CoEXist

Deliverable 2.8

Guide for the simulation of AVs with a macroscopic modelling tool

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Abbreviations

Abbreviation	Long form
AV	automated vehicle
CV	conventional vehicle
PCU	passenger car unit
VDF	volume-delay function
HDV	heavy duty vehicle
OD	origin-destination
USTUTT	University of Stuttgart – Chair of Transport Planning and Traffic Engineering

1 Introduction

1.1 Purpose of this document

This document provides guidance for modellers and model users for integrating automated vehicles (AV) and their impacts into macroscopic travel demand models. To capture the capability of AV on different levels, macroscopic models must be extended, which requires new methods or the application of tools.

1.2 Scope

This document sets the framework for the tools presented in D2.7 by introducing the ideas and approaches together with assumptions to include AV in macroscopic travel demand models. Furthermore, it contains practical advice and further recommendations for modellers.

While the tools described in D2.7 have been designed specifically for the software Visum, the approaches presented in this document may also be used for other macroscopic simulation tools as well.

The application of the tools described represent extensions to Visum by adding functionality to the software in form of Visum compatible scripts, Visum procedure files or Visum Add-Ins. The model user must plug them into Visum to make them work and to perform a certain task. They assist the model developer or model user by extending the capabilities of Visum. Apart from the automation of some tasks, the modeller still needs to adapt settings or adjust parts in Visum that cannot be accessed in another way. Therefore, it is required that the model user is familiar with working with Visum.

1.3 Overview

Traditional travel demand models apply the four-stage algorithm, where trip generation, destination choice, mode choice and route choice are covered to replicate people's behaviour and their movement. Departure

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time choice may also be considered as a step. Integrating AV or new mobility services into these models requires to establish and include new steps in the procedure. This could be for example the pooling of trips as well as the scheduling of vehicles for a ridesharing system with self-driving vehicles. Besides adding new model stages, impacts of AV on supply and demand must be taken into account on all stages of a travel demand model.

Figure 1 shows the extended sequence of a travel demand model, which includes assumed impacts of AV. Topics covered in this document are labelled with the corresponding chapters. Each main chapter starts with an introduction where the purpose of the specific topic is discussed. The following chapters outline ideas on how to approach the topic or problem in general, practical instructions on the implementation into Visum and further recommendations.

Chapter 6 covers a brief overview on the macroscopic use cases and which tools they incorporate.

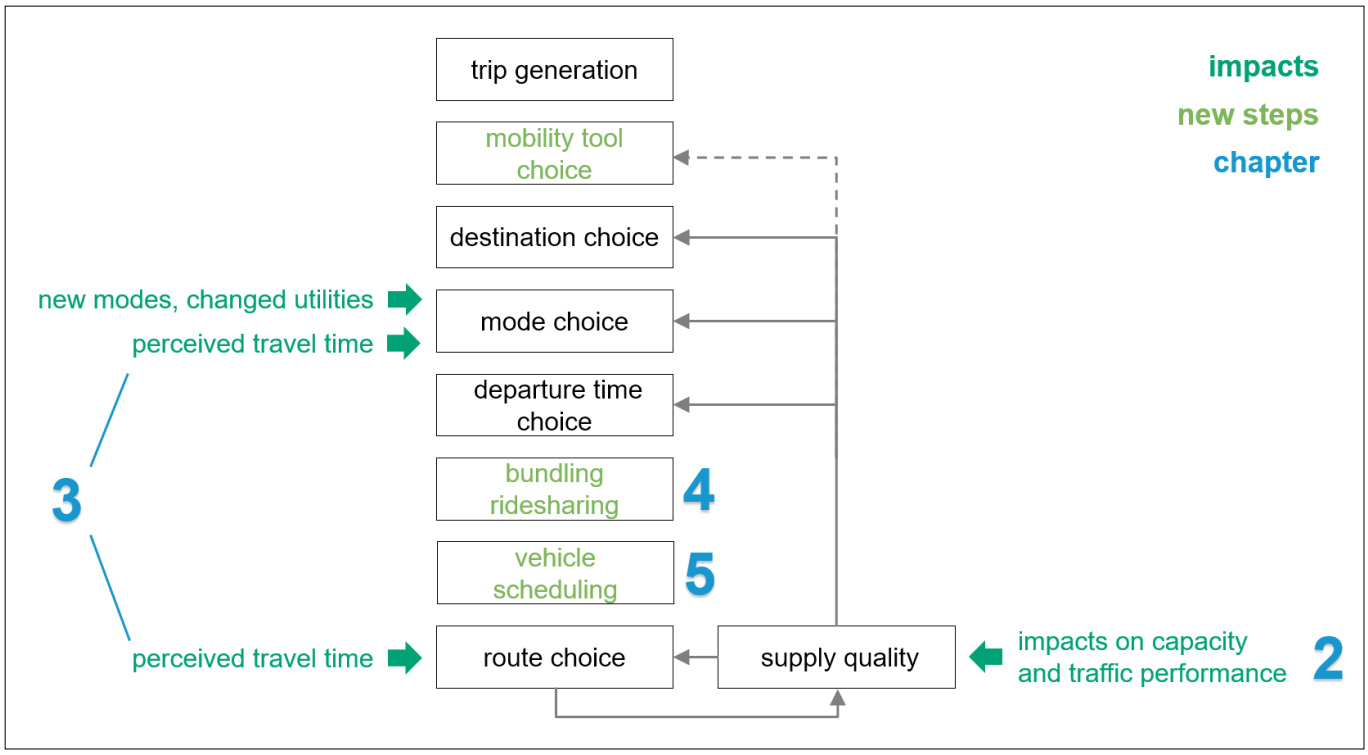

Figure 1: Modelling AV with macroscopic travel demand models

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2 Impacts of CAV on capacity and network performance

2.1 Purpose

CAV may change the capacity and performance of the road network. This section explains how the impacts of CAV on capacity can be modelled in a macroscopic travel demand model.

2.2 Approach

The American Highway Capacity Manual (HCM, 2010) defines road capacity as the maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic and control conditions. This definition treats capacity more or less as a constant value. Brilon et al. (2007) indicate that this assumption is not appropriate as observations show, that the maximum traffic throughput varies even under constant external conditions. They introduce the concept of stochastic capacities to replicate the relationship between traffic flows and traffic breakdown in a better way. Lohmiller (2014) shows that the throughput on a motorway depends on the traffic composition, i.e. the driver population influences the quality of the traffic flow. This leads to two interpretations for the relationship between demand, capacity and performance. The performance, which can be measured by the indicator delay time per vehicle, depends either on variable capacity values or on the ability of a given demand composition (driver / vehicle population) to use a given (constant) capacity.

