel time and money

To calibrate the demand models, empirical evidence of traveller's route choice, mode choice, or departure time choice is needed. This evidence is often obtained from stated preference (SP) interviews. In section 4.2 we discuss a practical issue in the design of these SP experiments – namely how travel time uncertainty should be presented to respondents.

Section 4.3 summarises the numerical results from valuation studies.

4.1 Modelling behaviour

There exists a literature on how travel behaviour is affected by the variability of travel time. Most of this literature seeks to model transport decisions such as route choice, mode choice, or departure time choice in the presence of travel time variability.

Two competing approaches exist in the literature: The mean-variance approach and the scheduling approach. Both methods formulate the utility of the traveller in terms of travel time variability and other attributes of travelling, but they differ in their assumptions of how variability is perceived and interpreted by the traveller. The scheduling approach assumes that variability affects utility through scheduling considerations: How often one arrives late, and how much one arrives late (or early) on average. The mean-variance approach describes the inconvenience travellers experience from variability as due to the uncertainty in itself, no matter if one arrives early or late.

We introduce the two methods, one by one, and continue with a discussion of their relative advantages and disadvantages. Finally, we consider application of the methods to public transport, and the implications if travellers have an incorrect perception of the travel time distribution.

4.1.1 Mean-variance approach

The mean-variance approach assumes that the traveller's utility depends on travel cost C, the expected travel time ET, and the standard deviation σ_T of travel time:[8]

$$U = \delta C + \alpha ET + \rho\sigma_T \qquad (1)$$

δ, α, and ρ are the marginal utilities of cost, travel time, and variability, respectively, and are expected to be negative. The model is very popular because of its simplicity, but it has the serious drawback of lacking a solid economic foundation. Rather than being based on a theoretical description of individual travel demand, it is based on the measures of travel time variability directly available from network models describing the supply-side of the transport system, i.e. the mean and standard deviation of travel times.

Clearly, to apply the model, it must have a sensible interpretation in terms of the theory of travel behaviour. In economic theory it is customary to assume that travelling is a "necessary evil": an activity made not for the utility of travelling in itself, but with the purpose of arriving at another activity, such as work, shopping, visits etc. (Becker, 1965, DeSerpa, 1971). In this framework travel time variability complicates the planning of activities, which could be a source of disutility: Variability implies that the traveller will sometimes arrive earlier than average, and sometimes later, and thus affects his possibility for carrying out the planned activities: If he arrives late, there is less time to spend on the activity, or the activity may be inaccessible. A similar argument is suggested by Bates et al. (2001), who propose that uncertainty could cause anxiety, stress, or irritation from not knowing what will happen. Note that both arguments rely on the assumption that the standard deviation is an appropriate measure of travel time variability.

The model in eq. (1) can be extended to allow for observed heterogeneity among travellers by including covariates such as socioeconomic or trip characteristics.

A similar approach involves the median travel time instead of the mean and the difference between the 90th and 50th quartiles instead of σ_T. This approach is used by Brownstone and Small (2005), Lam and Small (2001), and

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[8] Since in the literature it is most often assumed that travellers trade mean travel time for standard deviation, as in eq.(1), it would be more correct to name the approach "The mean-standard deviation approach". However, we follow convention and refer to it as "The mean-variance approach".

Small et al. (2005). See Bates et al. (2001), Hollander (2006), and Noland and Polak (2002) for applications of the mean-variance approach.

4.1.2 Scheduling approach

The scheduling approach was originally proposed by Noland and Small (1995), based on work by Small (1982) on departure time choice without uncertainty. In the following, we use the notation from Bates et al. (2001), except that we include a travel cost term in the utility function.[9]

The traveller's utility depends on travel cost C, travel time T, on whether he arrives before or after his preferred arrival time (PAT), and by how much he arrives early/late compared to PAT. These attributes depend on the choice of departure time t_h, and possibly on the choice of route and transport mode. The model presented below considers departure time choice only, but can be generalised to include other types of choice as well.

The utility function is:

$$U(t_h) = \delta C + \alpha T + \beta SDE + \gamma SDL + \theta D_L \qquad (2)$$

where SDE and SDL are schedule delay early and late, respectively; the amount of time by which the traveller arrives early/late compared to PAT. D_L is a dummy for arriving late. $\delta, \alpha, \beta,$ and γ are the marginal utilities of travel cost, travel time, minutes early and minutes late, while θ is a fixed penalty for arriving late, no matter the size of the delay. All parameters are expected to be negative.

Heterogeneity among travellers can be modelled by including covariates in the scheduling model; e.g., by interacting the parameters with certain covariates, as in Small (1982) and Small et al. (1999).

Note that the scheduling approach, as opposed to the mean-variance approach, assumes that the marginal disutility from arriving one minute early may differ from the marginal disutility incurred by arriving one minute late. A common finding in studies by Bates et al. (2001), Hollander (2006), Noland and Polak (2002), Noland et al. (1998), Small (1982), and Small et al. (1999), is that $\gamma < \beta < 0$, i.e. that being late is more onerous than be-

[9] Both Noland and Small (1995) and Bates et al. (2001) leave out the cost term, as they consider departure time choices where all alternative departure times have the same travel cost (price).

ing early.[10] This asymmetry between being early and being late, which is further enhanced by allowing for an additional fixed penalty (θ) for late arrival, constitutes the main difference between the scheduling model and the mean-variance model.

When travel time is random, travellers are assumed to choose their departure time such that they maximise expected utility. Assuming that travel costs are known, the expected utility is:

$$EU(t_h) = \delta C + \alpha ET + \beta E(SDE) + \gamma E(SDL) + \theta P_L \tag{3}$$

where P_L is the probability of arriving late.

For a general distribution of travel time variability, the traveller's utility maximisation problem cannot be solved analytically. Noland and Small (1995) are able to find an analytical solution when travel time variability is independent of departure time t_h and follows a uniform or exponential distribution. In the exponential case (which is probably closer to reality than the uniform), the optimal expected utility can be expressed as (following Bates et al., 2001):

$$EU^* = \delta C + \alpha ET + \theta P_L^* + H(\alpha, \beta, \gamma, \theta, b, \Delta) b , \tag{4}$$

where b is the mean (and standard deviation) of the exponential distribution of TTV, and H is a function of scheduling parameters, b and Δ, which is the rate at which congestion increases when departure is delayed. P_L^* is the optimal probability of arriving late, which is

$$P_L^* = \frac{b(\beta - \eta\Delta)}{\theta + b(\beta + \gamma)} . \tag{5}$$

[10] If the opposite was the case, the traveller would never depart in the first place.

4.1.3 Comparison of the two approaches

Bates et al. (2001) and Noland and Polak (2002) show, that under certain simplifying assumptions the mean-variance approach and the scheduling approach can be shown to be equivalent. Assume as in eq. (4) above that:

- travel time variability follows an exponential distribution with parameter b,
- the travel time distribution is independent of departure time,

and further that

- $\theta = 0$ (no lateness penalty).

In this case eq. (4) simplifies to:

$$EU^* = \delta C + \alpha ET + b\beta \ln\left(\frac{\beta+\gamma}{\beta}\right) \quad (6)$$

As b is the standard deviation of T, the incurred disutility is linear in the mean travel time and its standard deviation, as in the mean-variance approach.

Noland and Polak (2002) find these simplifying assumptions unlikely to occur under normal conditions. It may well be that the travel time distribution is constant over the day for some specific routes (road or rail). Likewise, there may be cases where there is no additional disutility associated with the probability of being late, i.e. for certain non-work trips or work trips with flexible arrival schedules. However, assuming both to hold in general is unrealistic, and the result in eq. (6) hinges on the exponential assumption as well – an assumption that may not be a good approximation to the actual travel time distribution (Noland and Polak, 2002).

Nevertheless, Bates et al. (2001) claim that "[...] it has been shown empirically by others that the sum of the terms $\beta E(SDE(t_h^*)) + \gamma E(SDL(t_h^*))$ is well approximated by $H(\beta,\gamma)\sigma$ for a wide range of distributions, where σ is the standard deviation of travel time, and H can be considered constant for any given combination of β and γ." They argue that this provides some justification for using the mean-variance approach; however they do not recommend one approach in favour of the other.

Some studies have contributed to the discussion by testing the empirical performance of the mean-variance approach against the scheduling approach. We discuss these results below.

Noland et al. (1998) model the travel behaviour of car users in the Los Angeles region using stated preference (SP) data. Their basic model is a scheduling model with an additional term representing “planning costs”, or costs associated with the uncertainty per se. Planning costs are assumed to depend on the standard deviation of travel time. The preferred parameterisation of planning cost is a term proportional to the coefficient of variation (i.e. the standard deviation divided by the mean), however the term is not significant and the scheduling parameters change very little when the term is excluded from the model. The authors conclude that the effect of uncertainty is better explained by scheduling variables than by planning costs.

Small et al. (1999) use a SP survey to elicit values of time and variability (reliability in Small’s terminology) for car drivers using the California State Route 91. In their initial mean-variance model, utility is linear in the mean and standard deviation of travel time. In this initial model, both with and without covariates, the standard deviation has a significantly negative effect on utility. However, when scheduling variables ($E(SDE)$, $E(SDL)$, and P_L) are included in the model, the standard deviation loses its explanatory power. This is interpreted as the scheduling variables fully accounting for all the aversion to travel time uncertainty.

Hollander (2006) uses a similar approach on SP data from bus users in York: Travel time standard deviation is found to be significant when scheduling variables are not included, but its significance decreases when they are added. Hollander compares the results from the scheduling approach to results from a traditional mean-variance approach and finds that the latter overestimates the value of travel time and seriously underestimates the value of reliability.

The above experience covers only road traffic, but nonetheless the conclusion must be that the scheduling approach outperforms the mean-variance approach in behavioural models that involves choice of time-of-day. However, it is quite complex to apply the scheduling model for forecasting and evaluation of reliability improvements, because it demands the knowledge of travellers’ preferred arrival times. While the mean-variance approach yields a single VOR value (the marginal value of the standard deviation of travel time), the scheduling approach yields separate values for being early and late. To compute the value of a change in the distribution of travel time one needs to know each traveller’s incurred $E(SDE)$, $E(SDL)$, and P_L after the change, which requires knowledge of his preferred arrival time.

Hence, in practice it has so far often been necessary to use the mean-variance approach, especially for larger studies.[11] Therefore national VOR studies tend to use this method, c.f. Netherlands (AVV, 2005) and Sweden (Transek, 2006).

New theoretical results show, however, that it is not necessary to assume an exponential travel time distribution to obtain equivalence between the scheduling approach and a generalised mean-variance approach, where the coefficient of standard deviation is a function of the utility parameters and the tail of the standardised travel time distribution. We elaborate on this in section 5.

4.1.4 Application to public transport

The scheduling approach presented above assumes that departure time choice is continuous, as is the case for car travel. However, for public transport with scheduled services, the choice of departure time from home may be continuous, but the choice of service departure is discrete. Hence, the service departure time is not necessarily that which would maximise expected utility in the continuous case, since travellers are restricted to choose according to schedule.

Bates et al. (2001) show how to deal with this: Once the continuous solution t_h^* is identified, the relevant options are the scheduled departure just before t_h^* and the one just after. The choice between these two options depends on the utility parameters. Therefore, to determine the traveller's choice we need to evaluate his utility for both options and check which is higher.

Other issues regarding public transport are waiting time at the station and interchanges: Travel time variability is likely to affect both. A scheduled departure may be delayed, causing additional waiting time, and a late arrival at an interchange point may result in travellers missing their connecting train or bus. These components can be incorporated in the scheduling model, as described in detail in Bates et al. (2001).

There is another interesting issue connected to public transport: The mean-variance approach assumes that what matters to travellers is the expected travel time and the variation around the mean. The scheduling approach assumes that the expected travel time and variation of the arrival time

[11] Hollander (2007) provides a simple example of the use of the scheduling approach to estimate bus travellers' benefit of an infrastructure investment.

around the preferred arrival time determines behaviour. It is likely that also the *scheduled* travel time and arrival time play a role – that what matters is the variation around the scheduled travel time/arrival time: If the train always arrives late according to schedule, the expected arrival will be later than the scheduled arrival, but travellers may compare their actual arrival time to the scheduled one and therefore experience larger "late arrivals" than when comparing to the expected arrival. When considering public transport, it is therefore relevant to control for the influence of schedule adherence.

Bates et al. (2001) do this by including in the scheduling model a mean delay variable, which is the mean difference between the actual and the scheduled arrival times. This variable is very significant, indicating that the scheduling model as presented in section 2.1.2 is not adequate when modelling public transport behaviour.

4.1.5 Subjective travel time distributions

In the behavioural models discussed above, it is the *subjective* distribution of travel time that matters for choices, i.e. the traveller's perception of the travel time distribution. This subjective measure may differ from the true distribution, and between travellers. When the subjective distribution differs from the true, the traveller will experience additional disutility, as he is not able to choose optimally (Bates et al., 2001).

It is plausible that travellers learn by experience, such that the perceived distribution approaches the true distribution the more times the traveller makes the trip. Hence, it is mainly for less frequent trips we expect the travel time distribution to be misperceived. There may be several explanations for why the subjective distribution deviates from the true distribution. A reason could be that travellers are not able to correctly process the information gathered from experienced events, or that they do not know or do not understand the service statistics of the transport service. These propositions are supported by empirical evidence from studies by Tversky and Kahneman (1974) and Kahneman and Tversky (1979), which suggest that people are not very capable of handling randomness and probabilities in decision making.

