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How to Adjust Cost-Benefit-Analyses for Evaluation of V2I Technologies?

1 INTRODUCTION AND ACKNOWLEDGEMENT

Transport engineers often have to justify their projects by proofing that the resulting benefits outweigh the costs. But what about transport researchers? With no doubt the "assessment" or "evaluation" has become an integrated part of almost all research and development projects. But most of the time it is done by comparing achieved traffic parameters or a single criterion like nowadays the CO_2 footprint. To ensure that new developed transport technologies not only tackle the problems they are directly addressed to but do so with a positive overall impact, a standardised evaluation framework has to be applied. This paper lays down how the existing method Cost-Benefit-Analysis (CBA) could be used on cooperative telematics systems, e.g., V2I, and which adjustments are required. Section 2 summarises the current CBA practice in road projects on the German example. Section 3 presents the particular V2I technologies under investigation, while section 4 contains the evaluation procedures where adjustments were found to be necessary and suggestions how to realize them.

The research was done within the KOLINE project which received financial support from the German Federal Ministry of Economics and Technology (BMWi) according to a decision of the German Federal Parliament within the 3rd transport research framework "Mobility and Transport Technologies". Project partners were the "Institut für Automation und Kommunikation e.V. Magdeburg (ifak)", Institute of Control Engineering TU Braunschweig, Transver GmbH Munich, and Volkswagen AG Wolfsburg (VW).

2 CBA IN ROAD TRANSPORT PROJECTS

2.1 Existing Regulations

Generally ex-ante evaluations of publicly funded projects are often legally demanded, e.g., in Germany by the Federal Budgetary Regulations or for major investments where the EU Cohesion Fund is involved [DG REGIO 2008]. Legal binding CBA procedures with detailed execution directives and cost unit rates are well established in many countries, e.g., New Approach to Appraisal (NATA) in the UK and Bundesverkehrswegeplan (BVWP) in Germany [BMVBW 2003]. An extensive overview about the practice in transport project appraisal in the EU25 countries can be found in [HEATCO 2005].

2.2 Criteria, Indicators, and Measures

Most of CBA procedures incorporate only four out of six global goals according to [TP 2007], [BOLTZE et al. 2006], leaving out *Security* and *Customer satisfaction* as intangible benefits which are hard to predict and value. On the example of the German BVWP Table 1 gives possible criteria, i.e., more detailed sub-goals, into these goals can be broken down. These criteria need physical indicators with measurement units also shown in the table. It comprises

the eight benefit criteria, whereas the two cost components of investments (building / acquisition) and infrastructure operation and maintenance are not shown.

Table 1: Criteria and Indicators of the German BVWP

Global Goals	**Criteria**	**Indicator Units**
1. Mobility	a) Vehicle Travel Time b) Pedestrians Delay Time	(PAX*h)/a
2. Resource Efficiency	c) Vehicle Operation + Maintenance *Vehicle Occupancy Rate (included above)*	km/a + h/a n_{PAX}
3. Environment Friendliness	d) Pollutant Immissions (NO_x, CO, HC, PA) e) Climate Gas Emission (CO_2) f) Noise Immissions g) Fuel Consumption	t/(km*a) t/(km*a) dB(A) l/(km*a)
4. Safety	h) Accidents and Fatalities	n/(km*a)

PAX: Passenger; a: year

Even for the current situation before project realisation, the so-called baseline, not all of these indicators are measured in reality, above all when the area of the envisaged project is quite big. It is rather common practice that models and traffic software are applied to emulate the measures, being calibrated on the baseline and producing the outputs for the project's scenarios.

After the differences of each indicator between the baseline and the project scenarios are computed they are monetised, i.e., multiplied with their respective cost unit rate, and simply synthesised into a single multi-annual sum expressing the overall benefit. Currently the benefits from time saving form the highest fraction of the overall result with up to 80% of the sum [Mackie et al. 2001].

