ORIGINAL PAPER

Value of travel time by road type

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Abstract

Travel time is less costly if it is comfortable or can be used productively. One could hence argue that the value of travel time (VTT) of car travellers in economic appraisal should be differentiated by road type, reflecting differences in road quality. We explain the theoretical foundation for such a differentiation, review the relevant literature and show the results of an empirical case study based on actual route choice of highway drivers in Norway. We find little existing literature discussing the link between road type and VTT, but closely related findings suggest that that the impact on VTT could be substantial. Our empirical case study also suggests that the VTT is lower on higher quality road types. Applying this to economic appraisal would imply higher user benefits of road projects that improve road quality.

Keywords: Value of travel time, Cost–benefit analysis, Road type, Road quality, Driving comfort, Revealed preference, Stated preference

1 Introduction

The economic benefits of shorter travel time typically account for a large share of the benefit side in cost–benefit analyses (CBAs) of transport investments. A considerable amount of research has therefore been devoted to obtaining accurate estimates of the value of travel time (VTT), both its overall level [21] and values for various sub-segments, for instance transport mode, trip purpose and contextual factors.

A key insight from microeconomic theory is that travel time is less costly if it is comfortable or can be spent productively [6]. In private car travel, this may depend both on the infrastructure, traffic conditions and characteristics of the car itself. While a number of studies consider the relationship between congestion and VTT [40], less attention has been given to the role of infrastructure quality. This is striking, given that obtaining a certain road standard or quality often seems to be a key motivation for public road investments. While part of the economic value of high road standard is related to road safety, we hypothesise an additional positive effect of road standard on the driving comfort level, resulting in a lower VTT.

In this paper, we first explain the theoretical foundations of VTT and how road type may be accounted for within this framework. We also discuss the distinction between driving comfort and traffic safety. We then give a brief review of studies that are relevant for assessing the relationship between VTT and road type and quality. Although there are no existing studies that present values of travel time differentiated by road type, there exists some relevant evidence that can be used to derive such a relationship. Some of these studies suggest that VTT varies substantially by road type, which would have strong implications for CBA if applied.

We also conduct our own empirical investigation based on aggregate data from three road projects in Norway, where travellers can choose between the old and the new road, and where the new road is subject to a road toll. The results from this case study indicate that VTT varies less by road type than suggested by the international literature, but the differences are still economically significant.

Based on the theoretical foundation and the empirical findings, we show how a differentiation of VTT by road type can be implemented in practice, classifying all roads as either one out of five main types. Such a differentiation could have considerable impact on CBA results, increasing the user benefits of road projects that raise the

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road standard. However, it would also imply a moderate decrease in VTT over time (other things equal) as the overall quality of the road network improves.

Our study makes the following contributions: First, it provides the first systematic review of the existing evidence on the relationship between road type/quality and VTT. Second, it contributes to the broader literature on VTT and contextual factors like transport mode [8], road congestion [40], crowding in public transport [42], and access and waiting time[36, 37].[1] A closely related topic is the role of infrastructure in cycling route choice [9, 19].

Third, our empirical investigation contributes to the growing literature on the use of revealed preference (RP) data for estimating VTT and related parameters, as opposed to stated preference (SP) data. Wardman et al. [39] find evidence that the VTT is higher in studies based on RP data. This is in line with the RP studies by Wolff [43], who estimates the VTT based on US data on gasoline prices and speeding behaviour,[2] and Goldszmidt et al. [14], who exploit data on waiting times and prices of ridesharing. Following Small et al. [31], Fezzi et al. [7] and Tveter et al. [33], we exploit variation in road tolls to identify the VTT.
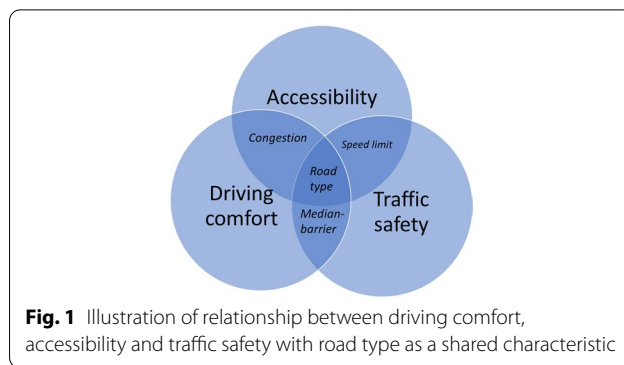
Our paper is organized as follows: In Sect. 2, we explain the theoretical foundation for differentiating VTT by road type. In Sect. 3, we review the existing empirical literature on this relationship and related topics. In Sect. 4, we show the results of our own empirical case study. In Sect. 5, we summarize the findings and discuss how they can be applied in practical CBA. Section 6 concludes.

2 Theoretical foundations

In transport economics, the value of travel time (VTT) refers to the monetary value associated with travel time changes. Its typically positive value suggests a willingness to pay for travel time savings and a willingness to accept higher costs to avoid travel time increases.

Microeconomic time allocation models, going back to Becker [2] and DeSerpa [6], suggest that the VTT for a given activity is the sum of the opportunity costs (i.e. the marginal value of what could be gained from alternative activities) and the marginal value of time spent in that activity (in our case driving).

Conceptionally, factors influencing the VTT can therefore be grouped into factors that affect opportunity costs (like income) and factors that affect the direct value of spending time in a certain activity. In our case of driving,

Fig. 1 Illustration of relationship between driving comfort, accessibility and traffic safety with road type as a shared characteristic

factors falling into the latter group include variables that improve driving comfort and facilitate a more productive and enjoyable car trip. To the extent that different road types contribute differently to driving comfort, we can expect the VTT to vary between different types of roads.

In our application, driving comfort should be defined widely and includes (at least).

A. Increased productivity (more useful use of travel time)
B. Increased driving pleasure (positive driving experience)
C. Reduced perceived insecurity (negative driving experience)

Road types do not only affect driving comfort but also accessibility (driving speed) and traffic safety. This is illustrated in the simplified Venn diagram below (Fig. 1).