Since it is not practical to incorporate travellers' subjective distributions in the behavioural models discussed above, any variation in perception will be indistinguishable from unobserved taste heterogeneity. Note also, that when evaluating reductions of variability it is the true travel time distribution that determines the traveller's incurred disutility.

4.1.6 Economic theory of choice under uncertainty

The basic neoclassical economic theory is the von Neumann-Morgenstern expected utility theory. In this theory, the utility of a random prospect is simply the mathematical expectation of the utility of the outcomes. This is the same as the probability weighted average of the utility of the outcomes. The expected utility theory follows from a short list of axioms prescribing rationality of preferences over lotteries.

Within expected utility theory there is the possibility to be risk averse or the contrary, risk loving. This depends on the curvature of the utility function. For example, the scheduling utility (3) is concave when the lateness penalty θ is omitted. In this case it is always preferred to be one minute late with certainty than it is to be three minutes late with 50 percent probability and one minute early with 50 percent probability.

There is now a lot of accumulated evidence that expected utility theory may not be always adequate. This is a subject of the field of behavioural economics. It will take us too far to review all of this literature, we constrain ourselves to present only a few highlights.

The seminal paper in behavioural economics is Kahneman & Tversky (1979). They present a number of carefully designed experiments concerning choice under uncertainty in which the behaviour of subjects systematically contradicts the predictions of expected utility theory. Kahneman & Tversky formulate their prospect theory in order to explain these phenomena. Since then, a plethora of theories have been proposed for choice under uncertainty and a range of anomalies relative to expected utility theory has been established (Starmer 2000). A common denominator of these theories is that the probabilities assigned to outcomes, e.g., the probabilities of various sized delays, enter in a more complicated way than just expected utility. Thus, the effect of uncertainty on choices differs between theories and the rationality prescriptions of expected utility theory.

Many theories also embody reference-dependent preferences. This is another anomaly relative to neoclassical preferences which are supposed to be stable and not affected by the status quo.

John Polak and collaborators seek in a series of papers to integrate risk preferences in the form of curvature of the utility function with scheduling utility and with alternatives to expected utility maximisation (Liu, X. & Polak, J.W. 2007, Michea, A. & Polak, J.W. 2006, Polak, J.W., Hess S & Liu, X. 2008).

The question is now what the consequence should be for definition and measurement of the value of travel time variability. How should we obtain valuation measures that can be used in applied cost-benefit analysis? How to use the 'behavioural' models of reference-dependence and probability weighting in a 'normative' cost-benefit evaluation? In a more general setting, this relation between behavioural economic models and normative welfare economic models is a main focus of the recent literature on behavioural welfare economics (for a recent survey, see Bernheim and Rangel, 2007). Different views have been defended. Some authors argue (e.g., Gul and Pesendorfer, 2001, 2004) that, in case certain "anomalies" are observed, the best answer is to expand the preference domain to explain the observed behaviour, and use the adapted behavioural model as the basis for a normative policy evaluation. Another school of thought suggests that, if choices cannot be explained by a set of coherent preferences or if people are observed to make systematic mistakes, it may be necessary to abandon the close relation between behavioural and normative economic models.

The latter strategy has been followed in De Borger & Fosgerau (2008) and Fosgerau & De Borger (2008) in the context of the value of travel time. They argue that people are imperfect optimisers of utility when they make choices, for example in an SP experiment. An underlying hedonic utility is assumed that satisfies the rationality axioms of neoclassical theory. The imperfect ability to maximise utility is manifest as anomalies, but it is the underlying hedonic utility that is the relevant object to measure and use in applied cost-benefit analysis. They then propose a model in which the relevant hedonic preferences may be inferred from choices in the presence of anomalies.

The analogous argument for the case of the value of travel time variability would maybe say that it is pertinent to account for the presence of anomalies when making measurement, but that anomalies should be corrected for before computing the value of travel time variability to be used for policy evaluation. This is a line of argument that we would like to develop in future research.

The literature on behavioural economics has developed a set of tight formats for eliciting preferences under uncertainty. One such format presents for example a certain alternative against an alternative gamble with two potential outcomes each of which is assigned a probability. This stands in contrast to the transport literature which has emphasised realism but has had trouble communicating probability distributions with many potential outcomes.

4.2 Presenting variability in SP exercises

Most often, the attitude towards travel time variability is measured in SP experiments, because it is difficult to obtain suitable revealed preference (RP) data: Apart from the difficulty associated with measuring the travel time distribution[12] and judging how well travellers know the distribution, it will often be the case that travel time, variability, and cost attributes are correlated such that separate valuations cannot be identified.[13] The main problem with using SP experiments, however, is how to present the travel time distribution to respondents in such a way that they perceive it correctly.

Even if we know the shape of the travel time distribution, the concept of a statistical distribution is likely to be too abstract to present to respondents. In an SP experiment, travel time variability must therefore be communicated in terms of specific features of the distribution, which the respondent can relate to and interpret.

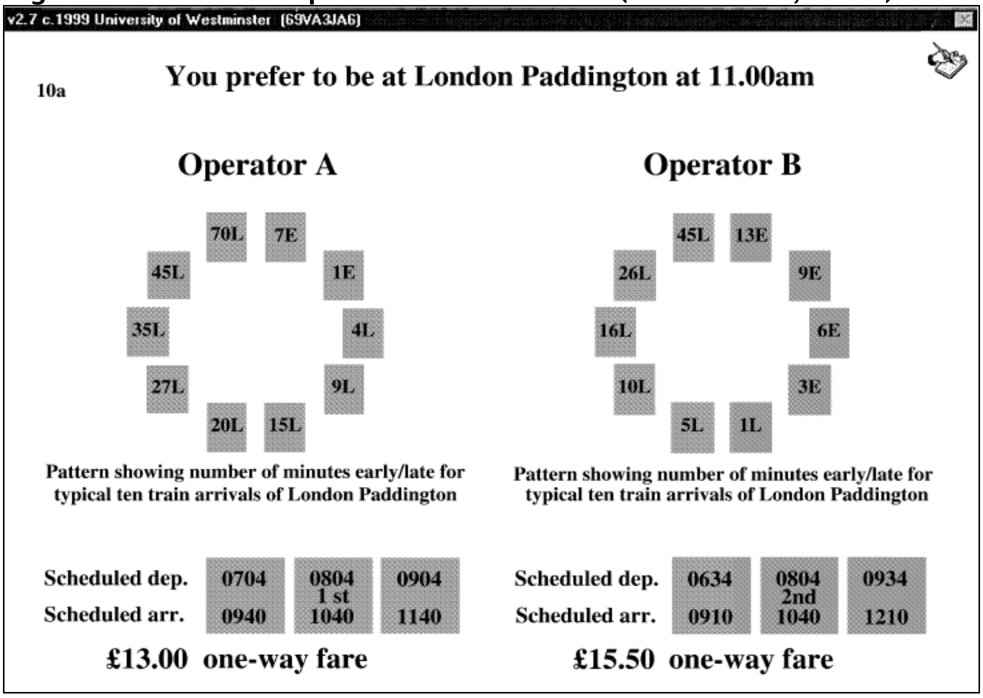
Early studies present different levels of reliability as "all trains on time", "1 train in 5, 5 minutes late" etc., but such formulations tend to be misunderstood by respondents (Bates et al., 2001). Instead later studies present a range of possible outcomes, expressed in terms of travel time, arrival time, or lateness. Small et al. (1999) prefer to present outcomes in terms of lateness (SDE and SDL) rather than travel time, because they find evidence that not all people are able to compute early and late arrivals from given travel times.

A potential problem with presenting respondents with a list of possible outcomes is that we cannot be sure how the sequencing of outcomes is interpreted. People may think that the outcomes are ordered chronologically or by increasing/decreasing frequency (Bates et al., 2001). Small et al. (1999) avoid this by emphasizing that outcomes are equally likely, while Bates et al. (2001) prefer to present the outcomes in a clock-face manner, such that the ordering is less obvious.

[12] See e.g. Lam and Small (2001).

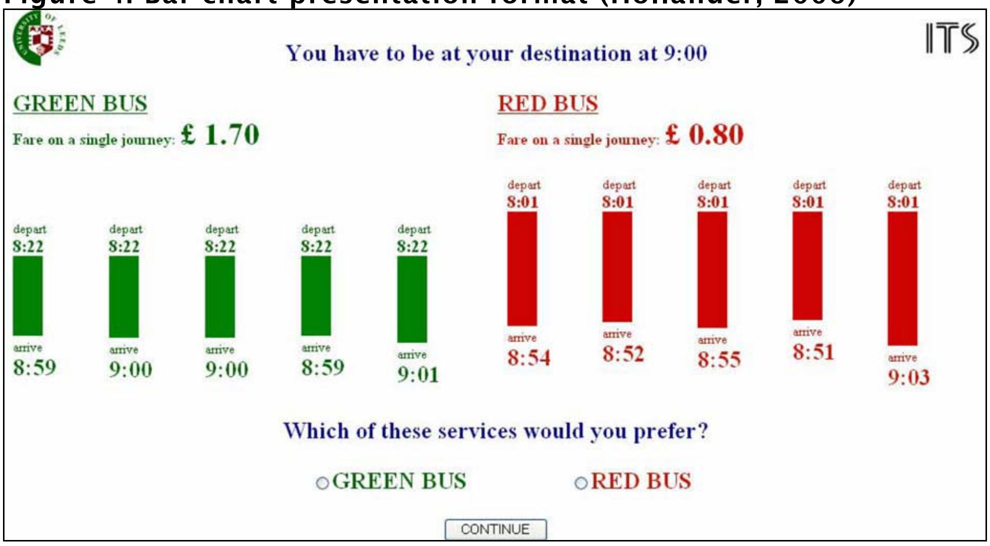
[13] An exception to this is the study by Lam and Small (2001), who use data from actual choices between a tolled and an untolled road, where the toll varies by the time of day.

Figure 3: Clock-face presentation format (Bates et al., 2001)



Hollander (2006) finds that a graphical representation of the travel time attributes improves interpretation of the questionnaire: He prefers to display the hours of departure and arrival times explicitly, while presenting the travel time attribute by a bar whose length is proportional to the travel time.

Figure 4: Bar-chart presentation format (Hollander, 2006)



Graphical presentations seem a useful tool to present detailed information in a simple way. However, care must be taken to introduce respondents to this way of conveying information in order to guarantee that respondents interpret the information as intended by the analyst. Bates et al. (2001) and Hollander (2006) provide examples, where the questionnaire includes an educational introduction to the graphical representation of travel time.

Copley et al. (2002) and Tseng et al. (2007) compare different representations of travel time variability, using in-depth interviews with small focus groups. Copley et al. (2002) test respondents' understanding of travel time histograms and conclude that people are able to understand the presented information and trade off mean travel time for travel time variability. Respondents prefer a (verbal) list of possible outcomes or a histogram to clock-face representations. Moreover, they prefer the list of outcomes over the histogram, as graphical representations are more easily misinterpreted. A series of choice exercises reveal that people are not consistent across different presentations, i.e. choices are affected by the framing of alternatives.

Tseng et al. (2007) find that a verbal representation with a list of outcomes performs very well in several tests. The clock-face format performs badly, while histogram representations perform well for some individuals and badly for others. An ordered bar chart (as in Hollander, 2006) performs very well, but a similar representation with unordered outcomes is considerably less attractive. Hence, Tseng et al. recommend that the bar chart representation should be tested further before applying it in a study.

Figure 5: Histogram presentation format (Tseng et al., 2007)