Macroscopic route choice and assignment models for private transport apply volume-delay functions to determine travel time in the road network. For links, the travel time is computed by multiplying the free flow travel time with a factor that is determined by a volume-delay function (VDF) as shown in equation (1). For nodes, a delay time is added to the free flow travel time as shown in equation (2). Equation (3) presents a simple example of a VDF. The VDF-factor depends on the volume / capacity ratio, i.e. the saturation rate x_s of a supply element *s,* which represents either a link or a node. The relationship between volume and capacity is described in equation (4). It uses the concept of passenger car units (PCU) where capacity and vehicle volumes are converted into passenger car equivalents. Examples for vehicle type specific PCU values are 1.0 for conventional passenger cars, 2.3 for heavy goods vehicles and 0.4 for motorcycles (Kimber et al. 1982).

$$t_{s=link}\left(x_s\right) = t_s^{free} \cdot VDF\left(x_s\right) \quad (1)$$

$$t_{s=node}\left(x_s\right) = t_s^{free} + VDF\left(x_s\right) \quad (2)$$

$$VDF\left(x_s\right) = 1 + \alpha \cdot x_s^{\beta} \quad (3)$$

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$$x_s = \frac{\sum_{i \in VehType} q_{s,i} \cdot f_i^{PCU}}{q_s^{max}} \quad (4)$$

where

$t_s(x_s)$	travel time on supply element *s* at saturation rate x_s [sec]
t_s^{free}	travel time on supply element *s* at saturation rate $x_s = 0$ [sec]
$VDF(x_s)$	volume-delay function with parameters α and β
x_s	saturation rate (volume/capacity ratio) on supply element *s* [-]
q_s^{max}	capacity of supply element *s* assuming that all vehicles are conventional pass. cars [PCU/h]
f_i^{PCU}	PCU of vehicle type *i* [PCU/veh]

The concept of PCU is a common concept in macroscopic assignment models. It is mainly used to convert heavy goods vehicles (HGV) into PCU. Assuming that AV have a performance that differs from conventional cars (CV) and that the performance additionally depends on the type of supply element, the PCU concept must be extended to AV as well as to road and intersection types (motorway or urban road, grade separated or at-grade intersections, signalized or unsignalized intersections). Since the PCU-factor will be multiplied with the volume of the related vehicle type, it is possible to model the impacts of different penetration rates of AV.

This extension can come in two forms making different assumptions. The first approach assumes a linear relationship between the share of AV and its impact on saturation. This requires a specific but constant PCU-factor for each combination of vehicle type and supply element type as shown in equation (5). In this first approach the PCU-factor does not depend on the share of AV. The second approach assumes a nonlinear relationship. In case of a low penetration rate the influence of a single AV is smaller than in cases with a higher penetration rate. To achieve this the PCU-factor must be adapted during an assignment depending on the AV share on the related supply element using equation (6). Its value ranges between the PCU-factors for an AV share of 0% and 100%.

$$x_s = \frac{\sum_{i \in VehType} q_{s,i} \cdot f}{q_s^{max}} \quad \text{where} \begin{cases} f = f_{s,i}^{PCU} & \text{linear impact AV} \\ f = f_{s,i}^{PCU}(p_{s,AV}) & \text{nonlinear impact AV} \end{cases} \quad (5)$$

$$f_{s,i=AV}^{PCU}(p_{s,AV}) = f_{s,i=AV}^{PCU,0\%} - p_{s,AV} \cdot \left(f_{s,i=AV}^{PCU,0\%} - f_{s,i=AV}^{PCU,100\%} \right) \quad (6)$$

where

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$f_{s,i}^{PCU}$	PCU of vehicle type *i* on type of supply element *s* [PCU/veh]
$f_{s,i}^{PCU}(p_{s,AV})$	PCU function dependent on the share of AV $p_{s,AV}$ [PCU/veh]
$p_{s,AV}$	AV share on supply element *s*
$f_{s,i=AV}^{PCU,0\%}$	PCU of vehicle type AV on supply element type *s* for an AV-share of 0% [PCU/veh]
$f_{s,i=AV}^{PCU,100\%}$	PCU of vehicle type AV on supply element type *s* for an AV-share of 100% [PCU/veh]
$q_{s,i}$	volume of vehicle type *i* on supply element *s* [veh/h]
q_s^{max}	capacity of supply element *s* assuming that all vehicles are conventional pass. cars [PCU/h]
$VehType$	set of vehicle types: CV, AV, HGV

This approach is valid for AV-ready supply elements. For supply elements that are not AV-ready, the driver has to take over control of the vehicle and the PCU would be 1 as for CV.

2.3 Instructions

This chapter comprises instructions and remarks for applying the tools provided for integrating impacts of AV on capacity and network performance in Visum travel demand models. Some steps include the use of scripts which are available as code in deliverable D2.7, but it is also possible for the model user to do everything manually. In principle, almost everything can be done by scripts, but these depend in detail on model properties and would always have to be rewritten by other users, so the authors refrain from doing everything possible by scripts within this guide.

The prefix '*CX_*' is introduced to uniquely identify all attributes, matrices, network elements or anything else to be part of CoEXist-specific methods.

Prerequisites

- A travel demand model in Visum with set VDF for each link type and capacities for each link where Car is a permitted transport system.
- A travel demand matrix for motorized vehicles.
- There is no specific requirement regarding the Visum version. The screenshots are taken out of Visum 17, but the approach with the provided VDF was successfully tested with Visum 14, 15, 16, 17 and 18.
- For Visum 2020, a new set of VDF was necessary due to fundamental changes in the functionality and structure of user-defined VDF. They are included in the revised version of Deliverable D2.7.

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Limitations of Visum 18 or lower

The current solution can only handle one transport system of type “AV”. This limitation comes from the capability of user-defined VDF in Visum, which support only a limited number of user-defined parameters (*AddVal1, AddVal2, AddVal3 and AddVal-TSys*). Each new “AV” transport system with a different set of PCU-factors and a different AV-ready network needs at least two, rather three own parameters that require user input.

With additional assumptions and restrictive simplifications it is possible to include multiple “AV” transport systems, but at this point it will not be discussed further.

Disclaimer: This document has been updated to provide guidance for Visum 2020 users as well. Therefore, instructions are available separately for Visum 2020 in chapter 2.3.2. Besides some changes in scripts or coding of VDF that are necessary due to structural changes of the software, some other steps may deviate from the counterpart in chapter 2.3.1. Based on the experience of the last two years in modeling AV, the updated instructions for Visum 2020 represent the approach that the authors would currently recommend.

2.3.1 Visum 18 or lower

It is recommended to carry out the instructions in the suggested order as the tools partly depend on each other. Any other sequence or modifications of names can cause errors in the modelling process or require additional effort from the model user.

- Go to menu *Demand – TSys/Modes/DSeg* and create a transport system for AV *CX_AV* as shown in Figure 2.
- Transfer the network attributes like speed and authorization for using links etc. from CV to AV.
- Do not alter the value for PCU of 1.00, this will be done in another way and only for AV-ready links, by default it should be the same as for CV.
- Create a mode and a demand segment with the same name automatically (see also Figure 3).
- Run the script for creating user-defined attributes (see Figure 4 for help) “CoEXist_Create_User-Defined_Attributes_-_Extension_for_handling_AV_in_volume-delay_functions.vbs”.
- The script will add six attributes. Check if they have been added by opening the list of user-defined attributes (*Network – User-defined attributes*), sorting by *AttID* and comparing to the attributes listed in Table 1 and shown in Figure 5.