2.3 Underlying Traffic Model

The established CBA procedures are tailored for appraising civil engineering constructions like new motorways or broadening intersections, which lead to significant changes in the demand and patterns of traffic flow. These changes mostly manifest in the number of vehicles per hour [veh/h] or per average day q which is assigned to the links of a network, and the averaged travel speed v [km/h] respectively travel time t [s] on these links. The travel speed is commonly derived as capacity-restraint (CR) function incorporating the free-flow speed v_f and the actual flow q. Whereas the (open) CR functions for the German BVWP still indicate a low stop-and-go speed even when the road capacity is exceeded, the reality looks definitely more like the fitted Van Aerde CR function with a maximum capacity as can be seen in Figure 1. It also shows that in situations nearby saturation flow (in this case between 700 and about 950 veh/h) the speed can be significantly reduced and thus two different traffic states and speed levels for the same flow exist. Nevertheless both functions try to approximate one (or

two) deterministic speed value(s) per flow value, where actually the measured data underlies a stochastic distribution with a range larger than ±5 km/h.

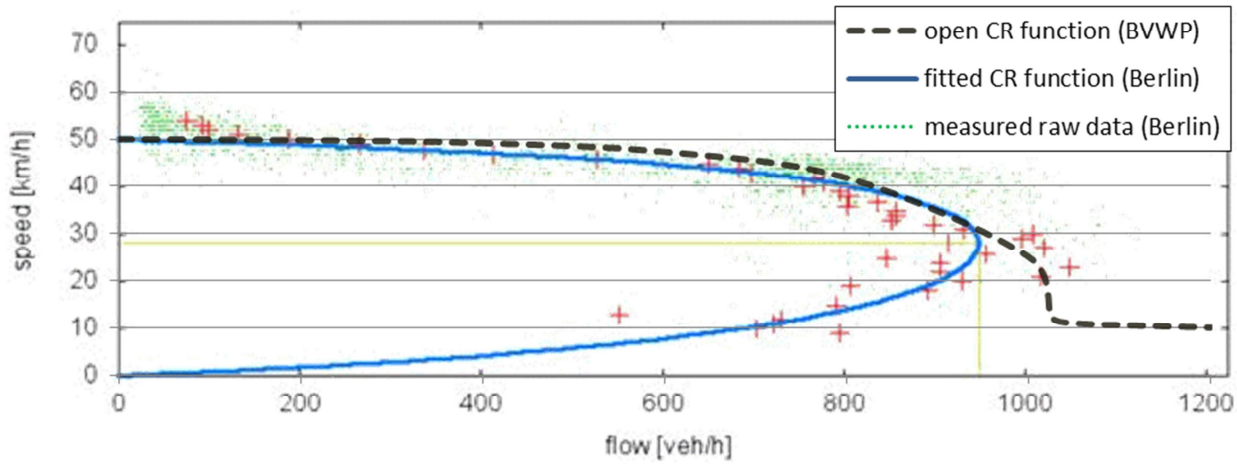


Figure 1: CR functions for an urban arterial road with one lane

As state-of-the-art macroscopic models and software like VISUM or SATURN are applied to calculate the direct effects of road transport projects, i.e., the vehicle travel time as well as vehicle operation and maintenance costs (based on the travel length) as indicators of criteria (a) and (c), without distinguishing between the different traffic states and thus probably generating incorrect results for saturated situations.

2.4 Overlying Criteria Models

In the German BVWP the remaining six criteria are derived using additional functions and under consideration of further determinants such as the number of affected inhabitants.

The pedestrian delay time (b) is calculated depending on the type of road either as constant value or as a function of the vehicle flow q and multiplied by the number of inhabitants alongside the road.

Pollutant (d') and climate gas emissions (e) are given for four different discrete traffic states sub-categorised by the type of road and the vehicle class. The tabled values are taken and simplified from the database HBEFA [INFRAS 2010], which contains data for Austria, Germany, Norway, Sweden, and Switzerland. In other CBA procedures a function which incorporates the average speed and road slope is used. This counts also for the fuel consumption (g). The pollutant immission (d) takes into account the average wind speed, type and distance of road accompanying buildings in a logarithmic model.