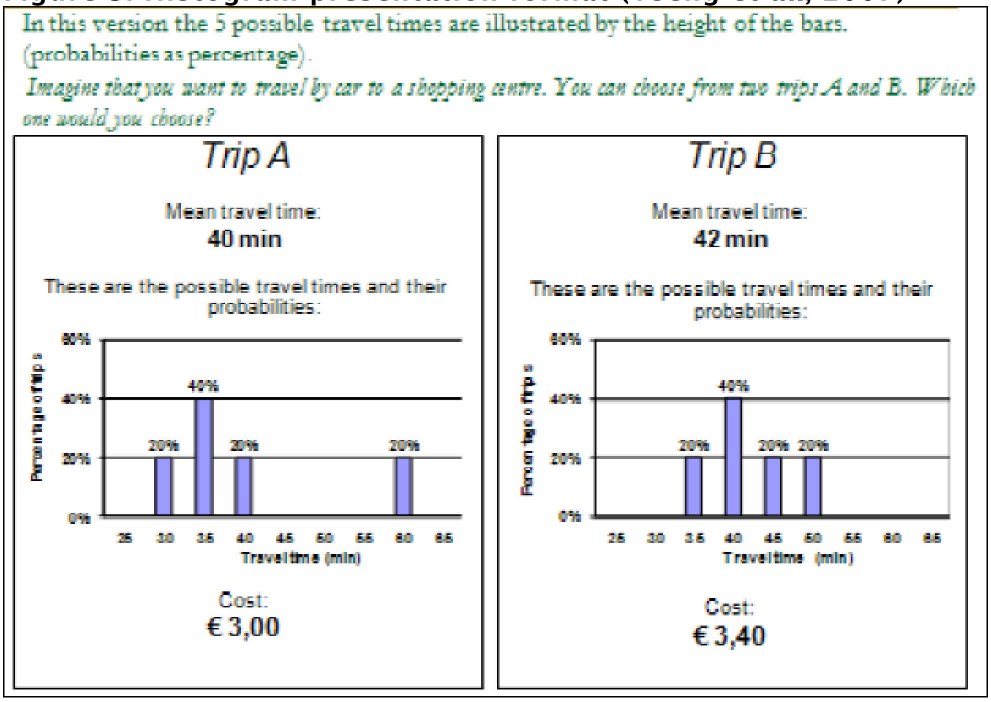
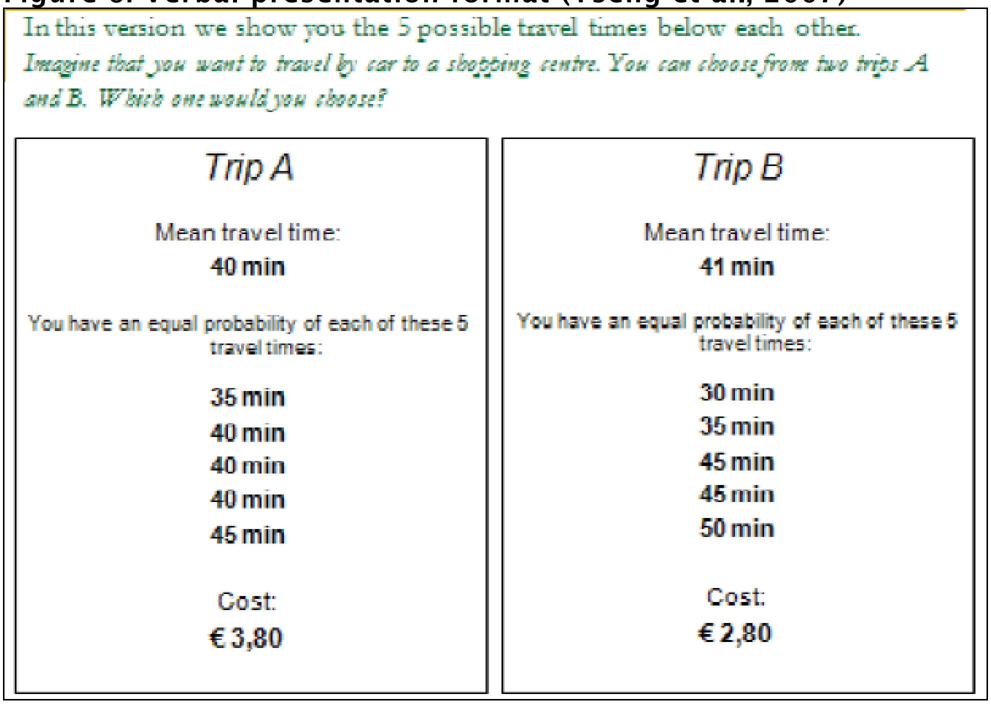


Figure 6: Verbal presentation format (Tseng et al., 2007)



4.3 Evidence from valuation studies

At present national studies of valuation of variability are under way in Sweden, Norway, and the Netherlands. So far, no results are available, and the only empirical evidence concerning the value of variability (VTTV) comes from smaller studies of specific areas or corridors and/or specific groups of travellers. Table 14 in the Appendix gives a summary of this evidence.

The studies reviewed are mainly from USA or UK and represent both the mean-variance approach and the scheduling approach. Most studies use SP data. The resulting valuations differ considerably between studies, making it quite difficult to establish a common VTTV, reliability ratio (which is the value of a minute's standard deviation divided by the value of travel time), or reliability multiplier (the value of a minute's mean delay divided by the value of travel time).

Three of the studies have estimated the parameters of the scheduling model in its most simple form, namely that of eq. (3) with fixed parameters. The parameter estimates are listed in Table 3 below for future reference[14]. We also give parameter estimates from Small (1982), who estimate the scheduling model without uncertainty. In all four studies, the parameter estimates are obtained from stated preference interviews and apply to commuting trips only. All studies use discrete choice models with utility of the travel alternatives as latent variables; since utility has no scale, only relative parameter values (parameter ratios) can be directly compared across studies, and not the parameters themselves.

Table 3: Empirical evidence of scheduling parameters

	α	β	γ	θ
Bates et al. (2001)		-0.04714	-0.09568	
Hollander (2005,2006)	-0.07173	-0.07173	-0.1974	
Noland et al. (1998)	-0.0976	-0.0945	-0.1280	-1.529
Small (1982)	-0.106	-0.065	-0.254	-0.580

[14] We use the values to compute the values in Table 7 on page 57.

5 A new approach

This section describes a new approach, due to Fosgerau and Karlström (2007). As discussed in section 4, there is a choice between two approaches for attaching a value to travel time variability. The first approach includes the standard deviation or another summary measure of variability directly into the utility function. This approach lacks, however, firm theoretical motivation while it is easy to apply. The second approach defines utility in terms of outcomes of being early and late and is hence more fundamental. It suffers, however, from the drawback that it is hard to apply in practice since it generally requires knowledge of the preferred arrival times of individual travellers. As mentioned in section 4, Bates et al. (2001) and Noland and Polak (2002) show that the two approaches are equivalent under the assumptions that there is no fixed penalty for arriving late, and that the travel time distribution is exponential and independent of the choice of departure time.

Fosgerau and Karlström (2007) generalise this result, relaxing the strict assumptions on the travel time distribution. The result is that the value of travel time as well as the value of travel time variability, expressed as standard deviation of travel time, may be expressed in terms of scheduling parameters, i.e. the costs of travel time, earliness and lateness. The approach is described in section 5.1 for the case of car travel, where the departure time may be chosen freely. This is a key feature of the model: When the departure time is optimally chosen it turns out not to be necessary to know the preferred arrival time in order to apply the model and an expression emerges for the expected cost involving the standard deviation of travel time.

The Fosgerau and Karlström approach does not generalise directly to the case of scheduled services such as bus or rail, operating according to a fixed schedule, since in such case the travellers can not freely choose their departure time. We offer instead a reinterpretation of the scheduling model, where the role of providing optimality resides with the operator of the service. This conforms to the actual behaviour of Danish bus operators, who design schedules such that 30 percent of arrivals will be late (section 3.3.1). Using this fact, it is possible to derive a value of travel time variability for public transport that parallels the value for car travel. This is described in section 5.2.

Application of the approach poses certain demands on the empirical distribution of travel times. In particular, it should be the case that the standardised travel time distribution, after removing changes in the mean and standard deviation over the day, should be independent of the time of day. Moreover, it eases application of the results if a certain summary statistic for the standardised travel time distribution is constant across different road and rail trip types. We examine these issues empirically in section 5.3 and find that the application of the Fosgerau and Karlström model is well supported.

The outcome is thus that it is theoretically and empirically well motivated to apply the standard deviation of travel time as the concept of travel time variability, while the associated value is calculated from scheduling parameters and a certain characteristic of the distribution of travel times.

5.1 Theoretical formulation for cars

To fix thoughts we may think of a traveller going to work in the morning. We say the preferred arrival time is time zero, it will not matter what it actually is. Then Fosgerau and Karlström (2007) define his scheduling cost in terms of actual travel time T and head start D. The head start is defined as the length of the interval between departure time and the preferred arrival time. Thus, the traveller departs at time $-D$ when the preferred arrival time is zero.

As in the Noland and Small (1995) scheduling model, it is assumed that the traveller incurs disutility from travel time per se and from the amount of time he arrives late. However, where the scheduling approach describes the traveller as experiencing disutility from arriving early, Fosgerau and Karlström assume disutility is incurred from interrupting a prior activity. Thus, omitting the travel cost for simplicity, the utility of travelling becomes:

$$U(D,T) \quad = \quad \eta D + \omega T + \lambda (T-D)^{+} \tag{7}$$

where all parameters are expected to be negative, and $(T-D)^{+}$ denotes the positive part of $(T-D)$, which is $(T-D)$ if this is positive, and zero otherwise. Hence, since preferred arrival time is zero, $(T-D)^{+}$ denotes the amount of time the traveller arrives late (SDL). As demonstrated in the Appendix, this formulation is just a reparameterisation and in fact equivalent to the original Noland and Small (1995) formulation in eq. (2), with the exception that the delay penalty θ is omitted here. The correspondence between the parameters, α, β, and γ in the Noland and Small model (eq. 2) and the parameters η, ω, and λ in the Fosgerau-Karlström model is: $\eta = \beta$, $\omega = \alpha - \beta$, $\lambda = \beta + \gamma$ (see the Appendix for details).

Travel time T is assumed to be random, and is expressed as

$$T = \mu + \sigma X \tag{8}$$

where X is a standardised random variable with mean 0, variance 1, density function ϕ, and cumulative distribution function Φ. The parameters μ and σ are allowed to depend on D, such that the mean and variance of the travel time distribution vary with time of day. However, the underlying standardised distribution (of X) is assumed fixed with respect to D, μ, and σ.[15]

Fosgerau and Karlström (2007) consider two cases for car traffic: In the simple case where μ and σ are constant (do not vary with D), utility maximising behaviour leads to an expected utility that is linear in μ and σ, as in the mean-variance model. In a more general case, where μ and σ depend linearly on D, this result does not hold exactly, but can still be used as an approximation. This is described in more detail in the following.

5.1.1 Constant travel time distribution

In this simple case, μ and σ are constant and equal to μ_0, σ_0. The traveller maximises expected utility (with utility given by eq. (7)) by choosing his departure time. Fosgerau and Karlström show that this problem may be solved analytically for the general travel time distribution defined by eq. (8), yielding the following expression for the optimal expected utility:

$$EU(D^*) = (\eta + \omega)\mu_0 + \lambda\sigma_0 H(\Phi, \frac{\eta}{\lambda}), \tag{9}$$

where

$$H(\Phi, \frac{\eta}{\lambda}) = \int_{1-\frac{\eta}{\lambda}}^{1} \Phi^{-1}(x)dx \tag{10}$$

This is a significant result. The optimal choice of head start D^* turns the expected utility into a linear function of the mean and the standard deviation of travel time.

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[15] Note that this restricts the class of travel time distributions to which this approach can be applied.

- The term $\eta+\omega$ is the value of travel time, which is determined in value of time studies such as The Danish Value of Time Study (Fosgerau et al., 2008).[16]
- The term $\lambda H(\Phi,\eta/\lambda)$ is the value of travel time variability, which multiplies the standard deviation of travel time.
- The scheduling parameters η, λ and ω may be estimated on the basis of scheduling choices.
- The term $H(\Phi,\eta/\lambda)=\int_{1-\frac{\eta}{\lambda}}^{1}\Phi^{-1}(x)dx$ may be estimated from an empirical travel time distribution given knowledge of η/λ. This ratio is the optimal share of trips arriving late.

So the Fosgerau and Karlström result provides an important generalisation of previous attempts to unify the scheduling and the mean-variance approach. It is straight-forward to apply and it is quite feasible to estimate empirically the required quantities.

5.1.2 Time-varying travel time distribution

The main issue with the above result is that the mean and the standard deviation of the travel time distribution are assumed to be constant. But on real roads there are pronounced systematic variations in traffic over the day. Generally, both the mean and the standard deviation of travel time increase during the first half of a peak and decrease afterwards. It turns out that the Fosgerau and Karlström result in eq. (9) still holds as an approximation, when

- mean travel time μ and standard deviation σ vary linearly with the head start D (this is a stylised description of the travel time distribution on either side of a peak),
- the marginal changes in μ and σ with a change in D are small for the interval of head start values considered by the traveller.

Note that we maintain the assumption that the distribution of travel time T is determined by eq. (8), where the distribution of X does not depend on μ, σ, and D.

[16] Actually, the unit of $\eta+\omega$ is utility units per time unit. To obtain the monetary value of travel time, we need to divide by the marginal utility of income. The same is the case for the VTTV, $\lambda H(\Phi,\eta/\lambda)$.

For this situation, Fosgerau and Karlström (2007) show that the value of travel time is exactly the same as in the simple case, while the error involved in still using $\lambda H(\Phi, \eta/\lambda)$ for the value of travel time variability is small. This means that we can use the simple and convenient result from the case when the mean and the standard deviation of travel time are constant also in the case where they actually vary in the way described above.

5.2 Theoretical formulation for public transport

As mentioned, the situation for a scheduled service is more complicated, since there the traveller is not able to choose the optimal head start but must select a departure from the schedule. Fosgerau and Karlström show that this causes the convenient result from above to break down. However, if we are willing to impose some additional (restrictive) assumptions, it is possible to make the simple result from above apply to a scheduled service as well.

We consider just one departure on some scheduled service and we assume that:

- All travellers have the scheduled arrival time as their preferred arrival time; i.e. travellers adapt themselves to the timetable. This assumption implies that we ignore variation in PAT.[17]

- The frequency or the headway of the service does not enter the picture.[18]

- Travellers are identical and derive (dis)utility from travel time per se and from arriving early or late relative to schedule. Thus we are assuming that the scheduling of departure times has no bearing on utility, travellers are able to adapt to this at no cost.

The problem here is that the traveller has no choice in the scheduling of the service. He is not able to influence the travel time allocated in the schedule and hence the probability of arriving late, this is in the hands of the operator.

This observation also provides the solution. We can assume that the operator knows the preferences of the travellers and plans the schedule accord-

[17] For comparison, Bates et al. (2001) find that only about a third of their train sample has a PAT equal to scheduled arrival time, and that the distribution of PAT's shows considerable variation.
[18] The welfare effect of changing the frequency must be handled separately as it is also done with present Danish appraisal methodology.

ingly to minimise the expected cost of travellers. It seems this is how operators actually behave, when they plan the schedule such that the probability of arriving late is 30 percent (section 3.3). A probability of being late of 30 percent is in the range predicted by the scheduling model.

With these assumptions it turns out that the value of time and the value of reliability for a scheduled service are exactly the same as for car.[19]

5.3 Empirical verification of model assumptions

We have now established a theoretical model whereby the value of reliability may be derived from scheduling costs and from a travel time distribution. This theoretical model works with the assumption that the standardised travel time distribution, after removing changes in the mean and standard deviation, is constant. In this section we provide some empirical evidence to check this assumption. It turns out to be fairly good for some large datasets containing observations of travel times.