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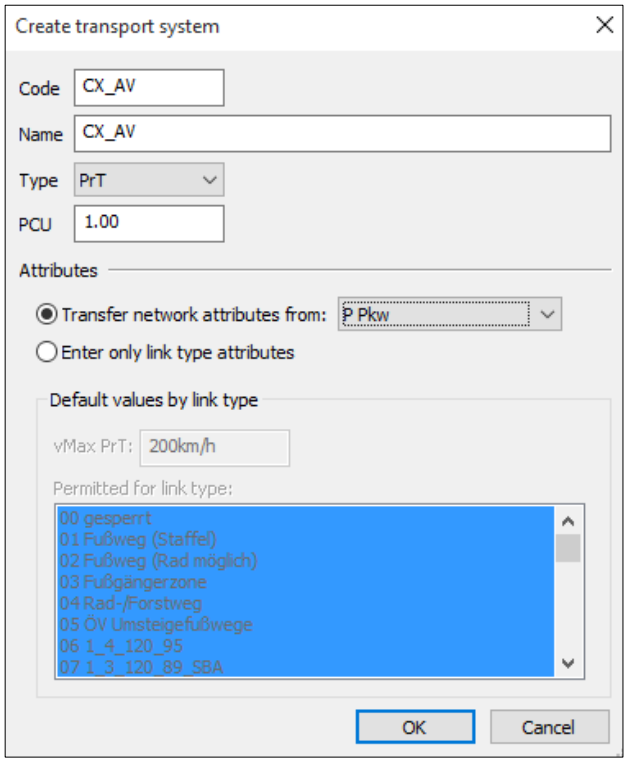

Figure 2: Create a new transport system for AV

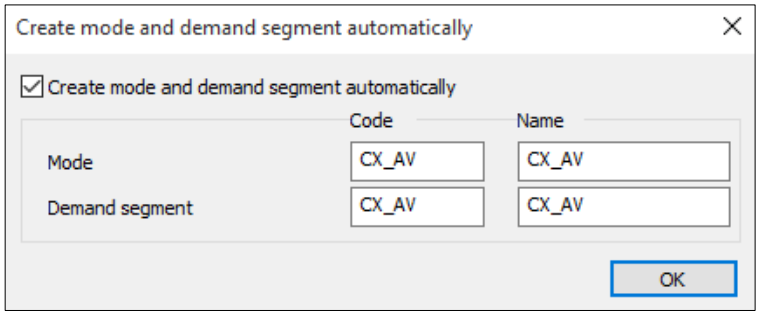

Figure 3: Create new mode and demand segment for AV

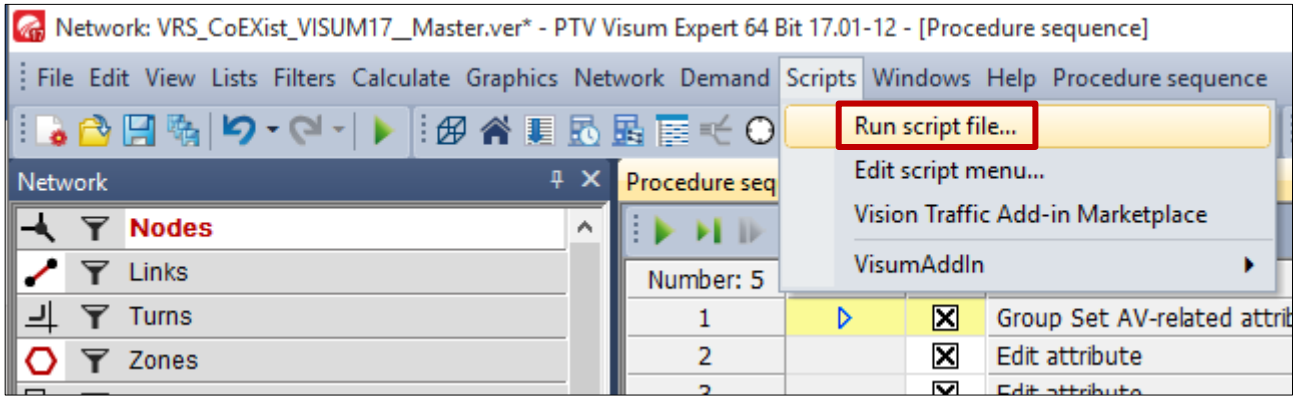

Figure 4: Run a script file in Visum

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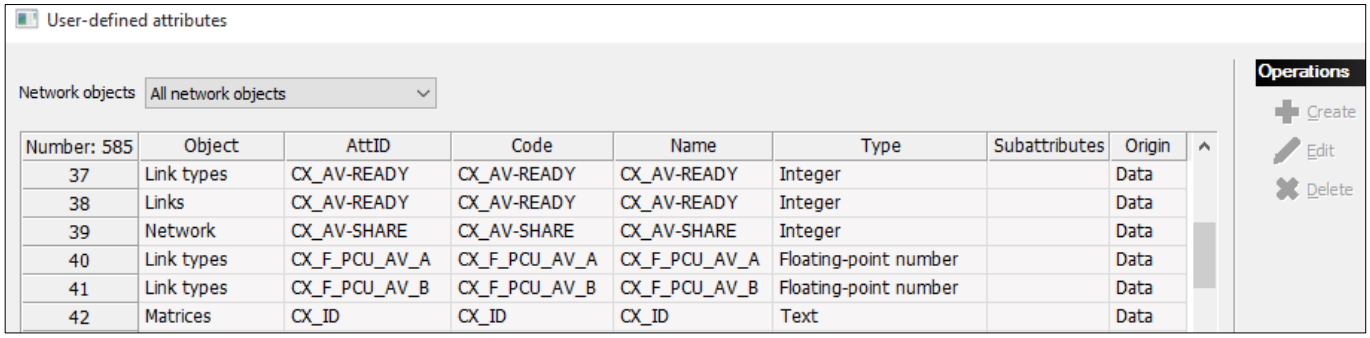
Table 1: Overview about user-defined attributes

attribute	object	input	description
CX_AV_READY	link type	by user	0: link type is not AV-ready, 1: link type is AV-ready
CX_AV_READY	link	by user	0: link is not AV-ready, 1: link is AV-ready
CX_AV-SHARE	network	by user	fixed AV share as a percentage for splitting the demand
CX_F_PCU_AV_A	link type	by user	PCU factor A for AV, which can be used stand-alone
CX_F_PCU_AV_B	link type	by user	PCU factor B for AV, which can be used additionally to factor A for a varying resulting PCU factor depending on the AV share
CX_ID	matrix	by user	CoEXist-unique identifier for working with formula matrices



Number: 585	Object	AttID	Code	Name	Type	Subattributes	Origin
37	Link types	CX_AV-READY	CX_AV-READY	CX_AV-READY	Integer		Data
38	Links	CX_AV-READY	CX_AV-READY	CX_AV-READY	Integer		Data
39	Network	CX_AV-SHARE	CX_AV-SHARE	CX_AV-SHARE	Integer		Data
40	Link types	CX_F_PCU_AV_A	CX_F_PCU_AV_A	CX_F_PCU_AV_A	Floating-point number		Data
41	Link types	CX_F_PCU_AV_B	CX_F_PCU_AV_B	CX_F_PCU_AV_B	Floating-point number		Data
42	Matrices	CX_ID	CX_ID	CX_ID	Text		Data

Figure 5: User-defined attributes for handling AV in volume-delay functions in Visum

- To make sure the script for adding formula matrices works properly, identify the demand matrix for car driver as calculated by the travel demand model and set the matrix attribute *CX_ID* to *CX_CAR_DEMAND. CX_ID* represents a unique identifier as short text for matrices altered or used for CoEXist purposes and prevents conflicts with other attributes.
- Run the script "CoEXist_Create_Formula_Matrices_-_Extension_for_handling_AV_in_volume-delay_functions.vbs" for creating formula demand matrices for CV and AV out of original demand matrix for car driver.
- As a result, there should be two new matrices. Matrix *CX_CV_DEMAND* will contain the demand of conventional vehicles, Matrix *CX_AV_DEMAND* the demand for AV. The user must define the share of the total travel demand by car drivers that is assigned to each matrix. Check the success of the script by comparing the formula matrices with Figure 6. The numbering of the matrices is not relevant for the further steps. The script uses the next numbers available. Model users may change the number after running the script.