Figure 1 includes some variables at the intersection between driving comfort, accessibility and traffic safety. For instance, congestion has a clear effect on accessibility and – as pointed out below – on driving comfort.[3] Typical road safety measures, such as median barriers, increase traffic safety and reduce the perceived insecurity of the driver and thus also have an effect on driving comfort. While speed limits may indirectly contribute to driving comfort, their main effects are on accessibility and traffic safety.

Differences in VTT by road type that reflect difference in driving comfort should not include accessibility gains from reduced congestion in absolute terms (minutes travel time saved). This is because the VTTs is a marginal measure that applies to the next full minute of (reduced) travel time. That a new motorway reduces travel time does therefore not point to how the VTT of the new motorway is compared to the old road. However, to the

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[1] Shires and de Jong [30] and Wardman et al. [39] provide a review of European studies on the value of travel time across all travel modes.

[2] However, the results of Wolff [43] also suggest that the VTT in other RP studies is biased upwards.

[3] On the other hand, the effect of congestion on traffic safety is somewhat ambiguous [29, 34]

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extent that different road types lead to different levels of congestion and to the extent that less congestion generates a separate utility gain in the form of more comfortable/less stressful car trips, congestion effects may enter the valuation of road type. For practical applications, one should in this case not apply additional congestion multipliers on the VTT, as this may lead to double counting in demand and/or cost–benefit analysis.

A similar argument applies to traffic safety measures. To avoid double counting, one should ideally separate effects of different road types on traffic safety between traffic safety (i.e. objective accident risk) and perceived traffic insecurity. While the former element is typically captured separately in the (cost–benefit) analysis,[4] i.e. independent of the value of travel time, the latter element would be included in road type multipliers. As pointed out in Sect. 5.2, it could be challenging to empirically quantify these two elements.

Mathematically, we can express VTT differences by road type in the form of multipliers on the average VTT, so called VTT multipliers. In our case, we refer to these as "road type multipliers". Multipliers associated with road types that have an above (below) average comfort level are assigned a value lower (higher) than one, as drivers have a lower (higher) willingness-to-pay to reduce travel time on more (less) comfortable roads.

Departing from microeconomic theory, time allocation models postulate that the effect of driving comfort on utility is time-dependent. Furthermore, the use of simple time multipliers implies that the effect is linear in time, i.e. that the difference in utility from driving on a more comfortable road vs. a less comfortable road increases linearly with travel time. If this is true or not is fundamentally an empirical question. It could be that the more comfortable road also has some characteristics that makes it more attractive, regardless of travel time. For instance, it could be easier to access due to design or traffic signs. In our empirical case study in Sect. 4, we therefore assume that the route choice of car travellers can partly be explained by a constant term capturing the 'signage effect' and partly by a comfort effect that is linear in travel time, i.e. the road type multiplier.

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[4] While this may be a reasonable practical approach, one may also argue that traffic safety should be captured by the VTT (and that only truly external effects should be treated as separate elements in CBA). This requires that travellers take personal accident risk fully into account and that the risk is proportional to time spent in traffic. This relates to the discussion about constant and time-dependent effects at the end of this section.

Table 1 Overall benefits of a four-lane road (cent/km per vehicle), rural strategic highways (relative to a winding two-lane road), based on Hensher and Sullivan [18]

Curviness	Road type		
	2 lanes	**4 lanes, without median**	**4 lanes, with median**
Almost straight, slight and moderate	3.0	7.6	14.3
Winding	0.0	1.7	8.5

3 Existing literature

In this section, we present the most relevant studies for VTT by road type and quality. Since the literature on this exact topic is quite limited, we also include related literature concerning valuation of other factors affecting the quality of travel.

3.1 Number of lanes and curviness

Hensher and Sullivan [18] estimate the willingness to pay (WTP) for road curviness and road type utilizing a stated choice experiment done in New Zealand. In the experiment, car and truck drivers undertaking regional and inter-urban trips evaluate alternative trip profiles and choose one of the trip profiles as the most preferred. It includes questions related to the value of driving in free-flow conditions and the value of being slowed down by other traffic, share of driving time with other vehicles tailgating them, the curviness of the road, the number of lanes, vehicle operating costs and road toll costs.

The authors do not find statistically significant differences between the parameters for almost straight, slight and moderate curviness within each alternative. Therefore, they treat them as having a single parameter relative to the worst scenario of curviness (a winding road).

Using the valuations from the experiment and a share of 14% truck drivers and 86% car drivers, Hensher and Sullivan derive WTP values for each combination of road type and curviness, illustrated in Table 1 (Table 6 in Hensher and Sullivan [18]).

Wardman et al. [41] study the introduction of the UKs first toll motorway, the M6 Toll road (M6T). M6T was designed to alleviate traffic congestion around Birmingham. Initially, the standard toll for cars was £2 and was increased up to £4 later. They model passenger choices utilizing the new tolled road with different toll regimes.

In addition to study the effect of the tolls in terms of time-toll trading, the authors examine other attributes that might influence the traveller's decision making. This includes estimating time valuations of infrastructure characteristics and road conditions including among

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others, lane width, number of lanes and road surface (see Sect. 3.2).

When it comes to lane width, they find that wide lanes (3.75 m) reduce VTT by 5% compared to standard lanes (3.35 m) and that narrow lanes (3.0 m) increase VTT by 9%. They also find that the number of lanes on motorways plays a role: 4-lane motorways would have a 7% lower VTT compared to standard 3-lane motorways, and 2-lane motorways have a 10% higher VTT.

3.2 Road surface

Road surface is another road quality factor that affects the VTT, as pointed out by Wardman et al. [41].

BCHF [1] did a valuation study using SP surveys, where they among other factors focus on the quality of the car ride related to the road surface and safety. They find that the quality of the car ride can imply significant variation in the VTT depending on which conditions the journey is undertaken in, and that these factors will have a significant effect on the VTT. Journeys done on rural roads with rough surface or rutted roads have VTT multipliers of 1,65 and 2,15 respectively. Urban roads with rough surface are estimated to have a slightly lower VTT of 1,59.