Noise emissions (f) are calculated on the average daily traffic (ADT) volume and the share of heavy goods vehicles; the transmission is simply mapped by look-up tables with different road attributes and multiplied by the number of inhabitants alongside the road.

The accident rates (h) are based on the ADT and the type of road. They can be altered according to the recorded rates of the baseline where necessary.

3 V2I TECHNOLOGIES UNDER INVESTIGATION

In the last few years an ever-growing range of *Intelligent Transportation Systems* (ITS) or *Telematics* components and *Advanced Driver Assistance Systems* (ADAS) has been introduced in order to tackle deficits in the road transport sector, both in urban and interurban areas. Such systems can be, e.g., variable message signs on the collective level, or adaptive cruise control (ACC) on the single vehicle level. A new component to be introduced from the year 2015 on is the communication between vehicles and traffic infrastructure (V2I) and amongst vehicles (V2V), so-called cooperative ITS [C2C 2012]. Vehicles need to be equipped with On-Board Units (OBU), and Roadside Units (RSU) are to be placed at the road infrastructure.

A distinctive attribute of these cooperative systems is that the envisaged goals are the better achieved the higher the rate of equipped vehicles is. This leads to the fact that through the evaluated multi-annual time period a rising equipment rate with different benefits has to be considered somehow.

Amongst the numerous possible V2I applications those developed in the national research project KOLINE shall be investigated. They aim at improving the mobility, resource efficiency and environment friendliness, but not safety. The description of the KOLINE components tailback estimation (*TRANSFusion*) and *Green Light Optimised Speed Advisory* (GLOSA), both in conjunction with signalised intersections, as well as the model based signal program optimisation are discussed in detail in [Naumann et al. 2012] resp. [Bley et al. 2012]. It becomes clear that such systems may not or only to a low degree influence the demand and patterns of traffic flow on the macroscopic level. They rather change the single driver's actions and interactions between (platooning) vehicles on a microscopic if not sub-microscopic level. Therefore the described traffic models and overlying indicator models cannot be used anymore for the still necessary cost-benefit-analyses of these transport-related technologies.

4 ADJUSTMENTS TO CBA PROCEDURES

4.1 Microscopic Traffic Simulation

As described above no changes in the flow and probably even the average speed will occur under V2I application. Therefore the macroscopic traffic simulation with its averaged and aggregated values must be replaced by a microscopic one where the movements of every single vehicle are based on physical vehicle type characteristics and driver behaviour models. They ensure that the actual traffic state, signalisation and surrounding traffic participants are

taken into account in very small time discretisation steps. Thus, e.g., the problem of unrealistic speeds during instable traffic states nearby saturation is avoided. Although basic traffic data like travel time (a) and average travel speed is calculated for every single object like vehicles, links, lanes and nodes, it should be averaged for suitable time periods, object classes or areas. If calculations regarding the further criteria like emissions and safety shall be conducted with external software it is often necessary to log vehicle traces – trajectories – for at least a fraction of all vehicles.
In KOLINE the software AIMSUN 6.1.3 by TSS was used, whilst other projects prefer VISSIM by PTV or the open source software SUMO by DLR.