It would be convenient if the term $H(\Phi,\eta/\lambda)=\int_{1-\frac{\eta}{\lambda}}^{1}\Phi^{-1}(x)\,dx$ could be assumed to be (largely) constant for different roads and also for different rail services. If a typical value of H could be established, there would be no need to establish values of H for every road and rail service in Denmark. That would ease application of the model considerably. Fortunately, this also turns out not to be a bad assumption to make.

We analyse the distribution of car travel time in two datasets, relating to

1. Frederikssundsvej, a radial road in Greater Copenhagen.
2. The motorways between Odense, Kolding, and Vejle (E20, E45).

For rail, we analyse the distribution of train travel time on a highly loaded railway section:

3. The Copenhagen-Ringsted railway route.

5.3.1 Data description

The road data are provided by Vejdirektoratet's TRIM system, which measures speed and traffic flows on some congested sections of the Danish road network, using cameras and automatic number plate recognition.

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[19] The results in this section will form the basis of a scientific paper at a later stage.

The Frederikssundsvej data are recorded on an 11.3 km section of a main radial road in Greater Copenhagen.[20] The data provide by minute observations of average travel time. We use data from weekdays between 6am and 10pm in the period January 16 to May 8, 2007, which gives us 24,271 observations in the direction towards Copenhagen, and 21,742 observations in the opposite direction, c.f. Table 15. in the Appendix.

The motorway data are recorded on motorways E20 and E45 between Odense, Kolding, and Vejle.[21] Each link in one direction between two junctions forms a segment and this network is thus divided into 30 segments of varying length (1.8-11.9 km), c.f. Table 16 in the Appendix. For each five-minute interval, data provide the median travel time of the 10 most recent cars to pass through the road segment, given that these entered the segment within the last hour. If there are less than 10 such observed cars, no data is produced. We use data from weekdays between 6am and 10pm in the period April 29 to July 31, 2007, leaving around 60,000 observations in most segments, c.f. Table 16.

The rail data are Trafikstyrelsen's RDS data for the 63.9 km railway section between Copenhagen and Ringsted. This section serves all trains between Copenhagen and Funen/Jutland, as well as international trains to/from Germany. It has 12 stations (including Copenhagen and Ringsted), though most of these are served by regional trains only. For each arrival at the 12 stations, the data provide the scheduled arrival time and the delay (difference between actual and scheduled arrival time). We use data for passenger trains from weekdays between 6am and 10pm in the period January 1 to December 31, 2006. We exclude observations where the arrival is more than 3 minutes early, as these are likely due to measurement errors. This leaves 123,706 and 126,285 observations for analysis in the direction away from and towards Copenhagen, respectively (Table 17).

There is a potential problem in using the rail data within a scheduling context, as the recorded delays are defined with respect to the operations timetable and not the passenger timetable. Since passengers do not know the operations timetable, there can be cases where the passenger does not know his scheduled arrival time, as this does not always appear in the passenger timetable. To apply the rail travel times in a scheduling context, we need to assume that the passenger has full information; corresponding to

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[20] The road section consists of Frederikssundsvej (from the Frederikssundsvej-Svanereden intersection), Herlev Hovedgade, Skovlunde Byvej, Ballerup Byvej, and Måløv Byvej (to the Måløv Byvej-Knardrupvej intersection).
[21] From exit 59 on E45 in the north to exit 64 on E45 in the south and exit 53 on E20 in the east.

modelling only the frequent passengers, who know by experience that the train arrives at a station, say, half a minute before its scheduled departure.

5.3.2 Analysis methodology

For each data set, we estimate the distribution of standardised travel time X, and check whether this is independent of time of day t, as is assumed in the model described above. We then compute values of the function $H(\Phi,\eta/\lambda)$ for a range of values of η/λ, and compare these across different data sets.

To compute standardised travel time, we first estimate the mean and standard deviation of observed travel times (or, for rail data: delays) as a function of t. For a given time of day t_0, the mean travel time $E(T \mid t = t_0)$ could be estimated simply by averaging travel times T over observations with $t = t_0$. However, since our data are very “noisy”, we prefer to use some kind of smoothed average, and therefore estimate $E(T \mid t = t_0)$ by a so-called non-parametric kernel estimator (Li and Racine, 2007): This is a weighted average of T, where observations are weighted higher the closer t is to t_0. For weighting, we use a Normal (Gaussian) weighting function (kernel), which is symmetric around t_0. The width of the weighting function is determined by a bandwidth parameter: When the bandwidth is small, observations far from t_0 receive little weight, and vice versa. The standard deviation as a function of time of day is estimated in a similar manner, and the standardised travel times are computed from travel times (or delays) by subtracting the estimated mean and dividing by the estimated standard deviation.

The density and distribution functions of standardised travel time X are also estimated non-parametrically, using the estimators from Li and Racine (2007) with Normal kernels. We first compute the distribution conditional on time of day t, and check whether it can be assumed independent of t. This turns out to hold approximately, and it is therefore meaningful to estimate the unconditional distribution Φ, which is used to compute values of $H(\Phi,\eta/\lambda)$.

The applied bandwidths are determined by least squares cross-validation or maximum likelihood cross-validation, c.f. Li and Racine (2007), except for some estimations of mean and standard deviation, for which cross-validation is either not possible or results in under-smoothing: For these estimations bandwidths are chosen by “eyeballing”, i.e. picking an appropriate value based on graphical inspection.[22] The bandwidths for the conditional distribution of standardised travel time are determined by the so-called “normal reference rule-of-thumb” (Li and Racine, 2007).

5.3.3 Analysis - road

We have selected Frederikssundsvej in the inbound direction as the typical case for road and present detailed results only for this road segment. Figure 7 shows the raw data with the time of day on the horizontal axis and the travel time in minutes on the vertical axis. Each point corresponds to a one-minute observation, i.e. the average travel time within the given minute. It is evident that there is a wide distribution of travel times at any time of day, with most dispersion during the peaks. There is a sharp peak in the morning and a smaller and wider peak in the afternoon.

Figure 7: Observations of travel time by time of day. Frederikssundsvej, inward direction

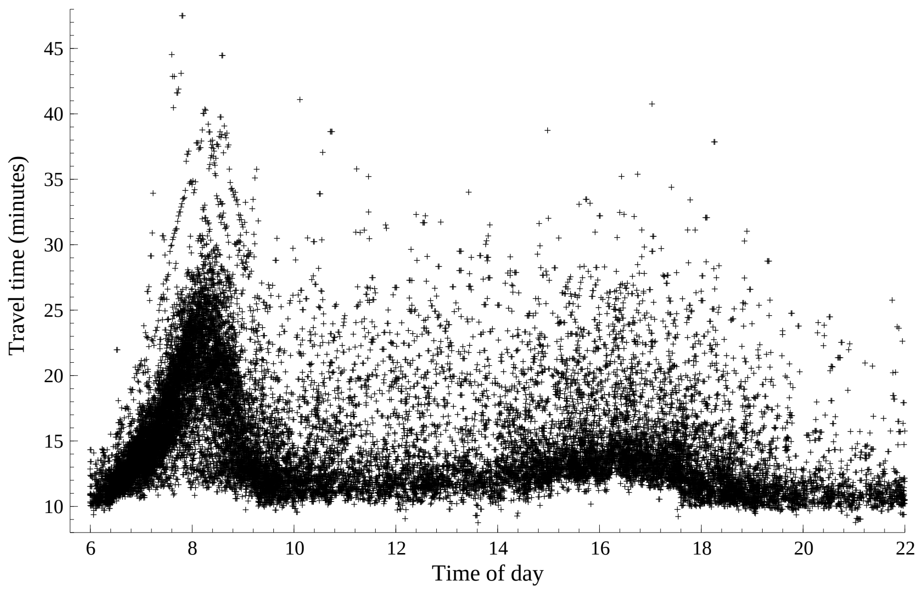

Figure 8 shows the estimated mean (with 95% confidence bands) and standard deviation as a function of the time of day. The morning peak is very distinct and results in a sharp increase in both the mean and the standard deviation. The afternoon peak is less pronounced.

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[22] All programming is carried out in Ox (Doornik, 2001) and R (http://www.r-project.org/). We were lucky to be able to use the Tsubame Grid Cluster at the Tokyo Institute of Technology for the heaviest computations. This reduced a typical computation time for cross-validation of one segment from 2-3 days on a standard pc to 2-3 hours.

Figure 8: Estimated mean travel time by time of day, with confidence bands (upper graph) and estimated standard deviation by time of day (lower graph). Frederikssundsvej, inward direction.

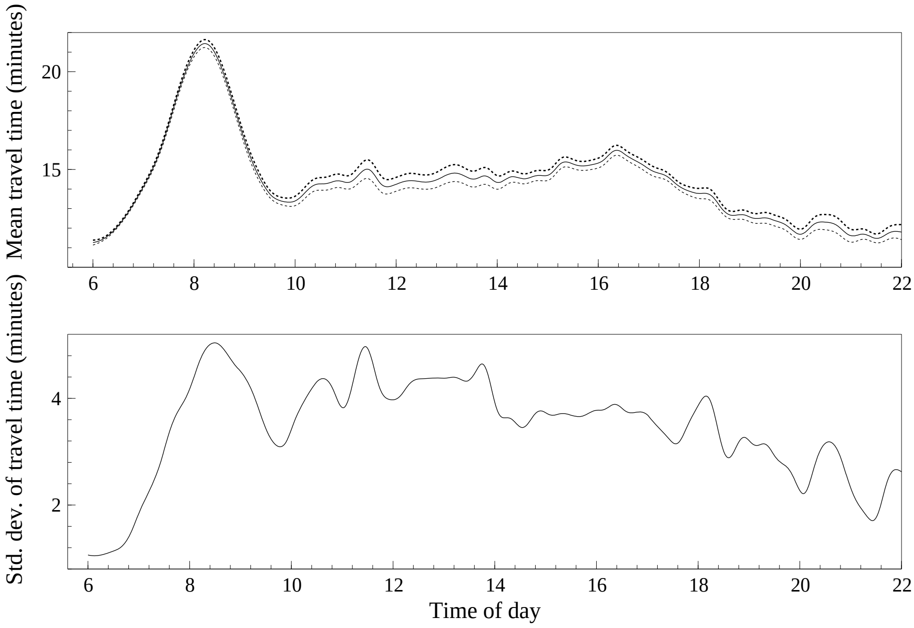


Figure 9 shows a scatter plot of the standard deviation against the mean travel time. The bubble to the right corresponds to the morning peak. The approximate times are indicated on the figure. It indicates that the standard deviation rises more slowly than the mean in the build-up phase and that the standard deviation persists at a high level after the mean has begun decreasing. This pattern has been observed in other cases and is probably typical. The bubble shape could be due to the peak lasting longer on some days than on others.

Figure 9: Scatter plot of mean travel time (horizontal axis) and standard deviation (vertical axis). Frederikssundsvej, inward direction.

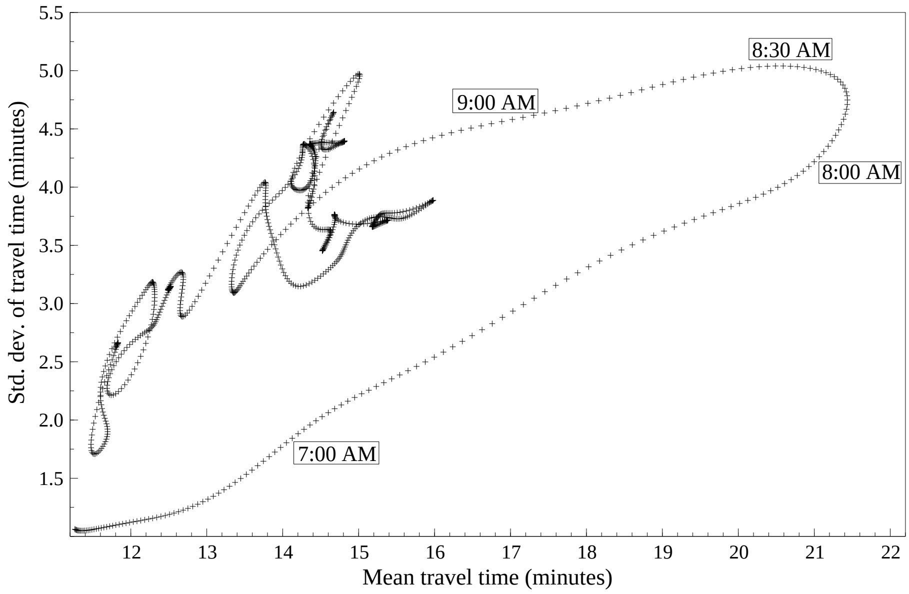
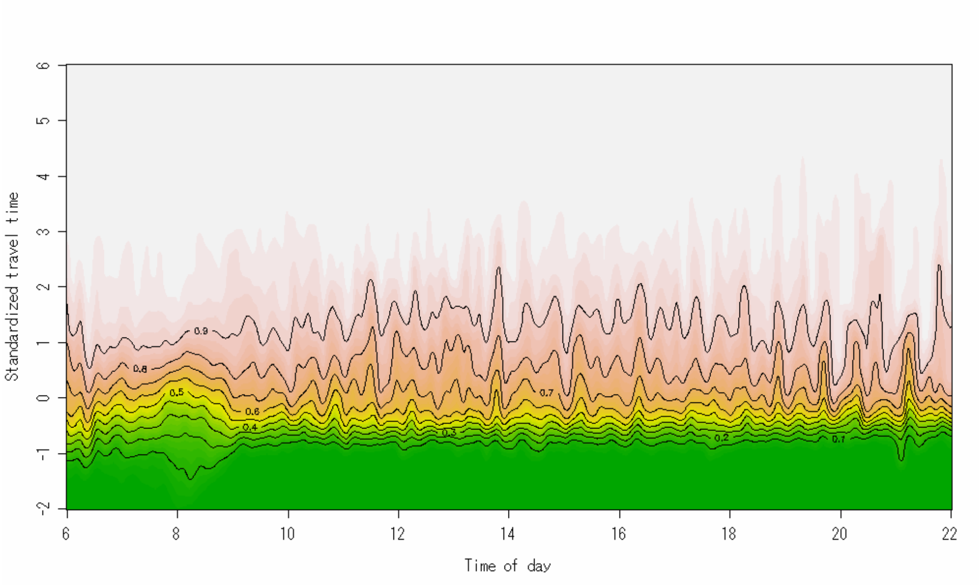


Figure 10 shows the contours of the standardised travel time distribution conditional on time of day. The horizontal curves correspond to the 10%, 20%, 30%, ..., 80%, and 90% quantiles of the distribution. As an example, the distribution at 6am has a 10% quantile equal to -1, a 50% quantile (median) around -0.3, and a 90% quantile around 1.6.