Wardman et al. [41] find that the VTT vary with different road surfaces, where concrete surface adds 12% to the VTT compared to a standard surface and high-level jointed sections of motorway increase the VTT by 9%.

Jamson et al. [22] study road users' perceptions about a range of road maintenance issues, with road surface being one of them. They illustrate the additional disutility of moving from perfect conditions to various imperfections with varying duration and frequency in minutes. A road surface that leads to various levels of shaking in the car is valued in the range of 7 to 30 min of travel, depending on the frequency and duration of the vibration or rumbling from the road surface or the noise from the road surface. Similarly, driving on a road surface which gives an unpleasant noise for the driver leads to a valuation of 2 to 18 min of travel.

NZ Transport Agency [25] has a handbook of monetised benefits and costs, which among other factors includes vehicle operating costs (VOC). In this VOC there is a component which indicates the car user's willingness to pay to avoid driving on uneven roads. If relevant, these costs are added to the fixed costs.

The NZ Transport Agency uses IRI (International Roughness Index) to measure the unevenness of the road. The higher the IRI is, the more uneven the road is. Using valuations from the manual, we have calculated relative VTTS multipliers illustrated in Table 2 under, where an

Table 2 Relative time values for roads with different road surface, estimated based on NZ Transport Agency [25]

IRI	Urban road	Rural road
0–2.5	1	1
7.5	1.44	1.71
11	1.83	1.94
15	2.05	2.20

even road (IRI = 0–2,5) is the baseline. The calculated multipliers span from 1,44 to 2,20.

3.3 Road characteristics and route choice

It is possible that the value of road characteristics could be captured implicitly in some estimates of the VTT based on RP studies using data on route choice. One example is the study by Fezzi et al. [7], who analyse survey data on route choice collected among visitors at recreation sites in Italy. Here, travellers can choose between routes with and without road tolls. Although the authors include some dummy variables that account for differences between the routes, they do not consider the possibility that the VTT could differ by road type. This could explain the relatively high estimated VTT, which is about 3/4 of the wage rate.

Tveter et al. [33] estimate the VTT based on a case study of a new motorway in Norway, where travellers can choose between the new road and an alternative route. They exploit that road tolls on the new road were introduced two months after the road was opened. Based on the change in traffic after the toll was introduced and assumptions regarding the distribution of the VTT, they estimate a VTT per traveller of 207 NOK (about 23 USD) for commuting trips and 120 NOK (about 13 USD) for leisure trips. These are relatively high values, which again could reflect that also other road characteristics explain route choice. We will get back to this in our empirical investigation in Sect. 4.

3.4 Congestion and travel time variability

As pointed out in Sect. 2, the infrastructure could also have an impact on traffic flow. If traffic flow is better, this will imply both shorter and more predictable travel times and a more pleasant driving experience. The former is typically referred to as the value of reliability or the value of travel time variability [5]. This can be captured in travel demand and cost benefit analysis through travellers' willingness to pay for a reduction in the uncertainty of travel time, for instance measured by

the standard deviation, variance, or certain percentiles of the travel time distribution.[5] In the meta-analysis by Wardman et al. [39], one unit reduction in the standard deviation of travel time is found to be equivalent to about a 0.7 unit reduction in travel time. In the recent Norwegian valuation study [10], this so-called 'reliability ratio' is about 0.4 and similar across modes.

The direct discomfort of congestion can be assumed to be proportional with travel time, which means that it can be expressed in terms of VTT multipliers. Wardman and Ibáñez [40] provide a review of the existing literature on such multipliers and find that most are in the range between 1,3 and 2,0, but some are higher. The definition of congestion varies, and some studies include different levels of congestion.

As most studies are based on SP, one might be worried that congestion multipliers would be biased upwards because respondents pay more attention to these in a survey setting than they do when making actual travel decisions. The study by Wardman and Ibáñez shows no evidence of a difference between SP and RP, but the number of RP studies is limited. An obvious challenge to RP studies of congestion is reverse causality: High demand causes high congestion.

In the recent Norwegian valuation study [10], the estimated VTT multipliers for commuting and leisure trips are 1,2–1,3 for moderate congestion and 2,3–2,4 for heavy congestion. Interestingly, the multipliers are somewhat lower for car passengers. The results are quite sensitive to whether those with little congestion on their reference trip are included in the sample. This suggests that the valuation is reference-dependent, i.e. that travellers assign a higher value to changes that involve a worsening in congestion compared to what they are used to. For CBA, the valuation of those who are not experienced with congestion might not be the most relevant.[6]

One might be concerned that since congestion and travel time variability is correlated, travellers might also take variability into account when choosing between alternatives with different levels of congestion in SP surveys. Flügel et al. [10] investigate this through a choice experiment where both congestion and variability are specified. Although the results from this choice experiment are less precise, they indicate that controlling for travel time variability does not reduce the congestion multipliers.

There are also some RP studies of the value of travel time and/or reliability that do not explicitly consider the effect of congestion on the VTT, but use variation in congestion to estimate other unit values. Notable examples are the studies by Brownstone and Small [4] and Small et al. [31] of road pricing experiments in California and the study by Bento et al. [3] of users of a high occupancy toll (HOT) lane in Los Angeles.

4 Empirical case studies

In this section, we present an analytical model to describe the relationship between the VTT and road type based on revealed preference data. In RP, we do not consider explicitly how trip attributes are presented to or perceived by the travellers, but rather how the importance of these attributes is reflected in their real-world choices.

The model is applicable to cases where there are two alternative roads for which market shares are observed over two periods. To identify – at least some of – the underlying behavioural parameters of the model, the monetary costs (e.g. road tolls) for at least one of the two roads need to differ across the two periods. A change in road tolls can be seen as constituting a natural experiment.

Deriving choice probabilities (market shares) from automatic traffic counts, we apply the model to three motorway projects in Norway. In all cases, drivers can choose between a newer motorway offering superior road quality (in terms of numbers of lanes and/or road quality) and a cheaper and slower alternative.