4.2 Microscopic Simulation Of Overlying Criteria Models

Additional to the basic traffic data, microscopic models for emissions (d', e) and fuel consumption (g) are often implemented into the simulation software, either with default parameters or ones to be edited by the user. It might happen that the needed parameter set must be derived by conversion from other forms, e.g., the acceleration factor is conceived of the factor for slope impacts since s [%] ~ $\frac{1}{10}$a [m/s²], or the continuously valid velocity parameter is computed from discrete values of traffic states fuzzily described as "free-flow" or "stop and go". This was done in KOLINE to get the HBEFA tables into the AIMSUN formula. Another way is to rely on external software which might have more coded expertise and up-to-date parameters, but needs the huge amount of trajectory input data from the actual traffic simulation software. A solution, yet to be executed very carefully, could be to base the emission and consumption simulation only on a significant percentage of all vehicle trajectories and scale up the result by this percentage. In both cases it should be ensured at the end that the fuel consumption meets the CO_2 emission, if not one value is derived by the other anyway. They are directly linked by the factors 2.328 kg CO_2/l (petrol) resp. 2.614 kg CO_2/l (diesel) [DEFRA 2011].
The transmission and consequential the immission of pollutants can be calculated applying external tailor-made software basing on complicated differential equations and on the expense of re-modelling the road network again. The more suitable way is to stick to the existing parameter-relying procedure as done in KOLINE.
A great advantage of microscopic simulation lies in the near-to-reality modelling of pedestrian movements, as long as this module is implemented into the evaluator's software suite. Then the pedestrian delay time (b) can be determined exactly and depending on the changing signalisations rather than approximating it with half the red time assuming uniformly distributed arrivals. Due to the unavailability of neither the AIMSUN plugin nor detailed pedestrian movement inputs the latter approach had to be used in KOLINE.
Noise emissions (f) are not yet implemented in many traffic software programs, and a rather big variety of models exists. Some of them comprise noise effects from acceleration and deceleration or, as a part of this consideration, the degree of flow harmonisation expressed by

the standard deviation of the speed. Here lies a potential to appraise the effects of V2I technologies since the average daily traffic (ADT) volume and the share of heavy goods vehicles as the sole parameters of the current model will not be changed significantly by V2I and hence will not yield noise emission reductions. AIMSUN does not comprise noise calculation and hence did not enable to take this criterion into consideration within KOLINE.
Another criterion which is not contained in microscopic traffic simulations is the number of accidents, since the underlying physical movement models prevent accidents. The existing approach - relying only on the ADT and type of road - will not yield any changes triggered by V2I, similar to noise emissions. The arising *Surrogate Safety Assessment Method* SSAM [FHWA 2008] could offer a way to predict accidents when only the conflictual interactions between traffic participants change, expressed by figures like *Time To Collision* TTC or speed differences. The number of conflicts and accidents then will be linked by regression and calibrated to observed accidents. Although the general feasibility of coupling AIMSUN with SSAM was proved in KOLINE no reliable parameter set and regression could be applied.

4.3 Microscopic Simulation with Added V2I

Essential for investigations of V2I functionalities is to correctly integrate them into the simulation. Up to now they are coded outside the actual traffic simulation, but act as software-in-the-loop via the *Application Programming Interface* (API) by altering the parameters of each desired object like vehicles and traffic lights. On the feedback channel vehicles attributed with an OBU serve as additional detectors to enhance the tailback estimation and traffic flow prediction which run outside the traffic simulation. Direct communication amongst vehicles (V2V) is not possible this way. In KOLINE the simulation software included the penetration rate as an edible vehicle type attribute and thus supported the V2I integration. Scenario parameters were set to rates of 0, 5, 15, 25, and finally 35%. In some projects like iTetris and PRE-DRIVE [Bieker et al. 2010] the simulation of communication was an additional task, but not performed in KOLINE as a model simplification with perfect propagation conditions was assumed. So far it is estimated that the message reception rate has a minor influence on the general V2I traffic effects.

4.4 Extrapolation In Time

Applying macroscopic traffic models for CBA demands calculating all 24 hours of a day and for different day types due to traffic demand changes throughout a year. In contrary microscopic models often concentrate on only a few hours of a typical day, e.g., the peak hour and an average off-peak hour. These scarce results leave effects outside the lower and upper bounds unrecognised and should not be simply extrapolated by an educated guess as it is currently practised, if at all. For a start, the extrapolation can be based on a standard annual load curve like in the BVWP, which includes 201 workdays, 101 Saturdays and workdays

during school holidays, and 63 Sundays plus public holidays. Every of these three day types is further split into five different classes with ADT factors as in
Table 2, where the resulting daily traffic volumes (DTV) of a fictional basic ADT_w with q=*2.000* veh/24h are given as example.