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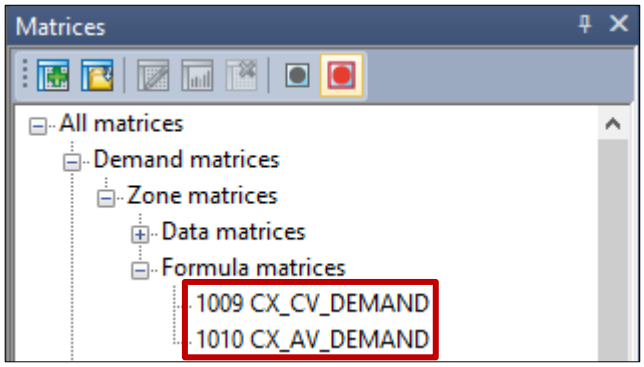
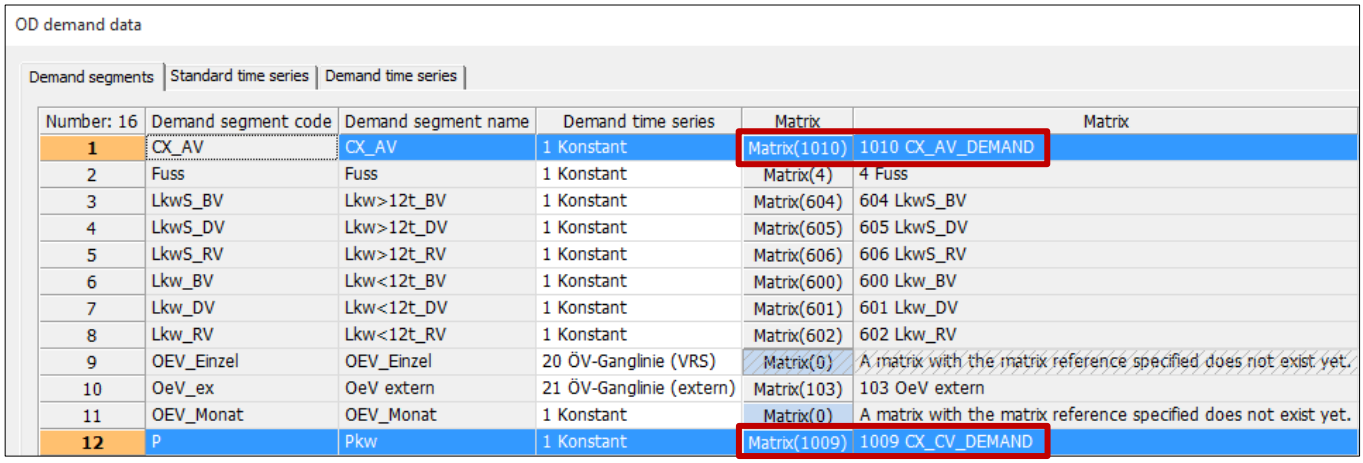


Figure 6: New formula demand matrices for CV and AV demand

- Choose these new matrices as input for the demand segments *CX_AV* and the one already in usage for CV in menu *Demand – Demand data – Demand segments* as shown in Figure 7



Number: 16	Demand segment code	Demand segment name	Demand time series	Matrix	Matrix
1	CX_AV	CX_AV	1 Konstant	Matrix(1010)	1010 CX_AV_DEMAND
2	Fuss	Fuss	1 Konstant	Matrix(4)	4 Fuss
3	LkwS_BV	Lkw>12t_BV	1 Konstant	Matrix(604)	604 LkwS_BV
4	LkwS_DV	Lkw>12t_DV	1 Konstant	Matrix(605)	605 LkwS_DV
5	LkwS_RV	Lkw>12t_RV	1 Konstant	Matrix(606)	606 LkwS_RV
6	Lkw_BV	Lkw<12t_BV	1 Konstant	Matrix(600)	600 Lkw_BV
7	Lkw_DV	Lkw<12t_DV	1 Konstant	Matrix(601)	601 Lkw_DV
8	Lkw_RV	Lkw<12t_RV	1 Konstant	Matrix(602)	602 Lkw_RV
9	OEV_Einzel	OEV_Einzel	20 ÖV-Ganglinie (VRS)	Matrix(0)	A matrix with the matrix reference specified does not exist yet.
10	OeV_ex	OeV extern	21 ÖV-Ganglinie (extern)	Matrix(103)	103 OeV extern
11	OEV_Monat	OEV_Monat	1 Konstant	Matrix(0)	A matrix with the matrix reference specified does not exist yet.
12	P	Pkw	1 Konstant	Matrix(1009)	1009 CX_CV_DEMAND

Figure 7: Select new demand matrices in OD demand data settings

- Load the procedure parameters (see Figure 8 for guidance) "CoEXist_Procedure_Parameters_-_Extension_for_handling_AV_in_volume-delay_functions.xml".

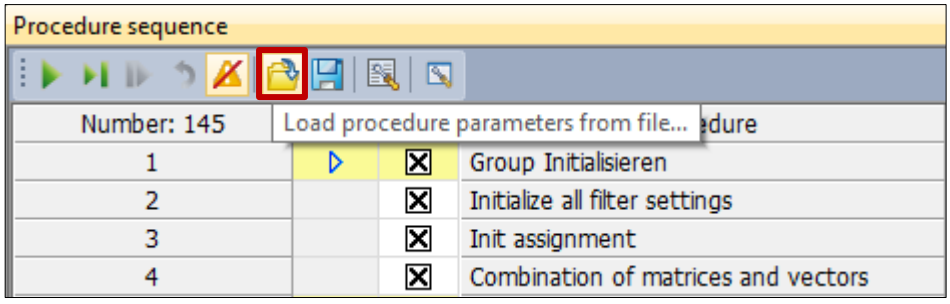


Figure 8: Load procedure parameters in Visum

- Figure 9 shows the corresponding dialogue that appears. Uncheck the box for loading *General procedure settings* and choose to insert the operations after a desired procedure step. It makes sense to place them in the beginning of the procedure sequence to be sure that the AV-related attributes are set before any skim or demand calculation.