Our analytical model departs from an equation (Eq. 1) that describes the probability (P_t^{New}) to choose the new motorway, in two time periods t where $t = 1, 2$, as a function of three variables, the generalised costs on the new motorway (GK_t^{New}), the old motorway (GK_t^{Old}) and a scale parameter μ.

$$(1)\, P_t^{New} = \frac{e^{\mu GK_t^{New}}}{e^{\mu GK_t^{New}} + e^{\mu GK_t^{Old}}} \text{ for } t = 1,2$$

The scale parameter describes the sensitivity of which differences in generalised cost lead to changes in route choice. Its value is a priori unknown. It is expected to be negative, as higher costs typically reduce choice probabilities. The generalized cost functions are further specified as follows:

(2) $GK_t^{Old} = C * D^{Old} + B_{Old,t} + \omega_{Old} * T^{Old}$ for $t = 1,2$

(3) $GK_t^{New} = \beta + C * D^{New} + B_{New,t} + \omega_{New} * T^{New}$ for $t = 1,2$

with

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[5] If information about individual departure and arrival times is available, it can also be captured through so-called scheduling parameters that capture the cost of late arrival and of early departure or arrival.

[6] In their recommended multipliers, Flügel et al. [10] exclude those who have no congestion at all on their reference trip.

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Fig. 2 New motorway (in purple) and old motorway (in red) between Tvedestrand and Arendal (case 1) in the south of Norway

- C: cost of driving per kilometre (in NOK/km), assumed to be constant for all roads and periods
- D^{Old}, D^{Old}: distance of the old and new road respectively (in km)
- ω_{Old}, ω_{New}: value of time per car on the old and new road respectively (in NOK/hour)
- T^{Old}, T^{New}: travel time of the old and new road, respectively (in hours)
- β: a constant term (in NOK)
- $B_{Old,t}$, $B_{New,t}$: road toll in the given period (in NOK)

The parameter β represents unobserved factors that make drivers prefer the new motorway. Mathematically, its value is expected to be negative as it enters the cost function of the new motorway. It represents effects of road signage, recommendations in navigation apps or other factors that influence route choice independently of travel costs and comfort-adjusted travel times. We refer to this effect (and the absolute value of the β parameter) as the "signage effect". The numerical value of the signage effect represents the willingness-to-pay in Norwegian kroners (NOK) for being able to use the new motorway if the alternatives are otherwise equal in terms of cost and 'effective' travel time, taking into account differences in the VTT (ω_{Old}, ω_{New}).

To connect ω_{Old} and ω_{New} to the official practice of CBA in Norway, we impose that the weighted average of the two needs to match the 'official' level of the value of travel time per vehicle (VTT) that would apply to each of our three cases. We use shares of cars on the new motorway in period 2 for weighting:

$$P_2^{New} * \omega_{New} + \left(1 - P_2^{New}\right) * \omega_{Old} = \text{VTT}$$

Combining the Eqs. 1 with $t=1$ and $t=2$ with Eq. 4 and inserting Eqs. 2 and 3 into 1, we get a system of equations with three equations and four unknowns. To solve this system of equations, we fix β and solve the system with respect to the three unknowns: μ, ω_{New} and ω_{Old}. See Appendix for a detailed solution of the system of equations.

Hence, we can derive an expression for μ (Eq. 5) that only depends on observable variables ($P^{New}{}_1$, $P^{New}{}_2$ and B_2).

$$\mu = \frac{\ln(P_1^{New^{-1}} - 1) - \ln(P_2^{New^{-1}} - 1)}{B_{New,2} - B_{New,1} + B_{Old,1} - B_{Old,2}}$$

With this, we can calculate the value of time on the old motorway as a function of β (see Appendix for details), as shown in Eq. 6 below.

$$\omega_{Old} = \frac{\ln(P_1^{New^{-1}} - 1)\left(C * D^{Old} + B_{Old,2} - B_{New,2} - \beta - C * D^{New} - \frac{\text{VTT} * T^{New}}{P_2^{New}}\right) - \ln(P_2^{New^{-1}} - 1)\left((C * D^{Old} + B_{Old,1} - B_{New,1} - \beta - C * D^{New} - \frac{\text{VTT} * T^{New}}{P_2^{New}}\right)}{\left(\ln\left(P_2^{New^{-1}} - 1\right) - \ln\left(P_1^{New^{-1}} - 1\right)\right)\left(T^{Old} + \frac{\left(1 - P_2^{New}\right) T^{New}}{P_2^{New}}\right)}$$

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Table 3 Input data to our model

Variable	Explanation/measurement/unit	Case 1	Case 2	Case 2
P_1^{New}	Share of cars on the new road as measured by traffic counts in period 1, in %	85.5	70.7	96.2
P_2^{New}	Share of cars on the new road as measured by traffic counts in period 2, in %	71.3	82.1	91.3
B_1^{New}	Road toll on new road in period 1 incl. discounts, in NOK	0	34.4	19.2
B_2^{New}	Road toll on new road in period 2 incl. discounts, in NOK	35.2	17.6	19.2
B_1^{Old}	Road toll on old road in period 1 incl. discounts, in NOK	0	0	14.4
B_2^{Old}	Road toll on old road in period 2 incl. discounts, in NOK	0	0	0
C	Behavioural relevant cost of driving, NOK/km	1	1	1
D^{New}	Distance of the new road, in km	25,4	10	9.5
T^{New}	Travel time of the new road, in hours	0.245	0.12	0.12
D^{Old}	Distance of the old road, in km	26.5	11	12.2
T^{Old}	Travel time of the old road, in hours	0.375	0.2	0.22
VTT	Average value of travel time per car (all passengers), in NOK/hour	359	305	357

Similarly, based on Eqs. (5) and (4), we also get an expression of ω_{New} as a function of β (Appendix).