Table 2: Day types per year, corresponding ADT factors and resulting DTV

Workdays						**Σ p.a. [d/a]**
count	14	48	77	48	14	201
factor	0,91	0,95	1,0	1,05	1,09	
ADT_w:*2.000*	*1.820*	*1.900*	*2.000*	*2.100*	*2.180*	
Workdays (school holidays) and Saturdays						
count	7	24	39	24	7	101
factor	0,8	0,9	1,0	1,1	1,2	
ADT_{h+s}: *1.320*	*1.056*	*1.188*	*1.320*	*1.452*	*1.584*	
Sundays and public holidays						
count	4	15	25	15	4	63
factor	0,81	0,9	1,0	1,1	1,19	
ADT_{s+p}: *1.000*	*810*	*900*	*1.000*	*1.100*	*1.190*	

Afterwards a given particular proportional daily load curve [%/h] is assigned to every DTV leading to 24 hourly traffic volumes per DTV [veh/h] according to *Figure 2*. Summing up, 360 different hour categories have to be considered in theory – in practise there might be less due to some pairs of hours with equal traffic volumes. With the fictional DTVs from Table 2 there are seven hour categories with a flow of *q*=20 veh/h ($DTV_{w1,0}$-hours 0-1, 1-2, 4-5, 5-6, 23-24, $DTV_{s+p1,0}$-hours 21-22, 22-23).

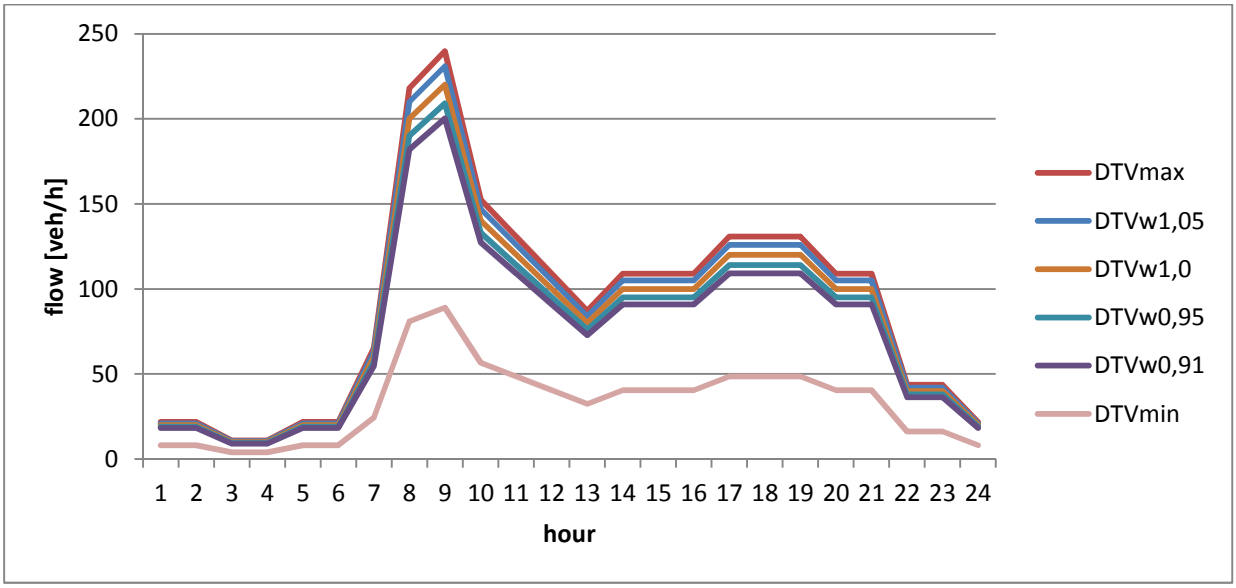


Figure 2: Hourly traffic volumes for selected DTV

Taking into consideration that microscopic simulations have to be repeated several times – in KOLINE 16 runs were necessary – to ensure the statistical significance of the final (average) result, computing all 360 hours can become unbearable time consuming, above all when the embedded V2I functionalities slow the simulation down to real-time. As a compromise a real hour could be shortened, at least those with uncongested conditions, and the results be re-scaled afterwards.