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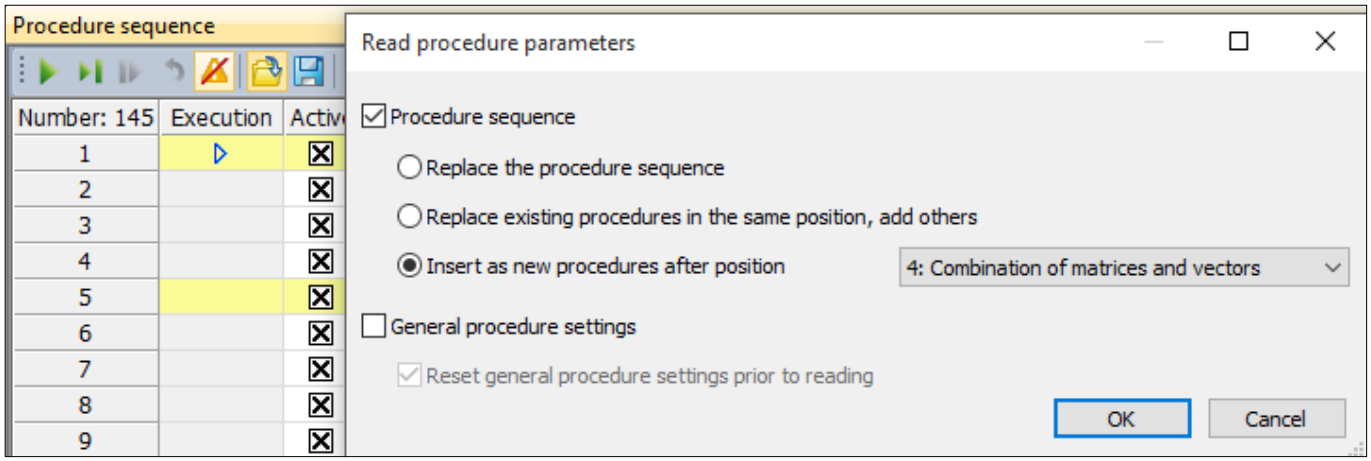

Figure 9: Dialogue for reading procedure parameters

- A procedure group consisting of five operations as shown in Figure 10 is inserted. Some of them are deactivated by default. Here, the attribute for AV-readiness is transferred from link type level. Assuming the impact of one AV to be independent of the AV share, PCU-factor A is the only one considered.

Number: 151	Execution	Active	Procedure	Reference object(s)	Variant/file	Comment
1		☒	Group Initialisieren	2 - 4		Initialisieren
2		☒	Initialize all filter settings			Filter
3		☒	Init assignment		All	Init Umlegung
4		☒	Combination of matrices and vectors	Matrix(13) := 0*1		
5		☐	Group Set AV-related attributes regarding capacit	6 - 10		Set AV-related attributes regarding capacity/performance
6		☒	Edit attribute	Network - CX_AV-SHARE		User input: AV share [percentage]
7		☒	Edit attribute	Links - AddVal1		Transfer AV-readiness [0/1] from link type level to uval1
8		☐	Edit attribute	Links - AddVal1		Transfer AV-readiness [0/1] from link level to uval1
9		☒	Edit attribute	Links - AddVal2		Transfer PCU-factor A for AV from link type level to uval2
10		☐	Edit attribute	Links - AddVal3		Transfer PCU-factor B for AV from link type level to uval3

Figure 10: Added group of operations in procedure sequence

- Table 2 shows which user-defined attributes correspond to the attributes accessed by the VDF and the variables introduced in the approach in Chapter 2.2.

Table 2: Variables used in approach and corresponding attributes in Visum

variable in approach	user-defined attribute	attribute accessed by VDF	network element level
- not used -	*CX_AV_READY*	AddVal1	link type **or** link
$f_{s,i=AV}^{PCU,Min}$	*CX_F_PCU_AV_A*	AddVal2	link type
$f_{s,i=AV}^{PCU,Max}$	*CX_F_PCU_AV_B*	AddVal3	link type

- There are default values set for the new attributes on link type level as shown in Figure 11. The user needs to decide which link types or links should be AV-ready. Set *CX_AV-READY* = 1, if a link type is AV-ready, i.e. AV show a different performance than CV. Additionally, the relevant PCU-factors need to be set for the AV-ready link types. PCU-factors for link types that are not AV-ready (*CX_AV-READY* = 0) do not have any effect on traffic performance.

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List (Link types)

Select list layout...

Number: 100	No	Name	Strict	Rank	TSysSet	NumLanes	CapPrT	CX_AV-READY	CX_F_PCU_AV_A	CX_F_PCU_AV_B
1	0	gesperrt	☐	99	...	0	0	0	1.00	1.00
2	1	Fußweg (Staffel)	☐	99	F,Fuss	0	9999	0	1.00	1.00
3	2	Fußweg (Rad möglich)	☐	98	F,Fuss,Rad	1	9999	0	1.00	1.00
4	3	Fußgängerzone	☐	99	B,F,Fuss,LkwS_BV,LkwS_DV,LkwS_RV,Lkw_BV,Lkw_DV,Lkw_RV,P,Ra	1	1500	0	1.00	1.00
5	4	Rad-/Forstweg	☐	98	F,Fuss,Rad	1	9999	0	1.00	1.00
6	5	ÖV Umsteigefußwege	☐	99	F	0	0	0	1.00	1.00
7	6	1_4_120_95	☐	11	LkwS_BV,LkwS_DV,LkwS_RV,Lkw_BV,Lkw_DV,Lkw_RV,NVBW,P	4	95000	0	1.00	1.00
8	7	1_3_120_89_SBA	☐	13	B,LkwS_BV,LkwS_DV,LkwS_RV,Lkw_BV,Lkw_DV,Lkw_RV,NVBW,P	3	89250	0	1.00	1.00
9	8	1_3_120_63_SBA	☐	13	LkwS_BV,LkwS_DV,LkwS_RV,Lkw_BV,Lkw_DV,Lkw_RV,NVBW,P	3	63000	0	1.00	1.00
10	9	1_3_120_70_SBA_SSF	☐	13	LkwS_BV,LkwS_DV,LkwS_RV,Lkw_BV,Lkw_DV,Lkw_RV,NVBW,P	3	70000	0	1.00	1.00

Figure 11: Link type list with new user-defined attributes

- If the AV-readiness is based on links instead of link types, the attribute *CX_AV-READY* on link type level is irrelevant. The user then needs to define *CX_AV-READY* on link level, but still the PCU-factors must be set on link type level. Furthermore, the procedures concerned must be activated or deactivated respectively: this means the user must activate either procedure 7 or 8 in the procedure sequence shown in Figure 10. Both operations transfer the values of *CX_AV-READY* to *AddVal1*.
- Place the DLL and corresponding BMP files for all volume-delay functions that should be considered under the directory
  "C:\User\...\AppData\Roaming\PTV Vision\PTV Visum 17\UserVDF-DLLs\".
- If the Visum application is still running, please save the current version file, close and restart the application. Otherwise the functions will not be detected and available for usage in Visum.
- Most settings related to VDF can be found under
  Calculate – General procedure settings – PrT settings – Volume-delay functions (see Figure 12).
- It is recommended not to alter the present functions, but to create new ones with the user-defined VDF types. The table *Link types* must also be adjusted accordingly.
- The following VDF are included in D2.7 and should be available to select, if placed under the proper directory:
  - VisumVDF_CX_AV_PCU_CONST_BPR_x64.dll
  - VisumVDF_CX_AV_PCU_CONST_LOHSE_x64.dll
  - VisumVDF_CX_AV_PCU_VAR_BPR_x64.dll
  - VisumVDF_CX_AV_PCU_VAR_LOHSE_x64.dll