The three empirical cases are briefly described as follows[7]:

- **Case 1:** Between the cities of Tvedestrand and Arendal in the South of Norway, a new four-lane motorway was opened in July 2019 going largely parallel to an older two-lane highway (see illustration in Fig. 2 below). The Tvedestrand–Arendal corridor is part of the main motorway connection between the capital of Norway, Oslo, and the city of Kristiansand. Due to technical problems, the road toll on the new motorway was first introduced in September 2019.[8]
- **Case 2:** A new four-lane motorway between the town of Løten and the city of Elverum in Eastern Norway was opened July 2020 with road tolls being introduced shortly after. There were no tolls on the old road, which runs parallel to the new one. Tolls on the new road were reduced from February 2021 as a result of the national budget settlement.
- **Case 3:** As part of the long-distance corridor between Oslo and city of Trondheim, a tunnel ("Øyertunnelen") and a two-lane motorway with overtaking lanes were opened in December 2012. Tolls were collected on both the new road and the old road from the start. Tariffs for passenger cars were unchanged from 1 July 2016 to January 2021, when tolls on the

old road were removed as a result of the national budget settlement.

Next, we derive numerical results using the following input data (Table 3).[9] Note that the market shares only include passenger cars, not heavy vehicles.

The average value of travel time is derived based on the official Norwegian values of travel time, assuming a continuous relationship between VTT and travel distance [12]. We take into account differences in trip purpose, distance, and car occupancy between the three cases, based on transport model simulations. This will indirectly also pick up the effect of other local characteristics like for instance income level, although these are not directly controlled for. We do not expect large differences in the income level of travellers between the three areas considered.

In all three cases, we observe the behavioural change after the new road toll structure was introduced. In case 1, choice probabilities on the new motorways dropped from 85.5 to 71.3% after the road toll was introduced. In case 2, the market share of the new road increased from 70.7 to 82.1% after the road toll was significantly reduced. In case 3, the new road lost some market share (going down from 96.2 to 91.3%) after the road toll on the old road alternative was removed.

Given this observed behaviour, we can calculate the VTT on the old and the new motorway under different assumption of the signage effect. This is shown in Fig. 3.

Assuming no or a reasonably low signage effect, the VTTs on the new motorway are—as expected—lower

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[7] More details can be found in Halse et al. [16].

[8] This case was also studied by Tveter et al. [33], who derived absolute values of travel time from this case and compared it against estimates from stated preference studies. Tveter et al. did not consider effects of different road types on the VTT.

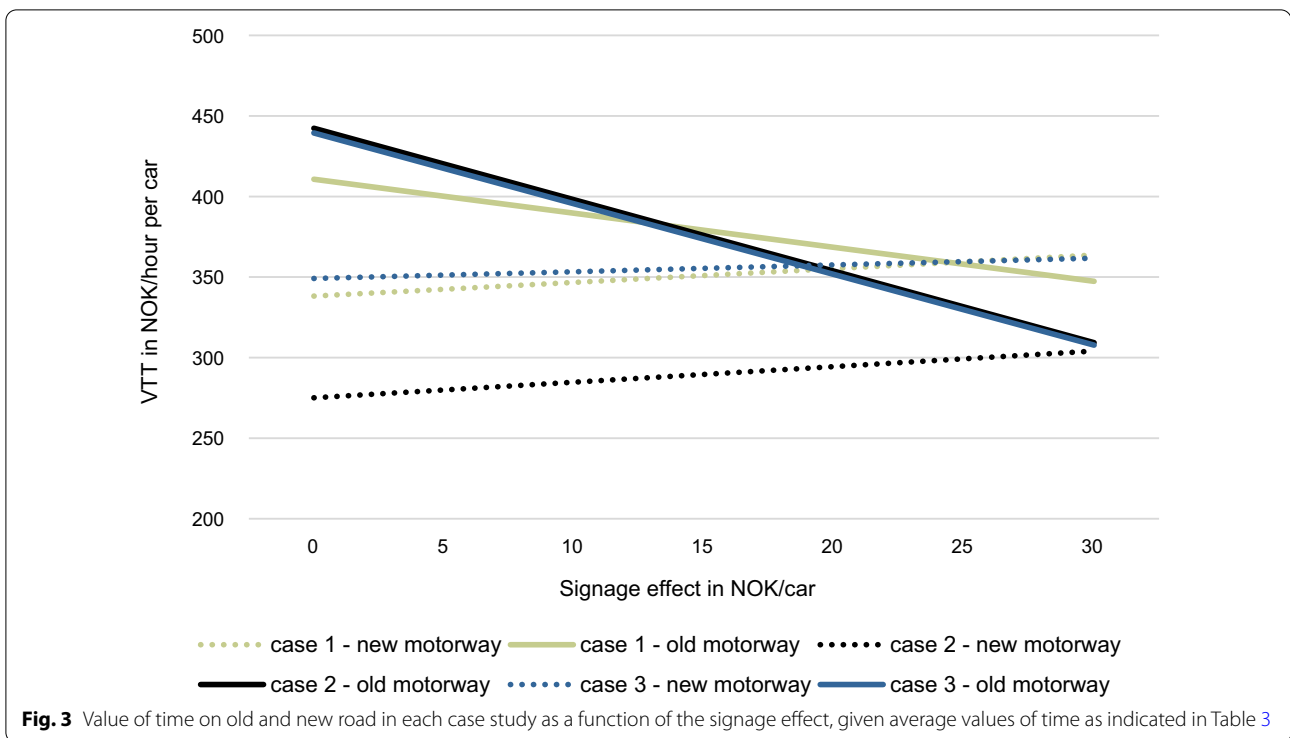[9] The assumptions behind the data inputs are documented in greater detail in Halse et al. [16].

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Fig. 3 Value of time on old and new road in each case study as a function of the signage effect, given average values of time as indicated in Table 3

Table 4 Relative value of time given different assumptions of the signage effect

VTT rate (old/new)	Assumed signage effect		
	None	Medium (10 NOK)	Large (20 NOK)
Case 1	1.21	1.12	1.04
Case 2	1.61	1.40	1.20
Case 3	1.26	1.12	0.98

than on the old road. This can be attributed to the higher perceived comfort and safety on the new motorway.