Another probably less resource consuming approach is to convert the disadvantage of the numerous necessary simulation runs into an advantage by applying statistics on them. As already discussed in sec. 3.2 and illustrated by *Figure 1* the relationship flow→speed is rather stochastic. Thus the probability distribution of speed or travel time (intervals) for a given flow (class) can be stated as in *Figure 3* instead of a deterministic average value. For this example of a 83 m long subordinate junction access road with one lane in Braunschweig the raw data of 15-minute-intervals between 6 a.m. and 10 p.m. within 17 simulation runs was counted in each flow class what can be seen in *Figure 4*, and afterwards normalised to 100%.

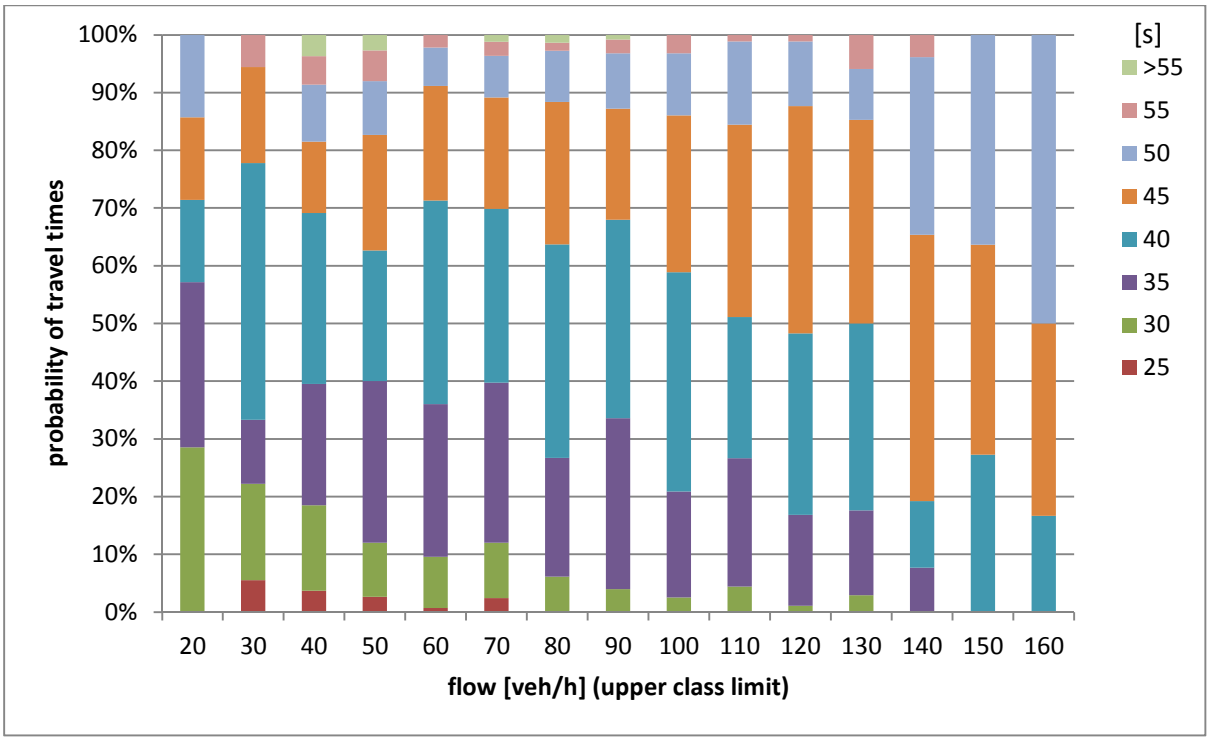


Figure 3: Probability distribution of travel time levels [s] on a 83 m long link

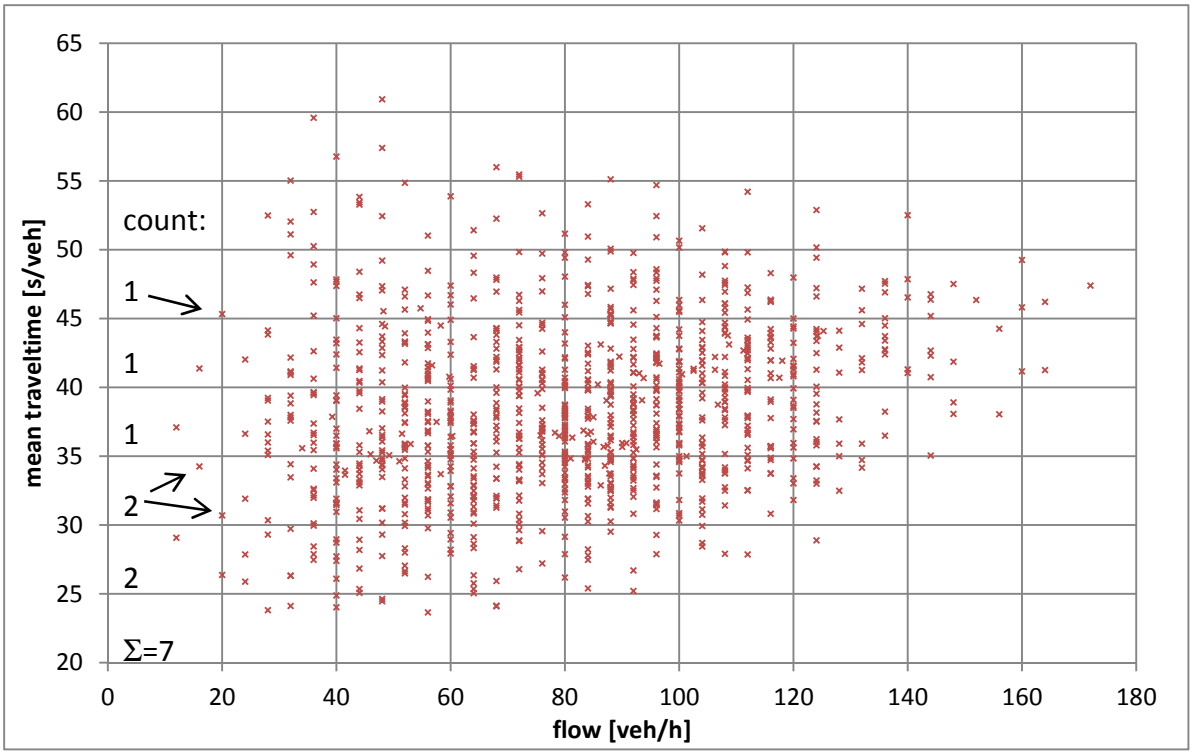


Figure 4: Flow→travel time raw data from simulation

In a last step these probability distributions must be mapped onto the right amount of hours per year with the respective flow *q*. According to Table 3 a flow *q*=20 veh/h occurs on 435 hours a year on this link.

Table 3: Hours per year with a flow of *q*=20 on the link

Daytype	**Day factor**	**Day count**	**hours *q*=20**	**Σ p.a. [h/a]**
Workdays	1,0	77	5	385
Sundays and public holidays	1,0	25	2	50
				435

During these 435 hours five different travel time intervals were found to be possible with the following probabilities and resulting absolute counts (Table 4). Rounding issues remained unsolved so far.

Table 4: Hours per year with a flow of *q*=20 and particular travel time interval on the link

Travel time interval	]25,30]s	]30,35]s	]35,40]s	]40,45]s	]45,50]s	*]25,50]s*
Probability	28,6%	28,6%	14,3%	14,3%	14,3%	*100,1%*
Hours per year	124	124	62	62	62	*434*
Travel time per year	68.200 s	80.600 s	46.500 s	52.700 s	58.900 s	*306.900 s*

This procedure is repeated for all flow classes so the annual amount of 8.760 hours is distributed to one particular flow→travel time relation in order to compute the overall travel time.