File Edit View Lists Filters Calculate Graphics Network Demand Scripts Windows Help List (Link types)

General procedure settings

Network

Nodes
Links
Turns
Zones
Connectors
Main nodes

PrT settings
Volume-delay functions
Impedance
Assignment
Skims
Node impedances
Signal cycle and split optimization
P+R volume-delay function
Blocking back model

PrT settings - Volume-delay functions

Link types

	*0	*1	*2	*3	*4	*5	*6	*7	*8	*9
0*	1	1	1	1	1	1	1	1	1	1
1*	1	1	1	1	1	1	1	1	1	1
2*	9	9	9	9	9	10	10	2	2	3

Volume-delay functions

No	Function
1	LOHSE (0.80 3.00 1.00 1.00)
2	LOHSE (1.20 4.00 1.00 1.00)
3	LOHSE (1.15 3.00 1.00 1.00)
4	LOHSE (1.15 4.00 1.00 1.00)

Figure 12: Settings for volume-delay functions in the general procedure settings

- The basic characteristics of the provided VDF types are listed in Table 3 below.

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Table 3: Overview on user-defined VDF types provided in D2.7

VDF type – DLL	basic type	impact of one AV
VisumVDF_CX_AV_PCU_CONST_BPR_x64	BPR	constant, fixed PCU
VisumVDF_CX_AV_PCU_CONST_LOHSE_x64	LOHSE	constant, fixed PCU
VisumVDF_CX_AV_PCU_VAR_BPR_x64	BPR	variable, PCU depending on AV-share
VisumVDF_CX_AV_PCU_VAR_LOHSE_x64	LOHSE	variable, PCU depending on AV-share

- Please note that these function types are tailored for the transport systems of the Stuttgart Region travel demand model, i.e. the code for the transport system car is *P* and additional six HDV transport systems are considered within the calculation. Models with different codes for transport systems need a VDF that takes these into account. Guidance for creating or editing function types can be found under Chapter 8.1 in the appendix.
- After selecting a function type, the user must set parameters. Any representation of a user-defined function should clearly show which parameters are taken into account for calculations Figure 13 shows a function type which includes the parameters *a*, *b* and *c*. Please note that in the expression for saturation, the German terms for Car (*Pkw*) and HDV (*Lkw*) are used.
- When selecting any user-defined VDF, all parameters are displayed as available, independent of a possible incorporation in the calculation rule. Altering the parameters not used in the function type does not affect any results.
- The equation regarding the saturation shown in the ‘Function’-Box at the bottom is fixed and cannot be removed.
- Add the transport system *CX_AV* to all PrT Assignment operations in the procedure sequence. Do not consider the mode *CX_AV* for travel demand calculation or mode choice. The demand for AV is generated out of the demand for ‘Car driver’ as before.
- Since the AV-related attributes are transferred to *AddVal1/AddVal2/AddVal3*, do not forget to check whether these are used for any other purposes. If this is the case, shift them to new user-defined attributes.
- Start the procedure sequence and run all active operations.

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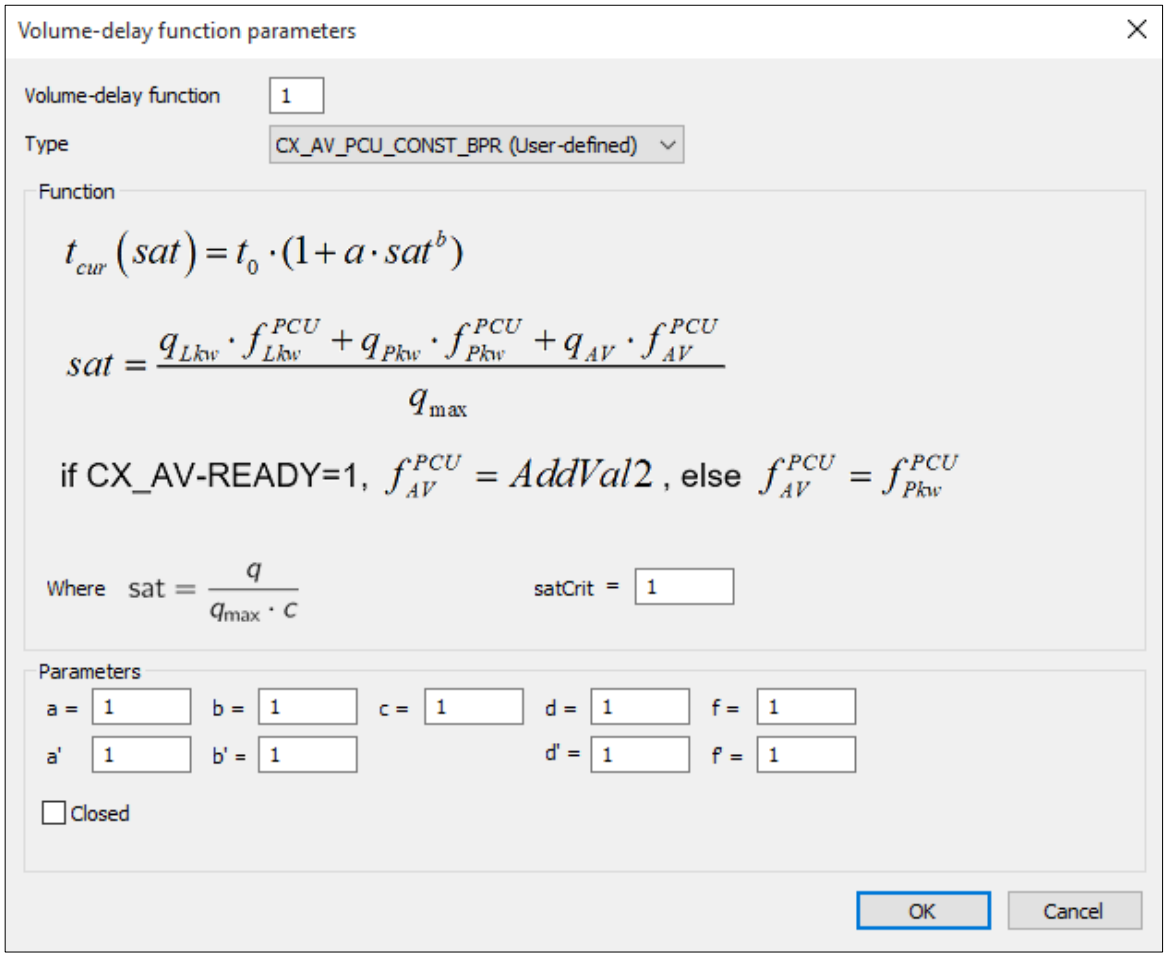

Figure 13: Type, representation of calculation rule and parameters for selected volume-delay function

- Afterwards, check if the expected changes have occurred. For this purpose, there is an Excel template that might be helpful. It is provided by PTV included in the Visum installation located under the directory
  "C:\Program Files\PTV Vision\PTV Visum 17\Doc\Eng\VolumeDelay_functions.xlsx"
  and includes calculations and charts for several VDF types, where the user can set the parameters as desired to easily compare current travel times.