When the signage effect exceeds certain values, however, the VTTs on the new motorway would—according to our model and with our data—be higher than on the old motorway. In this case, the signage effect alone would be so high that it would explain the observed route choice and the indicated preference for the new motorway.

Table 4 gives some values for the relative VTT (old/new) for different assumptions of the signage effect. Values greater than 1 indicate higher VTT on the old motorway.

Besides the signage effect, our results are sensitive to other assumptions and input values, such as the average value of the VTT. If the applied VTT values in Table 3 are higher (lower) than the actual VTT in the three cases, we would underestimate (overestimate) the VTT difference by road type.[10]

5 Discussion and application
5.1 Summary of findings

The existing evidence on the relationship between road type and VTT is scarce. One highly relevant international study is the one by Hensher and Sullivan [18]. Their results in cent/km per vehicle (see Table 1) can be translated into VTT multipliers given knowledge of the VTT of one of the road types and an assumption of average speed. As Hensher and Sullivan [18] only report a generic VTT ($7.68/h[11]), we derive a conservative estimate by assuming that this equals the VTT of a straight four-lane motorway with a median. Assuming an average speed of 90 km/h and a base level of straight 4 lanes motorways with median, we calculate VTT multipliers of 2.32 and 2.68 for straight and curvy two-lane motorways, respectively.[12] These values, derived from SP results, are substantially higher than what we derive in our RP case studies (Sect. 4).

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[10] This applies as the new motorway is the faster alternative in all our cases.

[11] Calculated as a weighted average of truck driver ($5.08/h) and car driver ($15.6/h). The currency is 2001 New Zealand dollars.

[12] Assuming a lower absolute VTT for straight 4-lane motorways with median equals, these multipliers would get even higher.

Table 5 Recommended VTT multipliers for use in cost–benefit analysis in Norway [16]

Road type	VTT multiplier, not adjusted for accident risk	VTT multiplier, adjusted for accident risk	VTT multiplier, adjusted for accident risk and normalized*
(1) Urban roads/streets (speed limit ≤ 50 km/h)			1.0
(2) Four-lane motorway	1.0	1	0.87
(3) Three-lane motorway	1.1	1.075	0.93
(4) Two-lane highway with median strip	1.2	1.15	1.00
(5) Two-lane highway without median strip	1.44	1.33	1.15

Private travel

* Based on the share of traffic on each road type in Norway [11]

Our preferred estimates from our empirical case studies suggest that the VTT is between 1.2 and 1.6 times higher on the old two-lane highway compared to the new four-lane motorway, assuming no signage effect. This is moderate in light of the findings by Hensher and Sullivan [18], but it still implies a substantial difference in the VTT. It is also in a similar order of magnitude as the multipliers derived by Wardman et al. [41].

The differences in VTT may very well reflect several characteristics of the new motorway and old highway like the number of lanes, curviness and road surface. This implies that a more modern two-lane highway would have a multiplier closer to one, while other two-lane highways of more moderate standard could have higher multipliers. The results of Hensher and Sullivan [18] indicate that a curvy two-lane highway would have a 15% higher VTT that a straight or moderately curvy two-lane highway.

The results of Wardman et al. [41] also suggest that lane width matters for the VTT, which is interesting given that building narrower lanes is a common strategy for reducing construction costs.

5.2 Application in CBA of road projects

Our findings suggest that the difference in VTT between road types can be substantial. Hence, accounting for this in CBA will provide more accurate estimates of the economic benefits of road projects. In this section, we briefly discuss how the results can be incorporated in practical CBA of road projects. For more detail, see Flügel et al. [11] and [16].

First, one must choose a classification of road types, taking into account both which characteristics are important for the VTT and data availability. Flügel et al. [11] propose the following classification for Norway: (1) Urban roads/streets (speed limit up to 50 km/h), (2) Four-lane motorway, (3) Three-lane motorway, (4) Two-lane highway with median strip and (5) Two-lane highway without median strip. The reason for using median

strip as a criterion is that this characteristic is easily available in road network data, and is likely to be correlated with other relevant characteristics, like curviness.

Second, if accident costs are already included in the CBA, one should adjust the road type multipliers downwards in order to avoid double-counting. Third, multipliers should be expressed relative to the VTT of a typical trip, which means that some multipliers may be lower and some greater than 1.0. Based a joint consideration of the evidence in the existing literature and from the empirical case studies, Halse et al. [16] recommend the multipliers in Table 5. We emphasize that these are practical recommendations based on the evidence available so far, and that more research is needed.

If segmentation by trip purpose is possible, one may consider using multipliers closer to 1.0 for business travel, where a part of the VTT represents the cost to the employer [38] which might not depend as much on driving comfort. As argued by Halse et al. [16], the multipliers should not be applied to heavy goods vehicles. It seems unlikely that shippers or carriers are willing to accept a significantly higher cost or shipping time in order for the driver to choose a route with better road quality. Finally, if congestion is high and this is taken into account using congestion multipliers (see Sect. 3.4), segmenting by road type in addition might be less relevant.

Applying VTT multipliers by road type in CBA of actual road projects could potentially have a large impact on the estimated net benefits of road projects where a less comfortable road (e.g. type 4) is replaced by a more comfortable one (e.g. type 2), compared to existing practice. The increase in net benefits would depend on several factors, like how much of the benefits is due to time savings, how travellers allocate themselves between different routes etc. On the other hand, the net benefits of a project that shortens travel time on a road that is already of the most comfortable type (type 2) would be lower if applying these multipliers.

5.3 Limitations

While our study is an important step towards more knowledge on a previously unexplored topic, it is important to also note the limitations. First, we only consider private car travel and not other modes of transport. Second, our empirical evidence is based on three case studies, which might not be representative of traveller behaviour more generally. For instance, there could be local differences in income or other socio-economic factors. Third, the analysis is based on aggregate data, which makes parameter identification more challenging and implies that we cannot estimate values for sub-segments of travellers. Forth, combining this evidence with the international evidence from other contexts is not straightforward, and applying the results in CBA requires additional assumptions. Finally, our road type classification based on of four road types might not fully take into account the importance of road quality characteristics that also vary within road type.