We use Figure 10 to investigate visually whether the distribution of standardised travel time can be assumed to be independent of time of day. If this were the case, the quantiles would be constant over time of day, i.e. the contours would be completely horizontal. Although they are not exactly horizontal on the figure, they are nevertheless very close. It thus seems independence of the standardised travel time distribution and the time of day is a reasonable assumption to make.

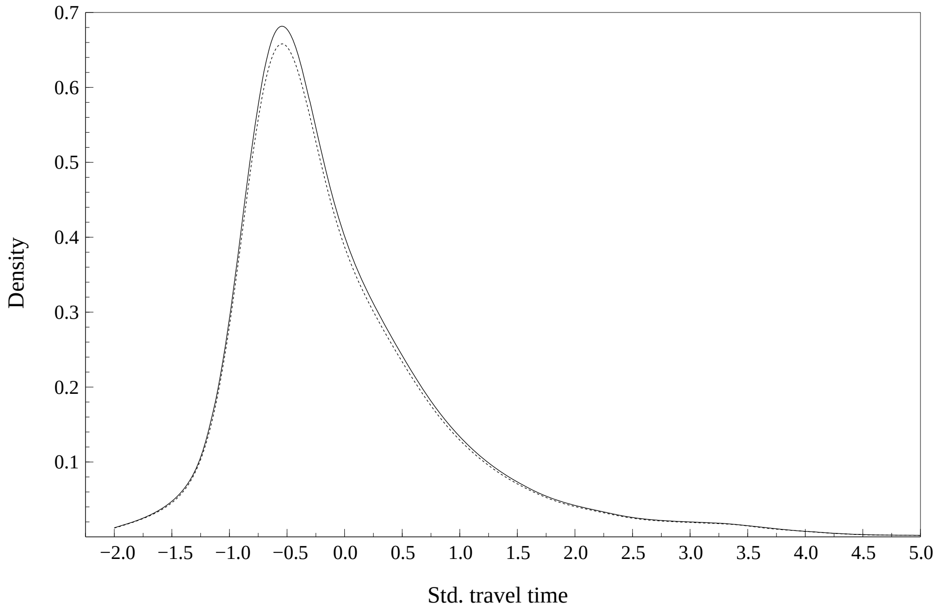
Figure 10: Contours of the CDF of standardised travel time (vertical axis) conditional on time of day (horizontal axis). Frederikssundsvej, inward direction.



It is then meaningful to compute the standardised travel time distribution, not conditioning on the time of day. This density provides the basis for computing the term H in the value of travel time variability. The estimated density of the standardised travel time distribution is shown in Figure 11. The resulting shape is typical for all the cases we have examined and resembles a so-called stable distribution.[23]

[23] Stable distributions have the property that the sum of two random variables with the same type of stable distribution also has a stable distribution of the same type. If it turns out that standardized travel time distributions are, more or less, of the same type, then it becomes very easy to aggregate from section to route level. This would be extremely useful. Mogens Fosgerau and Daisuke Fukuda are currently investigating this hypothesis.

Figure 11: Estimated (unconditional) density of standardised travel time, with lower confidence band. Frederikssundsvej, inward direction.



5.3.4 Analysis - rail

We have performed similar calculations on the rail data for Copenhagen-Ringsted. We present graphically the results for the direction from Copenhagen to Ringsted. Figure 12 presents the raw data. Recall that the data record deviations from the schedule such that values less than zero are rare. We see a wide spread of delays with many observations close to zero delay and some observations exceeding two hours.

Figure 12: Observations of train delay (in minutes) by time of day. RDS data, Copenhagen-Ringsted.

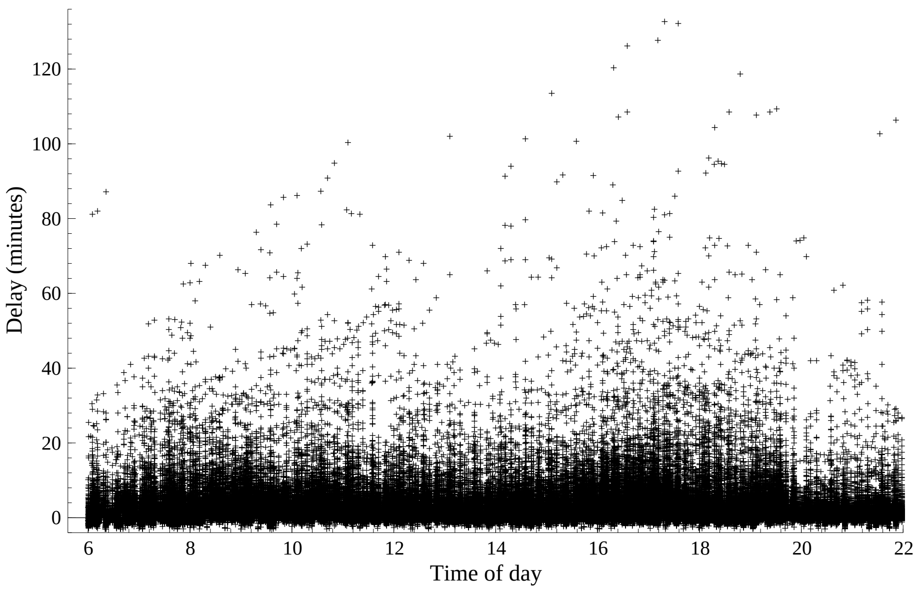


Figure 13 presents the estimates of mean and standard deviation of delay by time of day. The pattern seems to be two peaks, one around 10-11am and the other around 17pm.

Figure 13: Estimated mean delay by time of day, with confidence bands (upper graph) and estimated standard deviation by time of day (lower graph). RDS data, Copenhagen-Ringsted.

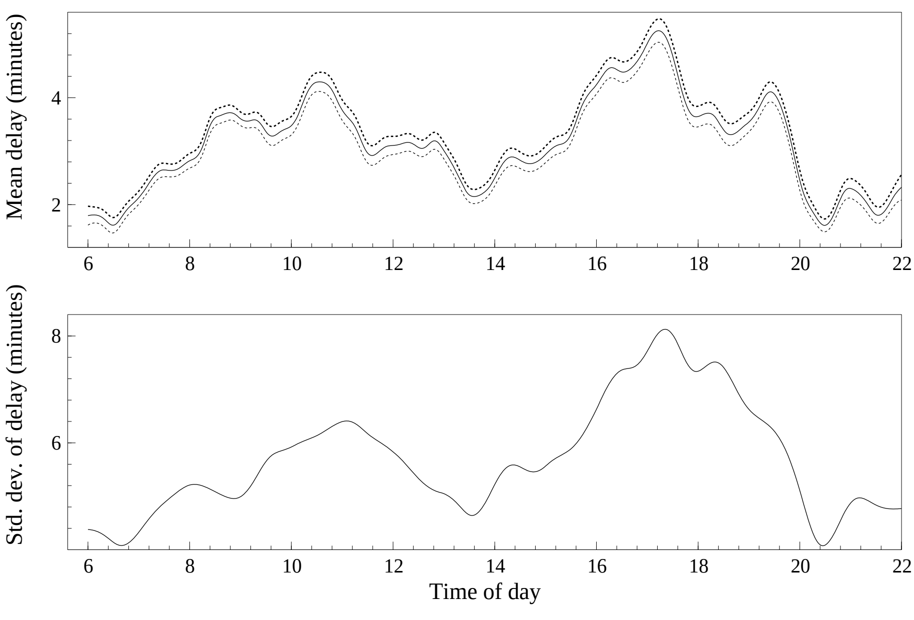
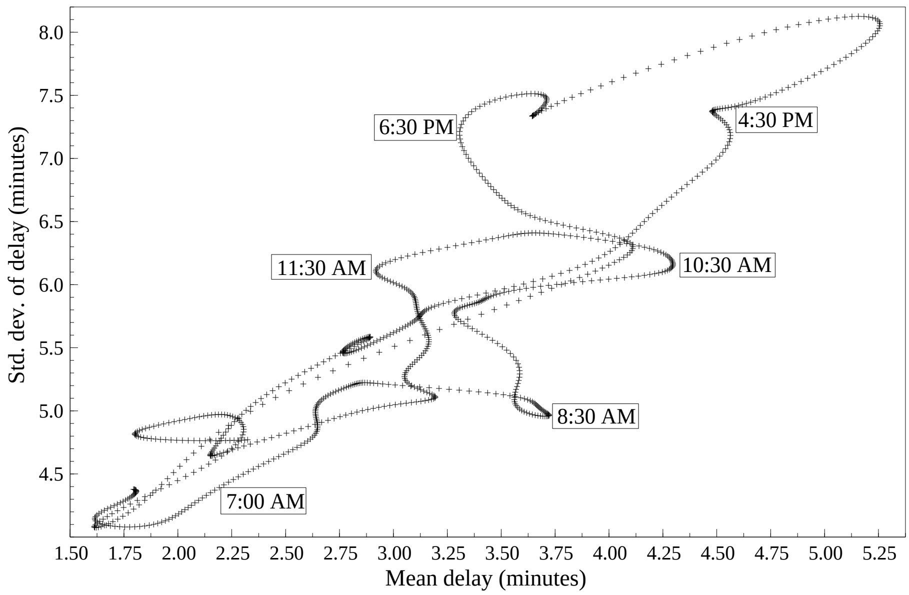


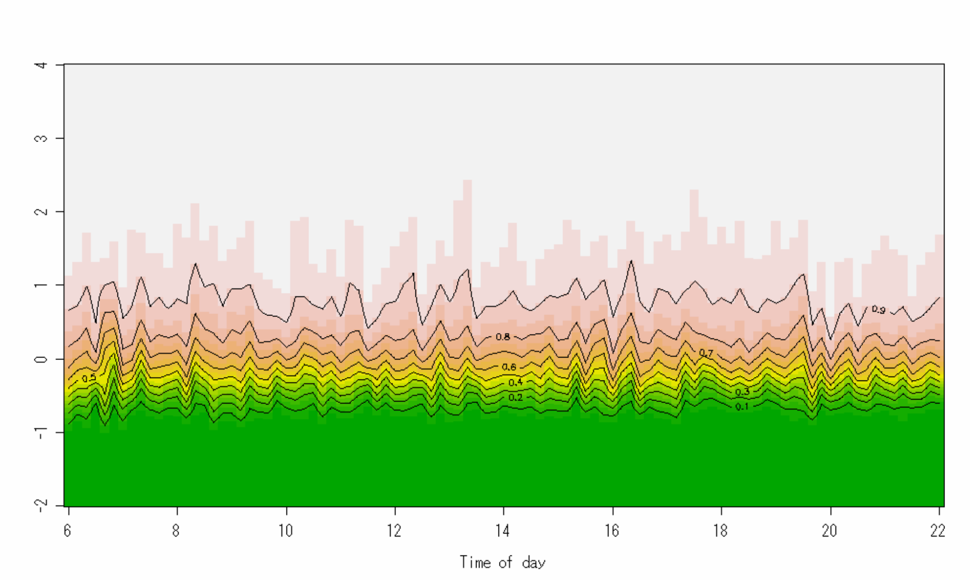
Figure 14 presents a scatter plot of standard deviation against mean delay. The large bubble to the north-east corresponds to the period 4pm-7pm.

Figure 14: Scatter plot of mean delay (horizontal axis) and standard deviation (vertical axis). RDS data, Copenhagen-Ringsted.