2.3.2 Visum 2020

It is recommended to carry out the instructions in the suggested order as the tools partly depend on each other. Any other sequence or modifications of names can cause errors in the modelling process or require additional effort from the model user.

- Go to menu *Demand – TSys/Modes/DSeg* and create a transport system for AV *CX_AV* as shown.
- Transfer the network attributes like speed and authorization for using links etc. from conventional cars to AV.
- Do not alter the value for PCU of 1.00, this will be done in another way and only for AV-ready links, by default it should be the same as for CV.
- Create a mode and a demand segment with the same name automatically.

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- Run the script for creating user-defined attributes "CoEXist_Create_User-Defined_Attributes_-_Extension_for_handling_AV_in_volume-delay_functions_Visum2020.vbs".
- The script will add five attributes. Check if they have been added by opening the list of user-defined attributes (*Network – User-defined attributes*) and comparing to the attributes listed in Table 4.

Table 4: Overview about user-defined attributes

attribute	object	input	description
CX_AV_READY	link	by user	0: link is not AV-ready, 1: link is AV-ready
CX_F_PCU_AV_1	link	by user	PCU factor 1 for AV, which can be used stand-alone
CX_F_PCU_AV_0	link	by user	PCU factor 0 for AV, which can be used additionally to factor 1 for a varying resulting PCU factor depending on the AV share
CX_AV-SHARE	network	by user	fixed AV share as a percentage for splitting the demand
CX_ID	matrix	by user	CoEXist-unique identifier for working with formula matrices

- User-defined Volume-delay functions (VDF) provided in D2.7 assuming a constant PCU factor for each AV ("VisumVDF_CX_AV_PCU_CONST_..._2020_x64.dll") use *CX_F_PCU_AV_1* and VDF assuming a share-dependent PCU factor ("VisumVDF_CX_AV_PCU_VAR_..._2020_x64.dll ") make usage of both PCU attributes. Then, *CX_F_PCU_AV_1* corresponds to the PCU value of each AV for 100% AV share and *CX_F_PCU_AV_0* accordingly to the PCU value for 0% AV. In between the used PCU factor follows a linear course according to the AV share.
- There are default values set for the new attributes on link type level. The user needs to decide which links should be AV-ready. Set *CX_AV-READY* = 1, if a link is AV-ready, i.e. AV show a different performance than CV. Additionally, the relevant PCU-factors need to be set for the AV-ready links. PCU-factors for links that are not AV-ready (*CX_AV-READY* = 0) do not have any effect on traffic performance as those are not considered by the VDF.
- To make sure the script for adding formula matrices works properly, identify the demand matrix for car driver as calculated by the travel demand model and set the matrix attribute *CX_ID* to *CX_CAR_DEMAND. CX_ID* represents a unique identifier as short text for matrices altered or used for CoEXist purposes and prevents conflicts with other attributes.
- Run the script "CoEXist_Create_Formula_Matrices_-_Extension_for_handling_AV_in_volume-delay_functions_Visum2020.vbs" for creating formula demand matrices for CV and AV out of original demand matrix for car driver.
- As a result, there should be two new matrices. Matrix *CX_CV_DEMAND* will contain the demand of conventional vehicles, Matrix *CX_AV_DEMAND* the demand for AV. The user must define the share of the total travel demand by car drivers that is assigned to each matrix. The numbering of the matrices is not relevant for the further steps. The script uses the next numbers available. Model users are free to change the number after running the script.
- Choose these new matrices as input for the demand segments *CX_AV* and the one already in usage for CV in menu *Demand – Demand data – Demand segments.*

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- Load the procedure parameters "CoEXist_Procedure_Parameters_-_Extension_for_handling_AV_in_volume-delay_functions_Visum2020.xml".
- A corresponding dialogue appears: Uncheck the box for loading *General procedure settings* and choose to insert the operations after a desired procedure step. It makes sense to place them in the beginning of the procedure sequence to be sure that the AV-related attributes are set before any skim or demand calculation.
- A procedure group consisting of one operation is inserted. With the operation on editing a network attribute, the AV share is set. Unlike with Visum 18 or older software versions, it is no longer necessary to transfer the attribute information on AV-readiness or PCU values to *AddVal*s because the VDF is able to access these attributes now directly on link level.
- Place the DLL and corresponding BMP files for all volume-delay functions that should be considered under the directory "C:\User\...\AppData\Roaming\PTV Vision\PTV Visum 2020\UserVDF-DLLs\".
- If the Visum application is still running, please save the current version file, close and restart the application. Otherwise the functions will not be detected and available for usage in Visum.
- Most settings related to VDF can be found under *Calculate – General procedure settings – PrT settings – Volume-delay functions*.
- It is recommended not to alter the present functions, but to create new ones with the user-defined VDF types. The table *Link types* must also be adjusted accordingly.
- The following VDF are also included in the revised D2.7 and should be available to select, if placed under the proper directory:
    - VisumVDF_CX_AV_PCU_CONST_BPR_2020_x64.dll
    - VisumVDF_CX_AV_PCU_CONST_LOHSE_2020_x64.dll
    - VisumVDF_CX_AV_PCU_VAR_BPR_2020_x64.dll
    - VisumVDF_CX_AV_PCU_VAR_LOHSE_2020_x64.dll
- The basic characteristics of the provided VDF types correspond to those shown in Table 3.
- Please note that these function types are tailored for the transport systems of the Stuttgart Region travel demand model, i.e. the code for the transport system car is *P* and additional six HDV transport systems are considered within the calculation. Models with different codes for transport systems need a VDF that takes these into account. Guidance for creating or editing function types can be found under Chapter 8.1 in the appendix.
- After selecting a function type, the user must set parameters. Any visual representation of a user-defined function should clearly show which parameters are taken into account for calculations. For the VDF provided, the parameters *a*, *b*, *c* and *satcrit* are used as in usual BPR or LOHSE functions.
- When selecting any user-defined VDF, all parameters are displayed as available, independent of a possible incorporation in the calculation rule. Altering the parameters not used in the function type does not affect any results.
- The equation regarding the saturation shown in the 'Function'-Box at the bottom is fixed and cannot be removed.
- Add the transport system *CX_AV* to all PrT Assignment operations in the procedure sequence. Do not consider the mode *CX_AV* for travel demand calculation or mode choice. The demand for AV is generated out of the demand for 'Car driver' as before.
- Start the procedure sequence and run all active operations.

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- Afterwards, check if the expected changes have occurred. For this purpose, there is an Excel template that might be helpful. It is provided by PTV included in the Visum installation located under the directory
  "C:\Program Files\PTV Vision\PTV Visum 2020\Doc\Eng\VolumeDelay_functions.xlsx"
  and includes calculations and charts for several VDF types, where the user can set the parameters as desired to easily compare current travel times.

2.4 Recommendations

The following list of recommendations for applied settings for user-defined VDF incorporating the impact of AV on network performance as described in the previous chapters represents the current state of the art and should not be considered as immutable:

- Do not alter values for capacity, since these are justifiably set and the model was calibrated and validated with these capacities.
- The basic type of the VDF should remain as it is (BPR, LOHSE, etc.) for each link type.
- Providing exemplary user-defined VDF types including BPR or LOHSE does not imply that these are recommended by USTUTT in any sense.
- Adopt the same values for related parameters (a, b, c, satCrit, etc.) for VDF types additionally considering AV of those that considered CV only before.