5.4 Extensions and further research

In practice, the quantities to which the road type specific VTT are applied in a CBA framework are typically predicted by transport models. Ideally, these transport models should also apply a road type specific VTT in the transport demand and route choice prediction. This is currently not the case in Norway. However, ongoing projects aim to include road specific VTTs in the Norwegian transport modelling framework. If road type has an impact on the VTT, accounting for this should improve the model fit of these models, particularly for route choice.

Based on our findings, we recommend to conduct more research on the relationship between road type and VTT. Preferably, this should be based on more disaggregate data such as GPS-tracking data, which would allow for more robust identification of the VTT and related multipliers [13]. Furthermore, we recommend to develop methods and tools for including this relationship in practical CBA in a sufficiently precise and at the same time tractable manner. An alternative to discrete road type categories would be to value the road quality elements (number of lanes, curviness, surface etc.) separately. This requires that data on these elements is available.

We have only considered the VTT of car travellers and not other modes of transport. In the case of car passengers we expect the relative importance of road type to be at least as high as for car drivers, since this could determine which activities the passenger can do (e.g. reading)

without becoming nauseous.[13] This could also have relevance for the VTT in future scenarios with autonomous vehicles [24].

Similar effects would apply to bus passengers, but one should investigate whether this also depends on the vehicle size and type. We expect the infrastructure to matter less for the VTT in railway travel, which is relatively comfortable. However, there could be exceptions for infrastructure of very poor quality. In air travel, the amount of turbulence and noise could have an impact on the VTT, which could be of interest given that climate policy is expected to result in development of new and possibly less noisy aircraft technology [44].

6 Conclusion

We have documented that the literature on the relationship between the VTT on road type and quality is scarce, with some notable exceptions. The existing evidence suggests that accounting for this relationship could have a large impact on the results of CBA. Our empirical case study suggests a smaller, but still economically significant effect. Accounting for this effect will increase the estimated benefits of projects that replace existing roads with a more comfortable road type. The results could also have implications for how to set toll rates in toll-funded highway projects. If travellers value road quality, tolls on new high-quality roads could be set slightly higher without diverting too much traffic.

However, accounting for the relationship between road quality and VTT will also decrease the benefits of projects that reduce travel time on existing high-quality roads, other things equal. Moreover, average VTT will decrease somewhat over time as roads become more comfortable. While the relationship between communication technology and VTT has received considerable interest, this offers an alternative explanation for why the VTT might increase less over time than predicted based on income growth [15, 21].

Our study also highlights the importance of accounting for contextual factors that affect the VTT more generally, both in private car travel and public transport. If such factors are not accounted for, comparisons of VTT estimates based on different approaches could be misleading. This is particularly important given the increasing interest in using RP data to estimate the VTT.

Appendix: Mathematical specification of model

We have the equation for the probability of choosing the new motorway, as shown in Eq. 1 below.

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[13] Many CBA guidelines do not distinguish between the VTT of car drivers and car passengers. In the current Norwegian guidelines [32], passengers have a lower VTT, based on the findings by Flügel et al. [10].

$$P_t^{New} = \frac{e^{\mu GK_t^{New}}}{e^{\mu GK_t^{New}} + e^{\mu GK_t^{Old}}} \tag{1}$$

Equation 1 translates to two equations with values of $t = 1$ and $t = 2$. In addition, we have the equation for the weighted average of value of time in Eq. 2.

$$P_2^{New} * \omega_{New} + \left(1 - P_2^{New}\right) * \omega_{Old} = VTT \tag{2}$$

By replacing the values of GK_t^{New} and GK_t^{Old} in Eq. 1 with

$$GK_t^{Old} = C * D^{Old} + B_{Old,t} + \omega_{Old} * T^{Old} \tag{3}$$

and

$$GK_t^{New} = \beta + C * D^{New} + B_{New,t} + \omega_{New} * T^{New} \tag{4}$$

we get a system of three equations, Eq. 1 with $t = 1$ and $t = 2$, combined with Eq. 2. By setting $B_1 = 0$ as described in Sect. 4, and by fixing β, we have a system of equations which is to be solved with respect to the three unknowns μ, ω_{New} and ω_{Old}.

$$\begin{cases} P_1^{New} = \frac{e^{\mu(\beta+C*D^{New}+B_{New,1}+\omega_{New}*T^{New})}}{e^{\mu(\beta+C*D^{New}+B_{New,1}+\omega_{New}*T^{New})}+e^{\mu(C*D^{Old}+B_{Old,1}+\omega_{Old}*T^{Old})}} & \#(5a) \\[2mm] P_2^{New} = \frac{e^{\mu(\beta+C*D^{New}+B_{New,2}+\omega_{New}*T^{New})}}{e^{\mu(\beta+C*D^{New}+B_{New,2}+\omega_{New}*T^{New})}+e^{\mu(C*D^{Old}+B_{Old,2}+\omega_{Old}*T^{Old})}} & \#(5b) \\[2mm] P_2^{New}\omega_{New} + \left(1-P_2^{New}\right)\omega_{Old} = VTT & \#(5c) \end{cases}$$

Equation 5c in the system can be rewritten into

$$\omega_{New} = \frac{VTT - \left(1 - P_2^{New}\right)\omega_{Old}}{P_2^{New}}$$

and inserted into Eqs. 5a and 5b. We get a system with two equations and two unknowns, ω_{Old} and μ:

$$\begin{cases} P_1^{New} = \dfrac{e^{\mu\left(\beta+C*D^{New}+B_{New,1}+\frac{VTT-\left(1-P_2^{New}\right)\omega_{Old}}{P_2^{New}}*T^{New}\right)}}{e^{\mu\left(\beta+C*D^{New}+B_{New,1}+\frac{VTT-\left(1-P_2^{New}\right)\omega_{Old}}{P_2^{New}}*T^{New}\right)}+e^{\mu\left(C*D^{Old}+B_{Old,1}+\omega_{Old}*T^{Old}\right)}} \\[6mm] P_2^{New} = \dfrac{e^{\mu\left(\beta+C*D^{New}+B_{New,2}+\frac{VTT-\left(1-P_2^{New}\right)\omega_{Old}}{P_2^{New}}*T^{New}\right)}}{e^{\mu\left(\beta+C*D^{New}+B_{New,2}+\frac{VTT-\left(1-P_2^{New}\right)\omega_{Old}}{P_2^{New}}*T^{New}\right)}+e^{\mu\left(C*D^{Old}+B_{Old,2}+\omega_{Old}*T^{Old}\right)}} \end{cases} \# \tag{6}$$