To which extent this method could be applied to the other criteria was not examined yet and should be investigated in the future. The KOLINE project and others applied only a rough estimation, e.g., that effects of the single simulated workday occur 201 times per year in the same manner and that the effects of the remaining 164 days are scaled linearly with the ADT. With regard to the importance of the single criteria within V2I projects Table 5 suggests that probably not all of them need to be considered that carefully within the extrapolation. The impact analysis of the KOLINE project reveals that travel time savings have the highest influence on the overall benefit outcome, followed by operation costs and CO_2 emissions. Pollutant immissions and pedestrian delay times - due to no changes of their green times - have hardly any impact.

Table 5: Ordered impact of criteria in V2I projects

Criteria	**Impact**
a) Vehicle Travel Time	[26,78] %
c) Vehicle Operation incl. (g) Fuel Consumption	[17,57] %
e) Climate Gas Emission (CO_2)	[5,17] %
b) Pedestrians Delay Time	0 %
d) Pollutant Immissions (NO_x, CO, HC, PA)	0 %

The evaluation period normally comprises several decades, e.g., 20 years in the BVWP. It can be assumed that during this time the V2X equipment rate rises what, as mentioned before in section 3, alters the respective benefit outcomes. Thus the benefit and cost results (see also sec. 4.5) of different technical scenarios with successive equipment rates should be wrapped into several multi-annual market scenarios which are distinguished by the speed of equipping the fleet. These market scenarios, and not the technical scenarios, should be compared since they make clear whether a strategy of quick introduction outvalues a smooth one or not.

4.5 Cost determination

The operation and maintenance costs of OBUs and RSUs seem to be negligible – the applied OBU *LinkBird-MX* of the KOLINE project for example consumes during normal operation only 3 W. The investment costs per node C_N comprise the RSU at estimated C_{RSU}=10.000€ and the optimisation software update at C_{SW}=3.000€ for the evaluation period of 20 years. The investment costs per OBU can be assumed at C_{OBU}=500€, the usage duration equals the average vehicle life cycle of 10 years. It is important to make further considerations, e.g., how many equipped nodes n_N a vehicle passes by during its trip, whether it is riding back and forth

during a day $\left(\frac{ADT}{2}\right)$, and how many different V2I functionalities are served by the OBU leading to only a fraction of the costs being assigned to one particular node and functionality. In the KOLINE case we assumed that the equipment rate R_{OBU} and the number of functions nF_{OBU} are rising at the same rate, that is $\frac{R_{OBU}}{nF_{OBU}}$ = const. = $\frac{5\%}{1}$ .. $\frac{35\%}{7}$=0,05. The resulting averaged annual costs for three different sample nodes are listed in Table 6.

Table 6: Annual system costs per node

Node	$\frac{ADT}{2}$ **(16 hours)**	**Number of passed nodes n_N**				
		1	**2**	**3**	**4**	**5**
K61	32.750	41.600 €	21.100 €	14.300 €	10.900 €	8.800 €
K47	51.050	64.500 €	32.600 €	21.900 €	16.600 €	13.400 €
K46	26.050	33.200 €	16.900 €	11.500 €	8.800 €	7.200 €
Sum				47.700 €	36.300 €	29.400 €

5 CONCLUSION AND OUTLOOK

The paper showed that cost-benefit-analyses (CBA) of transport projects on the one hand and microscopic traffic simulations of transport telematics projects on the other hand are well established. Yet the link between both lacks approved procedures and is loaded with uncertainties and unsolved questions. For a start the simulation of only a limited spectrum of flow levels which occur during a year must be expanded to include all possible effects, even if no or negative effects of the investigated technology appear. The accident prediction as part of a conventional CBA is left out until now but the upcoming method SSAM needs to be looked at whether its assumptions are valid and which adoptions are necessary. Also models for noise emission as CBA criterion must be integrated in or coupled with the traffic simulation, in a way it is already done with pollutant emissions. A final answer how far the restrictions of radio propagation of cooperative messages influence the traffic parameters must be found.

A promising concept for the temporal extrapolation of simulated results was presented, which transforms the vast data of the different simulation runs into probabilities rather than reducing the information by averaging values. The next research step is to apply a simple Bayesian network on this approach to consider the dependencies over time, i.e., several simulated time periods.

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