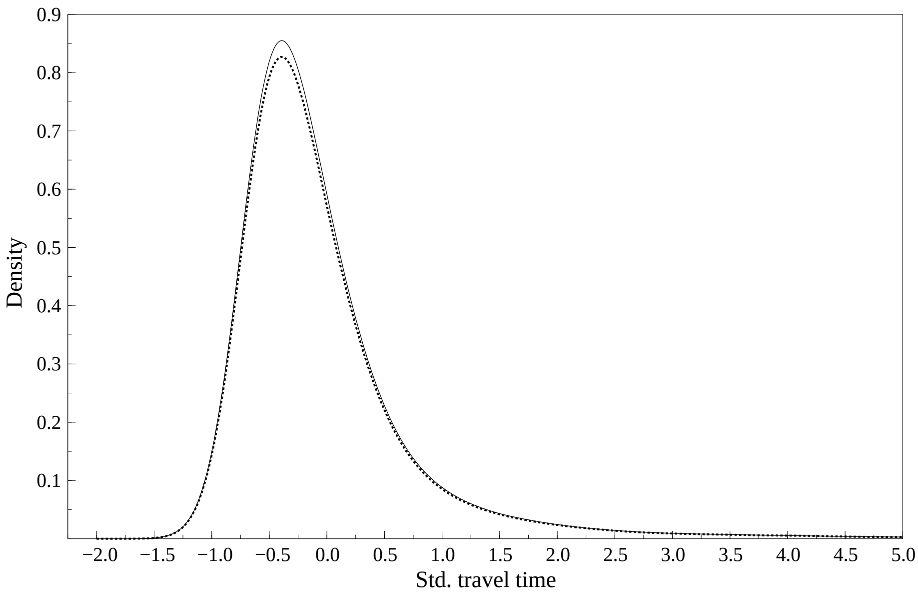
The contour plot for the standardised distribution of delays conditional on the time of day, presented in Figure 15, again shows a pattern of roughly horizontal lines. This is again roughly consistent with the hypothesis that standardised travel times are indeed independent of the time of day and we proceed under that assumption.

Figure 15: Contours of the CDF of standardised delay (vertical axis) conditional on time of day (horizontal axis). RDS data, Copenhagen-Ringsted.



We may hence estimate the density of standardised delays. The shape is similar to the distribution found above for car on Frederikssundsvej (Figure 11) and it may be conjectured that this also is well approximated by a stable distribution.

Figure 16: Estimated (unconditional) density of standardised delay, with lower confidence band. RDS data, Copenhagen-Ringsted.



5.3.5 Computation and comparison of H

Recall that the value of variability is proportional to the function $H(\Phi, \eta/\lambda)$, defined in eq. (10), where Φ is the standardised travel time distribution, and the ratio η/λ of scheduling parameters is the optimal probability of being late. This means that the value of travel time variability depends on the shape of the travel time distribution as summarised by H. In principle, it would therefore be necessary to assess the travel time distribution and compute H whenever the value of travel time variability was to be calculated. This could be quite impractical.

On the other hand, if H is more or less constant across the cases considered here, then it is reasonable as a first approximation and also extremely convenient to assume that a constant H represents the standardised travel time distribution on Danish roads.

To check this, we compute values of $H(\Phi, \eta/\lambda)$ for a range[24] of values of η/λ for each of the estimated distributions of standardised travel time, These values are listed in the tables below (for the motorway data, we only report summary statistics).

Table 4: Table of H by direction for Frederikssundsvej data

η/λ	0.50	0.33	0.25	0.20	0.15	0.10	0.05
Inwards	0.33	0.35	0.33	0.31	0.27	0.22	0.15
Outwards	0.35	0.37	0.35	0.32	0.28	0.23	0.14

Table 4 reports the estimates for the two directions on Frederikssundsvej, while Table 5 summarises the 30 segments in the motorway data. Comparing across datasets for a fixed value of η/λ, the values of H are generally very similar. Given the uncertainty involved in estimating the scheduling parameters, the differences here must be considered small. Based on this evidence it therefore seems quite reasonable to assume one fixed value of H to be applied uniformly across Danish roads.[25]

[24] Since there are so far no established Danish values of η and λ.

[25] We hope to qualify this conclusion in future work.

Table 5: Table of H for motorway data – mean and standard deviation of H over all segments

η/λ	0.50	0.33	0.25	0.20	0.15	0.10	0.05
Mean	0.31	0.31	0.29	0.27	0.24	0.20	0.14
std.dev	0.04	0.03	0.02	0.02	0.02	0.02	0.01

Table 6 similarly presents the estimates of H for the two directions in the rail data. It is clear that they are very similar, regardless of the value of η/λ.

Table 6: Table of H by direction for rail data

η/λ	0.50	0.33	0.25	0.20	0.15	0.10	0.05
Copenhagen-Ringsted	0.26	0.28	0.27	0.26	0.24	0.21	0.16
Ringsted-Copenhagen	0.24	0.27	0.27	0.26	0.24	0.22	0.16

5.3.6 Conclusion to analysis

In summary, we have computed the standardised travel time distribution for three large Danish datasets, two for road and one for rail. We have found that the standardised travel time distribution in all cases is roughly independent of the time of day as required by the theory. Hence we have sufficient justification to apply the theory. This is a very convenient result.

Moreover, we have found that the value of reliability is fairly constant across the many cases considered. We therefore feel justified in concluding that it is reasonable, given the available evidence, to apply a uniform value of reliability in the short term.

6 Short term Danish recommendations

In this section we first combine the new theoretical results with estimates of the scheduling parameters found in the literature review and characteristics of the travel time distribution found for Danish data for road and rail respectively. The result is a definition of the concept of travel time variability and a value that may be used in the short term. Then we provide some examples to illustrate the application of the proposed measures and the effects of including travel time variability in evaluations of road and rail.

6.1 Recommendations

In general we recommend that the new approach described in section 5 is used on short term in Denmark. The approach is based on optimal scheduling considerations; it is theoretically coherent and simple to apply.

From the expression for expected utility in equation (9) in section 5.1, we find that the expected time costs of a traveller may be summarised as

- $VTT * \mu + VTTV * \sigma$,

where VTT and VTTV are the value of travel time and the value of travel time variability and μ and σ are the mean and standard deviation of travel time.

Consequently, we recommend a simple concept of travel time variability, namely the standard deviation of travel time. This is probably the simplest possible measure.

It is convenient to rewrite the expected time costs slightly to become

- $VTT * \mu + VTT * \frac{VTTV}{VTT} * \sigma$,

since the value of travel time is given by the current cost-benefit guidelines. Expressing the value of travel time variability as relative to the value of travel time ensures against inconsistency when the value of travel time is updated.

VTT and μ are usually known, so in order to apply these new recommendations values for VTTV/VTT and σ are needed.

6.1.1 Variability ratio

The ratio VTTV/VTT, which we may call the variability ratio, expresses the value of travel time variability relative to the value of travel time. From the theoretical analysis in section 5 we note that

- $$\frac{VTTV}{VTT} = \frac{\lambda}{\eta + \omega} H\left(\Phi, \frac{\eta}{\lambda}\right).$$

Then the following elements are required in order to include travel time variability in economic appraisal:

- The ratio of lateness cost to the value of time: $\lambda/(\eta + \omega)$
- The optimal share of trips arriving late: η/λ
- The average standardised lateness $H(\Phi, \eta/\lambda)$ from the travel time distribution

All that is then left is to measure the mean and standard deviation of travel time. So far traffic models have supplied the mean travel time, but for this approach to be applicable the models should supply the standard deviation as well. However, this should be feasible, and at the same time it seems to be one of the easiest statistics to produce regarding variability.

The ratio of lateness cost to the value of travel time and the optimal share of trips arriving late

Until specific Danish values can be established, it is recommended to extract figures for the ratio of lateness cost to the value of travel time $\lambda/(\eta + \omega)$ and the optimal share of trips arriving late η/λ from the literature review.

Table 3 on page 36 presents the estimated parameters from four different studies. In general these parameters are not directly comparable, but ratios between them are. From these four studies, we compute the ratio of lateness to the value of travel time $\lambda/(\eta + \omega)$ as $(\beta + \gamma)/\alpha$, and the optimal probability of being late as $\beta/(\beta + \gamma)$, c.f. section 5.1. The results are given in Table 7.

Table 7: Transformations of scheduling parameters

	Lateness relative to travel time	Optimal share of trips arriving late
Bates et al. (2001)		0.33
Hollander (2005,2006)	3.75	0.27
Noland et al. (1998)	2.78	0.42
Small (1982)	3.01	0.20

Note: The table is based on the estimates in Table 3. The third and fourth studies included a fixed penalty for being late, which might tend to give low estimates of late arrival compared to the formulation suggested for a Danish context.

Based on Table 7 we find that lateness is valued around 3 times the value of travel time. We recommend this value for use in the short term in Denmark, and note that it can be seen as a conservative estimate. The interpretation of this value is that an average traveller is indifferent between travelling 3 minutes longer and arriving one minute later after the preferred arrival time.

We similarly find a value of 0.33 of the ratio η/λ. The interpretation of this ratio is that the average traveller, acting optimally, will be late on one out of every three trips.

The average standardised lateness

The other component in the VTTV is the term $H(\Phi,\eta/\lambda)$, which is interpreted as average time late in the standardised travel time distribution. This measure is large if the travel time distribution has a long right tail such that large delays occur. The term is determined by the shape of the standardised travel time distribution Φ and the ratio η/λ, which was set to 0.33 above.

Section 5 concluded that it was reasonable to assume that the standardised distribution of travel times is independent of the time of day. Consequently, H can be assumed fixed for the road sections examined as well as for the rail sections. If this result can be generalised to all road and rail sections (eventually for a number of categories of road and rail sections) it is sufficient to supply a general value for these sections. Table 4 through Table 6 show values of H for different values of η/λ. Based on these results preliminary recommended values of H are given in Table 8.

Table 8: Recommended values for H

Section type	H
Road	0.33
Rail	0.28

For rail, the term H is a little smaller than for road. This reflects that the tail in the standardised travel time for rail is shorter than for road: long delays are less frequent.

Recommended variability ratio

Thus we find that the variability ratio is 3*0.33=1 for road and 3*0.28=0.84 for rail. In other words, one minute of standard deviation on roads is worth the same as one minute of travel time on roads, whereas one minute of standard deviation on rail is worth 0.84 minutes of rail travel time.

These values can not be interpreted to say that travel time variability is more or less important than travel time: that depends on the mean and standard deviation of travel time.

6.1.2 Standard deviation

The standard deviation of travel time σ is supposed to come from traffic models along with the mean. However, this is not yet standard practice (see further recommendations in section 7).

Sweden and the Netherlands have used an approximation of the standard deviation until observations has been collected. A similar approach based on Danish data has been attempted in the appendix (section 9.4):

- $\sigma = \kappa\left(\mu - t\right) + K$,

where κ and K are constants and *t* is free flow or scheduled travel time.

For the car segments, we are unable to find a reliable estimate of this relationship, as the variation across segments is rather large. We therefore do not recommend making such an approximation based on the current data.

For rail, the estimated linear relationship between standard deviation and mean delay shows more resemblance between the two data segments. We therefore present an approximation to the generalised cost:

- $VTT\left(T_{sch}+1.8\cdot\left(\mu-T_{sch}\right)\right)$

However, we emphasize that such an approximation must be applied and interpreted with caution, as the two rail data sets do not provide sufficient information to estimate a general relation between standard deviation and mean delay.

6.2 Examples

This section provides two examples to illustrate the practical application of the suggested approach, one for road and one for rail. The examples compare two different times of day. In an application there would be a model predicting the change in mean and standard deviation of travel time following some policy measure.

The example for road is based on the data from Frederikssundsvej used in this report. The values of mean and standard deviation are shown in Figure 8, while a value of time of 80 DKK per hour (2008 prices) is used.

Table 9: Mean and standard deviation of travel time. Frederikssundsvej, inward direction.

	Mean	Standard deviation
8 AM	21.0 min	4.0 min
10 AM	12.9 min	3.2 min

Note: Values for all times of day are presented in Figure 8.

With the values presented above, 1 minute of car travel time is worth the same as 1 minute of standard deviation. The generalised time cost is calculated in Table 10.

Table 10: Generalised time costs based on new approach, Frederikssundsvej, inward direction.

	Costs of mean	Costs of standard deviation	Total effect
8 AM	21.0*80/60= 28.0 DKK	4.0*80/60= 5.3 DKK	33.3 DKK
10 AM	12.9*80/60= 17.2 DKK	3.2*80/60= 4.3 DKK	21.5 DKK

In this example, the inclusion of travel time variability adds 16-20 percent to generalised time costs, which must be considered significant.

For rail the example is based on Copenhagen-Ringsted. The values of mean and standard deviation are shown in Figure 13. It should be noted that Figure 13 shows the delay, so in Table 11 a scheduled travel time of 36 minutes is added to obtain the mean travel time[26].

Table 11: Mean and standard deviation of travel time, Copenhagen-Ringsted.

	Mean	Standard deviation
8 AM	36+2.8=38.8 min	5.2 min
10 AM	36+3.5=39.5 min	5.9 min

Note: Values for all times of day are presented in Figure 13.

With the values presented above 6 minutes of travel time is worth the same as 7 minutes of standard deviation. In Table 12 the generalised time cost is calculated.

Table 12: Generalised time costs based on new approach, Copenhagen-Ringsted.

	Costs of mean	Costs of standard deviation	Total effect
8 AM	38.8*80/60=51.8 DKK	5.2*0.84*80/60=5.8 DKK	57.6 DKK
10 AM	39.5*80/60=52.6 DKK	5.9*0.84*80/60=6.6 DKK	59.3 DKK

In this example, the inclusion of travel time variability adds 11-12 percent to generalised time costs.

When assessing the likely significance of travel time variability in economic appraisal, it should be kept in mind that time costs savings generally account for a very large share, often 60-80 percent, of the benefits of transport projects. Even fairly small changes to generalised time costs may have large consequences for the result of an appraisal.

[26] The scheduled travel time varies with time of day, but in this example we assume that it is 36 minutes both at 8 AM and 10 AM.

7 Recommendations for the longer term

Also for the long term we recommend using the new approach presented in section 5, as it combines the advantages of both the mean-variance approach and the scheduling approach and is easy to apply.

There are however a number of issues that it would be beneficial to address. In this section we sketch these issues and outline a sequence of projects that could potentially be realised to arrive at an improved basis for understanding and evaluating travel time variability.