Rewriting and simplifying this system[14] (6) of equations gives the following system of Eqs. (7).

$$\begin{cases} \ln\left(P_1^{New^{-1}}-1\right) = \mu\left(C*D^{Old}+\omega_{Old}*T^{Old}+B_{Old,1}-B_{New,1}-\beta-C*D^{New}-\frac{VTT-\left(1-P_2^{New}\right)\omega_{Old}}{P_2^{New}}*T^{New}\right) \\[4mm] \ln(P_2^{New^{-1}}-1) = \mu\left(C*D^{Old}+\omega_{Old}*T^{Old}+B_{Old,2}-B_{New,2}-\beta-C*D^{New}-\frac{VTT-\left(1-P_2^{New}\right)\omega_{Old}}{P_2^{New}}*T^{New}\right) \end{cases} \tag{7}$$

When the system (7) with two unknowns is solved[15] with respect to μ and ω_{Old}, we obtain the solution:

$$\begin{cases} \mu = \dfrac{\ln(P_1^{New^{-1}}-1)-\ln(P_2^{New^{-1}}-1)}{B_{New,2}-B_{New,1}+B_{Old,1}-B_{Old,2}} \\[5mm] \omega_{Old} = \dfrac{\ln(P_1^{New^{-1}}-1)\left(C*D^{Old}+B_{Old,2}-B_{New,2}-\beta-C*D^{New}-\frac{VTT*T^{New}}{P_2^{New}}\right)-\ln(P_2^{New^{-1}}-1)\left(C*D^{Old}+B_{Old,1}-B_{New,1}-\beta-C*D^{New}-\frac{VTT*T^{New}}{P_2^{New}}\right)}{\left(\ln\left(P_2^{New^{-1}}-1\right)-\ln\left(P_1^{New^{-1}}-1\right)\right)\left(T^{Old}+\frac{\left(1-P_2^{New}\right)T^{New}}{P_2^{New}}\right)} \end{cases}$$

---

[14] Applies when $P_1^{New} \neq 0$ and $P_2^{New} \neq 0$.

[15] This is true when $\omega_{Old} \neq \dfrac{\beta+C*D^{New}+\frac{VOT*T^{New}}{P_2^{New}}-C*D^{Old}-B_{Old,1}+B_{New,1}}{T^{Old}+\frac{\left(1-P_2^{New}\right)T^{New}}{P_2^{New}}}$ and

$\omega_{Old} \neq \dfrac{\beta+C*D^{New}+\frac{VOT*T^{New}}{P_2^{New}}-C*D^{Old}-B_{Old,2}+B_{New,2}}{T^{Old}+\frac{\left(1-P_2^{New}\right)T^{New}}{P_2^{New}}}$

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Further, we get an expression for ω_{New} by inserting ω_{Old} in Eq. 5c. This gives the full solution to the system of equations:

$$
\begin{cases}
\mu = \dfrac{\ln(P_1^{New^{-1}}-1)-\ln(P_2^{New^{-1}}-1)}{B_{New,2}-B_{New,1}+B_{Old,1}-B_{Old,2}} \\[2em]
\omega_{Old} = \dfrac{\ln(P_1^{New^{-1}}-1)\left(C*D^{Old}+B_{Old,2}-B_{New,2}-\beta-C*D^{New}-\frac{VTT*T^{New}}{P_2^{New}}\right)-\ln(P_2^{New^{-1}}-1)\left(C*D^{Old}+B_{Old,1}-B_{New,1}-\beta-C*D^{New}-\frac{VTT*T^{New}}{P_2^{New}}\right)}{\left(\ln\left(P_2^{New^{-1}}-1\right)-\ln\left(P_1^{New^{-1}}-1\right)\right)\left(T^{Old}+\frac{\left(1-P_2^{New}\right)T^{New}}{P_2^{New}}\right)} \\[2em]
\omega_{New} = \dfrac{VTT}{P_2^{New}}+\dfrac{P_2^{New}-1}{P_2^{New}}*\dfrac{\ln(P_1^{New^{-1}}-1)\left(C*D^{Old}+B_{Old,2}-B_{New,2}-\beta-C*D^{New}-\frac{VTT*T^{New}}{P_2^{New}}\right)-\ln(P_2^{New^{-1}}-1)\left(C*D^{Old}+B_{Old,1}-B_{New,1}-\beta-C*D^{New}-\frac{VTT*T^{New}}{P_2^{New}}\right)}{\left(\ln\left(P_2^{New^{-1}}-1\right)-\ln\left(P_1^{New^{-1}}-1\right)\right)\left(T^{Old}+\frac{\left(1-P_2^{New}\right)T^{New}}{P_2^{New}}\right)}
\end{cases}
$$

Abbreviations
CBA: Cost–benefit analysis; RP: Revealed preference; SP: Stated preference; VTT: Value of travel time; WTP: Willingness to pay.

Author contributions
Stefan Flügel has been responsible for Sects. 2 and 4 and contributed to all other sections. Askill H. Halse has been responsible for Sects. 1 and 6 and contributed to other sections. Knut L. H. Hartveit has been responsible for Sect. 3 and has contributed to Sect. 5. Aino Ukkonen has contributed to Sect. 4. All authors have participated in discussions of the results and their application and have approved the manuscript for publication.

Availability of data and materials
All calculations in this paper are based on data which has previously been documented in published research or which is publicly available via other sources. If requested, the authors will be happy to provide this data to those interested.

Declarations

Competing interests
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