7.1 Issues

The reasons for recommending the presented approach are the same as for the short term recommendations. However, in order to apply and develop the approach in the longer term, there are a number of issues that could be addressed.

7.1.1 The distribution of travel times

- It is important to test to what extent the assumption of constant standardised travel time distributions is valid. Also, our empirical evidence, indicating that a fixed value of H is appropriate, is still limited. It may turn out that our approach is too simple. Against this possibility speaks the fact that we are able to accept quite a lot of simplification in exchange for a clear-cut and simple applied approach.

- Another issue that needs to be clarified is the aggregation from link to trip level. The value of variability applies to a trip from origin to destination, while measures of travel time variability from traffic models may relate to the level of links.

- The means and standard deviations for road and rail sections should be obtained from traffic models. So far the models supply the mean through the formulation of speed-flow relations, but the models do not include standard deviations at present. For this purpose, it would be useful to develop general relationships between standard deviation and e.g. traffic density or flow. It is also crucial to understand and be able to model trip scheduling behaviour as this determines the shape of peaks, where travel time and variability is high.

7.1.2 Economic issues

- Our model for scheduled services is simple and the connection to the values for different parts of a trip (headway, waiting, etc.) has not been clarified in general. There is a need to develop a more general theoretical framework that captures all aspects of a scheduled service trip, in order to see how the value of reliability fits together with the value of in-vehicle time, waiting time, access/egress time, and interchanges.

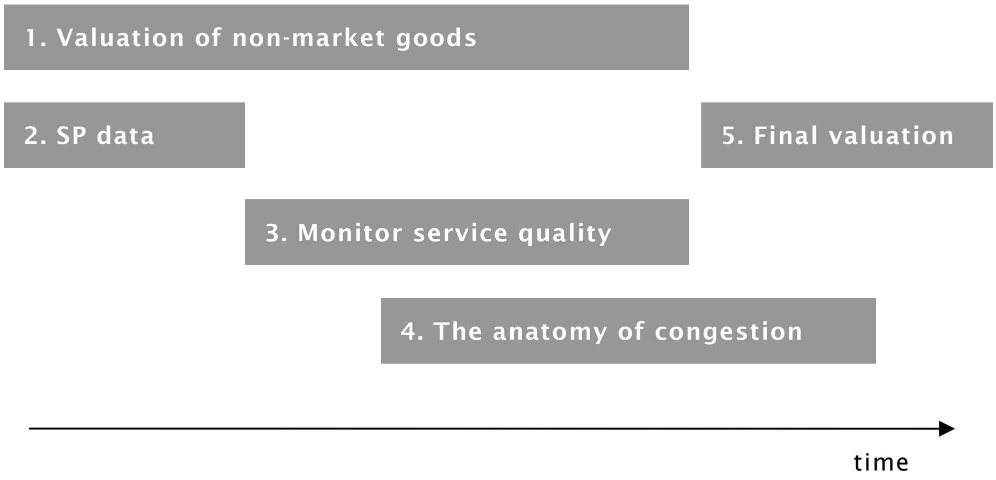
- The scheduling model assumes that all that matters in the end is outcomes in terms of actual travel time and how much one is early or late. Uncertainty in itself has no effect on utility. Whether this is a good description of travellers' preferences is an open question, which might be tested empirically.

It is possible and perhaps even likely that investigations of the latter issue, using hypothetical choices and the like, will show that uncertainty in itself has an influence. It does not necessarily follow from this, that preference for risk as a separate entity should be applied in evaluations. For example, in value of time, following Fosgerau and De Borger (2008), we distinguish between hedonic and choice preferences. Choice preferences are those revealed in choices. They are not in general the same as hedonic preferences, which are neoclassical and relevant for cost-benefit analysis. We use observations of choices to make inferences about hedonic preferences. In the same way, in the case of reliability, it could turn out that it is relevant to distinguish between hedonic and choice preferences. The hedonic preference would then be the scheduling model combined with expected utility maximisation, while choice preferences would exhibit preferences for risk as a separate entity, together with loss aversion. (Note here the references to Polak and coauthors given in section 4.1.6).

7.2 Outline of a research program

Many of the issues listed above are so far very much on the research frontier. We therefore feel it is appropriate at this stage to sketch not just a valuation study, but a series of projects that together can bring us forward on the measurement, modelling and valuation of congestion and travel time variability. We have tried to define projects that are suitable for different sources of funding. In addition to the Ministry of Transport, we are considering the Danish Social Science Research Council and the coming Transport Research Program.

Figure 17: Suggested outline of research program



Consequently, we suggest a number of activities over a three to four year period in order to clarify some of the above research issues as well as testing the formulation of SP exercises as discussed in section 4.2. An overview of the activities is given in Figure 17. The principal contents of each activity are described below.

7.2.1 Valuation of non-market goods, discrete responses and reference-dependent preferences

This project has already been granted by the Danish Social Science Research Council with a budget of 2.46 million DKK. It runs over the period 2008-2010 and comprises a PhD. project to be carried out by Katrine Hjorth as well as time for Mogens Fosgerau. The objective of the project is to work on the valuation of non-market goods, especially under uncertainty, in the presence of anomalies such as reference-dependence, which seems to be prominent in stated preference data. The project explicitly aims to work on the value of travel time variability.

7.2.2 Stated preference data collection

This project designs and collects a stated choice dataset concerning the value of travel time variability. As is clear from the literature survey as well as section 7.1, the state of the art regarding valuation of travel time variability is not yet established in the same way as the state of art for valuing travel time was when the DATIV project was started. As a consequence, the data collection will not aim at covering all modes and regions of Denmark but should be used to gather a data set that can be used to provide a first round of scheduling parameters for a Danish value of travel time variability as well as to provide a basis for further research into the above mentioned issues.

The study could cover both road and rail. Given the recommendations in this report, the design of choice experiments focuses first on the determination of scheduling costs, without explicit reference to uncertainty. The second objective would be to introduce uncertainty in a very controlled way in order to investigate the effect of uncertainty as a separate entity.

Thus, a first choice experiment could consider choices between safe alternatives defined by cost, departure time, travel time and arrival time relative to a preferred arrival time. A second choice experiment could consider choices between, e.g., a safe alternative and an alternative with two different potential outcomes with a probability assigned to each. The results from the two exercises could then be compared.

The results from such a study in the form of Danish estimates of average scheduling costs would be immediately useful as they would provide a Danish value of travel time variability.

The data would also be very useful by providing a basis for further research. The research project above would be well placed to utilise the resulting dataset, particularly if the data collection study could be carried out in 2008, since that would enable the PhD project to make use of the data. In this way, the already financed research project would give extra value for the money invested in the data collection.

We envisage this project to be financed by the Ministry of Transport with a budget of around 1 million DKK.

7.2.3 Monitoring the quality of service in the road network

There is great potential in the TRIM system to provide information on the mean and variability of travel times in the Danish road network. Unfortunately, most data are presently discarded after a short period of time. If retained, the data could contribute in a number of ways, e.g.:

- The mean and variability can be two of a number of measures or indicators describing the quality of service provided by the road network. With defined measures it is possible to answer questions such as how the service quality develops over time and how it is affected by schemes aimed at improving it.

- The mean and variability for a large number of roads and likely over longer periods of time can provide the data needed to estimate the interactions described in the research project of section 7.2.4, especially a relation between flow (or density) and variability. Along with the speed-flow relation this is essential for modelling effects of limited capacity in traffic models.

The idea of this project is to save, organise and refine the data collected by the TRIM system and similar systems. The objective would be to define and compute measures that are relevant from a policy perspective. It would be directed towards the needs of the Ministry of Transport and Vejdirektoratet and could be financed by these.

7.2.4 The anatomy of congestion

We are planning an application to the new Danish Transport Research Program for a project which aims to further our understanding of congestion and travel time variability. The general idea is to understand the interaction between travel demand, traffic flow, congestion, travel time variability, and individual scheduling choices.

There are many unresolved issues in this area that could be made the subject of research, drawing on economics and transport engineering. There is a large potential in analysing the data collected by the TRIM and RDS systems.

The outcome of the project would be increased knowledge and capability to model the relation from travel demand to travel time delay and variability, both at the link and at the network level. The project could also consider characteristics of the travel time distributions in order to verify the assumptions made in this report. Ideally, we would become able to predict the mean and standard deviation of travel time, as well as the shape of the standardised travel time distribution, as a function of demand and network characteristics. This project would have a budget of perhaps 3 million DKK.

7.2.5 Final valuation project

At the end of this series of projects, it might be useful to consolidate what has been learned in a final valuation project, aiming to obtain values of travel time variability that are representative and comprehensive for all of Denmark.

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9 Appendix

9.1 Terminology

Table 13: List of Danish and English terms

English term	Danish term	Definition
Free flow time	Køretid uden anden trafik	Travel time with no other traffic, i.e. shortest possible travel time.
Systematic delay	Systematisk forsinkelse	Additional travel time that can be anticipated.
Unexplained delay	Uforklaret forsinkelse	Additional travel time that cannot be anticipated.
Capacity utilization index	Belægningsgrad	Measure of the utilization of the railway system, compared to its capacity
Severe incident	Stor hændelse	Banedanmark service term: An event that necessitates the use of an emergency timetable
Operations timetable	Tjenestekøreplan/driftskøreplan	
Passenger timetable	Publikumskøreplan	
Product reliability	Produktregularitet	Banedanmark service term: See Table 1.
Traffic reliability	Trafikpålidelighed	Banedanmark service term: See Table 1.
Train punctuality	Kanalregularitet	Banedanmark service term: See Table 1.
Share of realised bus hours	Grad af udført kørsel	Movia service term: See Table 2.
Quality flaw	Kvalitetsbrist	Movia service term: See Table 2.
Reliability	Rettidighed	Movia service term: See Table 2.
Regularity	Regularitet	Movia service term: See Table 2.

9.2 Tables

Table 14: Summary of VOR valuation studies

Study	Data	Approach	Value of reliability (VOR)	Reliability ratio *	Reliability multiplier *
Bates et al. (2001)	UK. Train passengers. SP data.	Scheduling model	Early delay: 402 DKK/hour Late delay: 816 DKK/hour (2001 prices)		
Batley et al. (2007)	UK. Train passengers. SP data.	Mix of scheduling and mean variance model: Utility depends on mean and std.dev. of travel time, and on the lateness at boarding and destination.		Business/commuter: 1.35-2.71 Leisure: 2.48-3.28	Boarding: 1.17-2.93. Destination: Business/commuter: 0.62-3.29 Leisure: 0.94-4.82
Study by Black and Towriss, published 1993. (Source: Noland and Polak, 2002)	London, UK. All modes. SP data.	Mean-variance model (Reliability = std. deviation)		Car, commuter: 0.7 All: 0.55	
Hollander (2005,2006)	York, UK. Bus users, commuting trips. SP data.	Scheduling model	Early delay: 34 DKK/hour Late delay: 95 DKK/hour (2004 prices)		Early delay: 1.0 Late delay: 2.8
RAND Europe and Stratec (2006a, 2006b)	Paris, France. Suburban trains. SP data.	Utility depends on travel time, frequency of short (5-15 min.) and long (15+ min.) delays, comfort etc. (Reliability = delay freq.)			Equivalence of 5 percentage points freq. reduction: Short delay, low freq.: 4-6 Short delay, high freq.: 2-3 Long delay, low freq.: 7-9 Long delay, high freq.: 5-7
Lam and Small (2001) **	California, US. Car drivers. RP data.	Mean-variance model (Reliability = diff. between the 90^{th} and 50^{th} quantiles)	Men: 80-100 DKK/hour Women: 181-228 DKK/hour (1998 prices)		

Study	Data	Approach	Value of reliability (VOR)	Reliability ratio *	Reliability multiplier *
Noland et al. (1998)	California, US. Car drivers. SP data.	Mean-variance model (Reliability = std. deviation) Scheduling model		1.27	 Early delay: 0.89-0.97 Late delay: 1.24-1.31
Rietveld et al. (2001)	Netherlands. All modes. SP data.	Utility linear in in-vehicle time, probability of 15 minutes delay, and ticket price. However, delay prob. only takes values 0% and 50%. (Reliability = mean delay.)	A 50% probability of 15 minutes delay is worth 16 DKK (≈ 65 DKK/hour). (1997 prices)		2.4
Small et al. (1999)	California, US. Mainly car drivers and passengers. SP data.	Mean-variance model (Reliability = std. deviation) Scheduling model	56-87 DKK/hour (1995 prices) 5 min. early delay: 9-11 DKK/hour 10 min. early delay: 26-27 DKK/hour 15 min. early delay: 43 DKK/hour Late delay: 78-121 DKK/hour (1995 prices)		
Small et al. (2005)	California, US. Car drivers. RP/SP data.	Mean-variance model (RP data: Reliability = diff. between the 80th and 50th quantiles. SP data: Reliability = Probability of being delayed at least 10 minutes.)	VOR distribution characterised by median and diff. between 75th and 25th quantiles: RP data: Median: 137-172 DKK/hour Diff.(75th, 25th) : 185-208 DKK/hour SP data: Median: 37-39 DKK/incident Diff.(75th, 25th) : 46-56 DKK/incident (1999 prices)		
Transek (2002)	Stockholm, Sweden. Car drivers, SP data	Mean-variance model (Reliability = std. deviation)		0.96 (very preliminary)	

* The reliability ratio and reliability multiplier measure the value of reliability in terms of the value of travel time. The reliability ratio is the marginal value of a minute's standard deviation divided by the marginal value of a minute's travel time. The reliability multiplier is the marginal value of an extra minute's early/late mean delay divided by the marginal value of a minute's travel time. In RAND Europe and Stratec (2006a,2006b) the numerator is the marginal value of a 5 percentage points reduction in delay frequency. In Rietveld et al. (2001), the numerator is the marginal value of a minute's mean delay.

** The listed VOR's are from models of route choice, route/mode choice, route/transponder choice, and route/mode/transponder choice. A model of route/time-of-day choice yields much lower values: 40 DKK/hour (men) and 47 DKK/hour (women), but Lam and Small (2001) regard the accuracy of these estimates as doubtful.

Table 15: Frederikssundsvej data

Segment	Description	Length (km)	Obs	Free flow time (min)
1	Inward	11.3	24,271	11
2	Outward	11.3	21,742	11

Table 16: Motorway data

Segment	Description	Length (km)	Obs	Free flow time (min)
1	Route E20 Exit 53 Odense V - Exit 55 Aarup	10.3	18,493	5.13
2	Route E20 Exit 55 Aarup - Exit 53 Odense V	10.3	60,372	5.13
3	Route E20 Exit 55 Aarup - Exit 56 Ejby	8.5	61,032	4.10
4	Route E20 Exit 56 Ejby - Exit 55 Aarup	8.5	60,215	4.10
5	Route E20 Exit 56 Ejby - Exit 57 Nørre Aaby	3.8	61,132	1.82
6	Route E20 Exit 57 Nørre Aaby - Exit 56 Ejby	3.8	59,791	1.82
7	Route E20 Exit 57 Nørre Aaby - Exit 58 Middelfart	9.3	61,250	4.63
8	Route E20 Exit 58 Middelfart - Exit 57 Nørre Aaby	9.3	61,326	4.63
9	Route E20 Exit 58 Middelfart - Exit 59 Fredericia S	4.3	60,734	2.37
10	Route E20 Exit 59 Fredericia S - Exit 58 Middelfart	4.3	46,540	2.37
11	Route E20 Exit 59 Fredericia S - Motorkryds Taulov	2.8	61,143	1.53
12	Route E20 Motorway junction Taulov - Exit 59 Fredericia S	2.8	46,568	1.53
13	Route E20 Motorway junction Fredericia - Motorway junction Kolding N	9.4	37,409	5.13
14	Route E20 Motorway junction Kolding N - Motorway junction Fredericia	9.4	59,159	5.13
15	Route E20ø Motorway junction Fredericia - Motorway junction Skærup	11.9	60,869	6.48
16	Route E20ø Motorway junction Skærup - Motorway junction Fredericia	11.9	59,903	6.48
17	Route E45 Exit 59 Hornstrup - Exit 60 Vejle N	3.1	61,324	1.65
18	Route E45 Exit 60 Vejle N - Exit 59 Hornstrup	3.1	60,833	1.65
19	Route E45 Exit 60 Vejle N - Exit 61 Vejle S	5.3	61,062	2.88
20	Route E45 Exit 61 Vejle S - Exit 60 Vejle N	5.3	60,009	2.88
21	Route E45 Exit 61 Vejle S - Motorway junction Skærup	7.5	60,960	4.10
22	Route E45 Motorway junction Skærup - Exit 61 Vejle S	7.5	61,122	4.10
23	Route E45 Motorway junction Skærup - Motorway junction Kolding N	8.4	59,331	4.57
24	Route E45 Motorway junction Kolding N - Motorway junction Skærup	8.4	57,613	4.57
25	Route E45 Motorway junction Kolding N - Exit 62 Kolding Ø	2.7	60,494	1.05
26	Route E45 Exit 62 Kolding Ø - Motorway junction Kolding N	2.7	60,675	1.05
27	Route E45 Exit 62 Kolding Ø - Exit 63 Bramdrupdam	1.8	61,160	1.00
28	Route E45 Exit 63 Bramdrupdam - Exit 62 Kolding Ø	1.8	61,258	1.00
29	Route E45 Exit 63 Bramdrupdam - Exit 64 Kolding V	1.9	60,909	1.05
30	Route E45 Exit 64 Kolding V - Exit 63 Bramdrupdam	1.9	58,189	1.05

Table 17: RDS data

Segment	Description	Length (km)	Obs
1	Copenhagen-Ringsted	63.9	123,706
2	Ringsted-Copenhagen	63.9	126,285

9.3 Relation between Noland and Small model and Fosgerau and Karlström model

Recall from section 4 that in the Noland and Small model (using the notation from Bates *et al*., 2001), the traveller's utility is

$$U(t_h) = \delta C + \alpha T + \beta SDE + \gamma SDL + \theta D_L, \tag{A1}$$

where t_h is the departure time, C and T are travel cost and travel time, SDE (SDL) is the amount of time the traveller arrives earlier (later) than PAT and D_L is a dummy for arriving later than PAT, i.e.

$$SDE = (PAT - T - t_h)^+ \tag{A2}$$

$$SDL = (T + t_h - PAT)^+ \tag{A3}$$

$$D_L = 1\{SDL > 0\} \tag{A4}$$

and x^+ denotes the positive part of x, which is x if $x \geq 0$, and zero otherwise.

In the Fosgerau and Karlström model, it is assumed that θ=0, that PAT=0, and that the traveller departs at time $-D$ (i.e. D time units before PAT). Hence SDE and SDL can be written as

$$SDE = (D - T)^+ = D - T + (T - D)^+ \tag{A5}$$

$$SDL = (T - D)^+ \tag{A6}$$

Inserting this and θ=0 into eq. (A1), we obtain

$$\begin{aligned} U(D,T) &= \delta C + \alpha T + \beta\left(D - T + (T - D)^+\right) + \gamma (T - D)^+ \\ &= \delta C + \beta D + (\alpha - \beta) T + (\beta + \gamma)(T - D)^+ \end{aligned} \tag{A7}$$

Defining $\eta = \beta$, $\omega = \alpha - \beta$, and $\lambda = \beta + \gamma$, and omitting the travel cost (which does not affect utility maximisation, as it does not depend on D), we obtain the Fosgerau and Karlström model in eq. (7).

9.4 Approximating standard deviation by mean delay

Our recommended approach relies on standard deviations of travel time being available from supply-side traffic models. Since such models are not yet in practical use in Denmark, we have tried to approximate the recommended approach by expressing VTTV by mean delay as is current practice for Vejdirektoratet and Trafikstyrelsen.

We attempt to approximate the generalised cost by a linear function of mean delay and free flow travel time (car) or scheduled travel time (rail). To do so, we need to impose the additional assumption that standard deviation is a linear function of mean delay. For the car segments, we are unable to find a reliable estimate of this relationship, as the variation across segments is rather large. We therefore do not recommend making such an approximation based on the current data.

For rail, the estimated linear relationship between standard deviation and mean delay shows more resemblance between the two data segments. We therefore present an approximation to the generalised cost below. However, we emphasize that such an approximation must be applied and interpreted with caution, as the two rail data sets do not provide sufficient information to estimate a general relation between standard deviation and mean delay.

9.4.1 Approximation for car

Following our recommended approach (cf. section 6.1), and using for short $H \equiv H(\Phi, \eta/\lambda)$, the generalised cost of the traveller is

$$VTT\left[\mu + \frac{\lambda}{\eta+\omega} H \cdot \sigma\right].$$

Now consider the change in generalised cost due to a change $\Delta\mu$ in mean travel time and a change $\Delta\sigma$ in the standard deviation of travel time. The change in generalised cost is:

$$VTT\left[\Delta\mu + \frac{\lambda}{\eta+\omega} H \cdot \Delta\sigma\right]. \qquad \text{(A.8)}$$

Since delay is travel time T minus free flow time T_{ff}, mean delay can be written as

$$E(\text{delay}) = E(T - T_{ff}) = \mu - T_{ff}, \qquad \text{(A.9)}$$

The scatter plot in Figure 9 suggests that the relation between σ and μ can be approximated by a linear function. Many of the corresponding scatter plots for the remaining car segments (not shown here) show the same pattern as Figure 9, although not all. However, it is not straightforward to identify a general pattern, so for simplicity we assume a linear relation between σ and μ, implying a linear relation between σ and mean delay:

$$\sigma = \kappa \left(\mu - T_{ff}\right) + K \, , \qquad \text{(A.10)}$$

where κ and K are constants.

Inserting this in eq. (A.8), the change in generalised cost becomes

$$\begin{aligned} & VTT \left[\Delta\mu + \frac{\lambda}{\eta + \omega} H \cdot \kappa \cdot \Delta\left(\mu - T_{ff}\right) \right] \\ = \quad & VTT \left[\Delta T_{ff} + \left(\frac{\lambda}{\eta + \omega} H \cdot \kappa + 1 \right) \cdot \Delta\left(\mu - T_{ff}\right) \right] \end{aligned} \qquad \text{(A.11)}$$

where ΔT_{ff} denotes the increase in free flow travel time, and $\Delta\left(\mu - T_{ff}\right)$ is the change in mean delay.

We estimate κ and K for each data segment by regressing σ on mean delay $(\mu - T_{ff})$.

Table 18 below reports the results of this regression. Unfortunately, the variation of estimates is considerable across segments, which casts doubt on the validity of the approximation.

However, for illustration purposes, we demonstrate the approximation using the average κ = 2.6. Recall from section 6.1 that we recommend using the value $\frac{\lambda}{\eta+\omega}H$ = 1. Inserting this and κ=2.6 in eq. (A.11), we obtain the following expression of the change in generalised cost:

$$VTT\left(\Delta T_{ff}+3.6\cdot\Delta\left(\mu-T_{ff}\right)\right), \tag{A.12}$$

We emphasize that this approximation is very poor, and do not recommend using it in practice. It may be possible to obtain a better estimate of the relationship between standard deviation and mean delay with other data.

Table 18: Results from regression of σ on mean delay (car).

Data set	Segment	κ	K	R^2 of regression
Frederikssundsvej	1	0.28	2.53	0.41
Frederikssundsvej	2	0.55	1.39	0.69
Motorway	1	2.69	-0.01	0.68
Motorway	2	0.55	0.37	0.25
Motorway	3	0.58	0.21	0.54
Motorway	4	0.43	0.24	0.47
Motorway	5	1.16	0.09	0.1
Motorway	6	0.29	0.12	0.24
Motorway	7	4.18	0.08	0.73
Motorway	8	1.71	0.25	0.51
Motorway	9	7.03	0.80	0.98
Motorway	10	5.51	0.61	0.87
Motorway	11	0.36	0.12	0.44
Motorway	12	1.93	0.33	0.43
Motorway	13	3.91	1.57	0.72
Motorway	14	0.31	0.31	0.11
Motorway	15	5.59	4.67	0.94
Motorway	16	0.19	0.45	0.50
Motorway	17	2.93	0.36	0.72
Motorway	18	0.73	0.13	0.33
Motorway	19	1.86	0.33	0.71
Motorway	20	1.33	0.35	0.87
Motorway	21	1.68	0.47	0.64
Motorway	22	2.95	1.12	0.63
Motorway	23	4.55	0.49	0.80
Motorway	24	6.12	1.01	0.96
Motorway	25	5.02	-1.84	0.77
Motorway	26	6.01	-2.15	0.74
Motorway	27	3.65	0.39	0.58
Motorway	28	3.92	0.26	0.60
Motorway	29	4.23	0.12	0.69
Motorway	30	2.08	0.18	0.46

9.4.2 Approximation for rail

Following our recommended approach (cf. section 6.1), and using for short $H \equiv H(\Phi, \eta/\lambda)$, the generalised cost of the traveller is

$$VTT\left[\mu + \frac{\lambda}{\eta+\omega} H \cdot \sigma\right].$$

The change in generalised cost due to a change $\Delta\mu$ in mean travel time and a change $\Delta\sigma$ in the standard deviation of travel time, is:

$$VTT\left[\Delta\mu + \frac{\lambda}{\eta+\omega} H \cdot \Delta\sigma\right]. \quad \text{(A.13)}$$

For rail, delay is defined relative to the scheduled travel time T_{sch}, such that

$$E(\text{delay}) = E(T - T_{sch}) = \mu - T_{sch}, \quad \text{(A.14)}$$

The scatter plot in Figure 14 indicates an approximately linear relation between σ and mean delay for the inward direction – and the same is the case for the outward direction. We thus assume a linear relation between the two:

$$\sigma = \kappa \cdot E(\text{delay}) + K = \kappa\left(\mu - T_{sch}\right) + K. \quad \text{(A.15)}$$

Inserting this in eq. (A.13), the change in generalised cost becomes

$$VTT\left[\Delta T_{sch} + \left(\frac{\lambda}{\eta+\omega} H \cdot \kappa + 1\right) \cdot \Delta\left(\mu - T_{sch}\right)\right] \quad \text{(A.16)}$$

where ΔT_{sch} denotes the increase in scheduled travel time, and $\Delta\left(\mu - T_{sch}\right)$ is the change in mean delay.

We estimate κ and K for both directions by regressing σ on mean delay. The results are shown in Table 19 below.

Table 19: Results from regression of σ on mean delay (rail).

Data set	Segment	κ	K	R^2 of regression
RDS	1	1.03	2.46	0.75
RDS	2	1.07	4.27	0.52

We recommend in section 6.1 to use the value $\frac{\lambda}{\eta+\omega}H$ = 0.84. Fixing κ to 1.0 thus yields a change in generalised cost of

$$VTT\left(\Delta T_{sch} + 1.8\cdot\Delta\left(\mu - T_{sch}\right)\right). \qquad \text{(A.17)}$$

The validity of using the generalised cost in eq. (A.17) instead of the one given in section 6.1 is indicated by the R^2 values in the table – for these two data sets we obtain an acceptable goodness-of-fit. We are, however, not able to ascertain how good the relationship is for other O-D relations than those we have analysed here.