Example:

- VDF with the number 4 was a common BPR type with the parameters a=2, b=3, c=1 used for link types 10-29.
- Create a new VDF which takes AV into account with the basic type of BPR and the same parameter values a=2, b=3, c=1. Assign the number of this new VDF to the link types 10-29.
- To keep a good orderliness, choose a number for each new VDF consequently for all VDF that should be replaced, e.g. current VDF numbers 1, 2, 3 and 4 → new numbers 11, 12, 13 and 14.

Instructions, hints and troubleshooting for creating user-defined VDF can be found in Chapter 8.1 in the appendix.

Table 5 shows the derived PCU factors for the driving logics cautions, normal and all-knowing. Those represent the respective AV capabilities. The values are extracted from estimated capacities of microscopic traffic flow simulations conducted by PTV. More information is available in the report on Milestone 16 that is included in the Appendix of Deliverable 2.7.

Table 5: PCU factors for three types of AV driving behaviour depending on the roadway

Roadway	Cautious	Normal	All-knowing
Motorway	1.20	0.77	0.73
Arterial	1.26	0.81	0.76
Urban street	1.32	0.85	0.79

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Table 6 shows which driving behavior is used by each AV class on the different roadway types. Combining Table 5 and Table 6 results in Table 7, showing the PCU values for each AV class and roadway. It is expected that a vehicle of the first generation of AV (Basic AV) will be able to handle situations on motorways and on arterials on its own with high caution, while on urban streets it is still necessary to drive manually. That is the reason why the PCU of a Basic AV on urban streets corresponds to 1.0, the default PCU for conventional vehicles. For Intermediate AV the capability to operate in automated mode will be extended to urban road environments. Additionally, the included highway pilot doesn't need a driver as a fall back on motorways anymore. Finally, the Advanced AV is capable to handle driving in all three road environments on its own, yet it is still not able to manage all situations under all circumstances, which is why it is not a driverless vehicle.

Table 6: AV driving behaviours depending for each AV class and roadway type

Roadway	Basic AV	Intermediate AV	Advanced AV
Motorway	Cautious	Normal	All-knowing
Arterial	Cautious	Normal	All-knowing
Urban street	Manual	Cautious	Normal

Table 7: Resulting PCU factors for three types of AV for three types of roadway

Roadway	Basic AV	Intermediate AV	Advanced AV
Motorway	1.20	0.77	0.73
Arterial	1.26	0.81	0.76
Urban street	1.00	1.32	0.85

It needs to be stressed that the values in Table 7 only hold if the respective roadway types are considered to be automation-ready. If the model user wants to model impacts of AV for the assumption that these can only drive automated on motorways and motorway-similar roads, the PCU factors for the other roadway types need to correspond to 1.0.

More information on the definitions for the AV types is available in Deliverable 1.4.

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3 Perception of automated travel time

3.1 Purpose

Automated travel time corresponds to the time during which the vehicle takes control of the driving task. Car drivers in a CAV of level 3 and higher may use some of their driving time for non-driving activities. This may decrease the perceived travel time of a car trip and improve the benefits of car usage leading to changes in route choice, mode choice and destination choice. This section explains how the impacts of CAV on perceived travel time can be modelled in a macroscopic travel demand model.

3.2 Approach

The approach consists of two parts. The first deals with the idea on how the perceived travel times of CV and AV are merged in theory. The second part presents a way to implement the methodology into a travel demand model using formula matrices. The prefix *CX* is introduced to identify all attributes, matrices, network elements or anything else to be part of CoEXist-specific methods within Visum.

Travel demand models replicate the decision making process of individual travellers concerning the choice of destination, mode and route. In each choice situation travellers select from a set of choices. A utility function describes the utility of each choice considering the characteristics of the trip maker (user group) and the trip purpose (activity). These functions consider various time components (access, egress, driving, waiting, parking search), cost and travel comfort. Each component is weighted with a specific factor. For current transport modes, these factors can be estimated by mobility surveys. For choices with AV, the functions as well as the choice set need to be adjusted in a suitable way.

At the levels 3 and 4 AV still require a driver as fallback. Consequently, the set of choices remains more or less similar to the situation without AV. However, the attributes of a choice change for the mode car-driver. The value of time experienced in an AV differs from the value of time spent in a CV, because the driver can spend some time of the trip duration on other tasks than driving. If AV of level 3 and 4 can only drive automatically on certain road types or on certified network sections, they probably have an impact on route choice as well as mode choice. Such a behaviour can be integrated in existing travel demand models by adding an additional transport system AV with a specific utility function for route choice.

This specific utility function resembles already existing functions for CV but is supplemented by another factor $\beta_s^{t,AV} \leq 1$, which reduces the perception of travel time in an AV. Due to the fact that automated driving is only possible on certain parts of the road network, the factor needs to dependent on the road segment *s* used by the AV. For road segments that allow automated driving $\beta_s^{t,AV}$ represents the reduced perception of time spent in an AV, whereas for road segments that do not provide the necessary design standard there will be no reduced value of time for AV and therefore $\beta_s^{t,AV}$ is set to one. Equations (7) and (8) show how a weighted travel time v_{odr}^t can be computed for CV and AV using the factor $\beta_s^{t,AV}$.

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$$v_{odr}^{t,CV} = \beta^t \cdot t_{odr}^{CV} \quad (7)$$

$$v_{odr}^{t,AV} = \sum_{s \in r} \beta_s^{t,AV} \cdot \beta^t \cdot t_{odrs}^{AV} \quad (8)$$

where

$v_{odr}^{t,CV}$, $v_{odr}^{t,AV}$	weighted travel time value for CV and AV for the route r from origin *o* to destination *d* [-]
β^t	factor for travel time perception [1/s]
$\beta_s^{t,AV}$	factor for travel time perception in an AV on supply element *s* [1/s]
t_{odr}^{CV}	travel time with a CV for the route *r* from origin *o* to destination *d* [s]
t_{odrs}^{AV}	travel time with an AV on supply element *s* as element of the route *r* from *o* to *d* [s]

As an input for travel time values and comfort of AV, one can think of using the values for high-speed trains or survey based values. A study of de Looff et al. (2017), for example, focuses on the impacts of AV on the value of travel time for commuting trips in the Netherlands. As a result for an AV with an office interior they find a lower value (4.99 €/h) than for the conventional car (7.99 €/h). As indicated by Trommer et al. (2016), the perception of time spent in AV may vary for different user groups and activities. Additionally, reduced travel times from higher capacities and a reduced amount of time for parking because of valet parking options for AV should be considered in the utility functions.

Integrating AV into an existing travel demand model can be achieved by replacing the travel time matrix of CV by a travel time matrix $V^{t,Car}$ which is derived from the weighted travel time matrix of AV and CV. As presented in Figure 14 and in equation (9) the aggregated weighted travel time for mode car driver is derived by weighting the transport system-specific times with the share of AV in the car fleet p_{AV} . This share is an input value defined by the model user. Assuming that time usage depends on the duration of the fully automated section a certain threshold value t^{ε} (e.g. 10 minutes) can be set by the model user.

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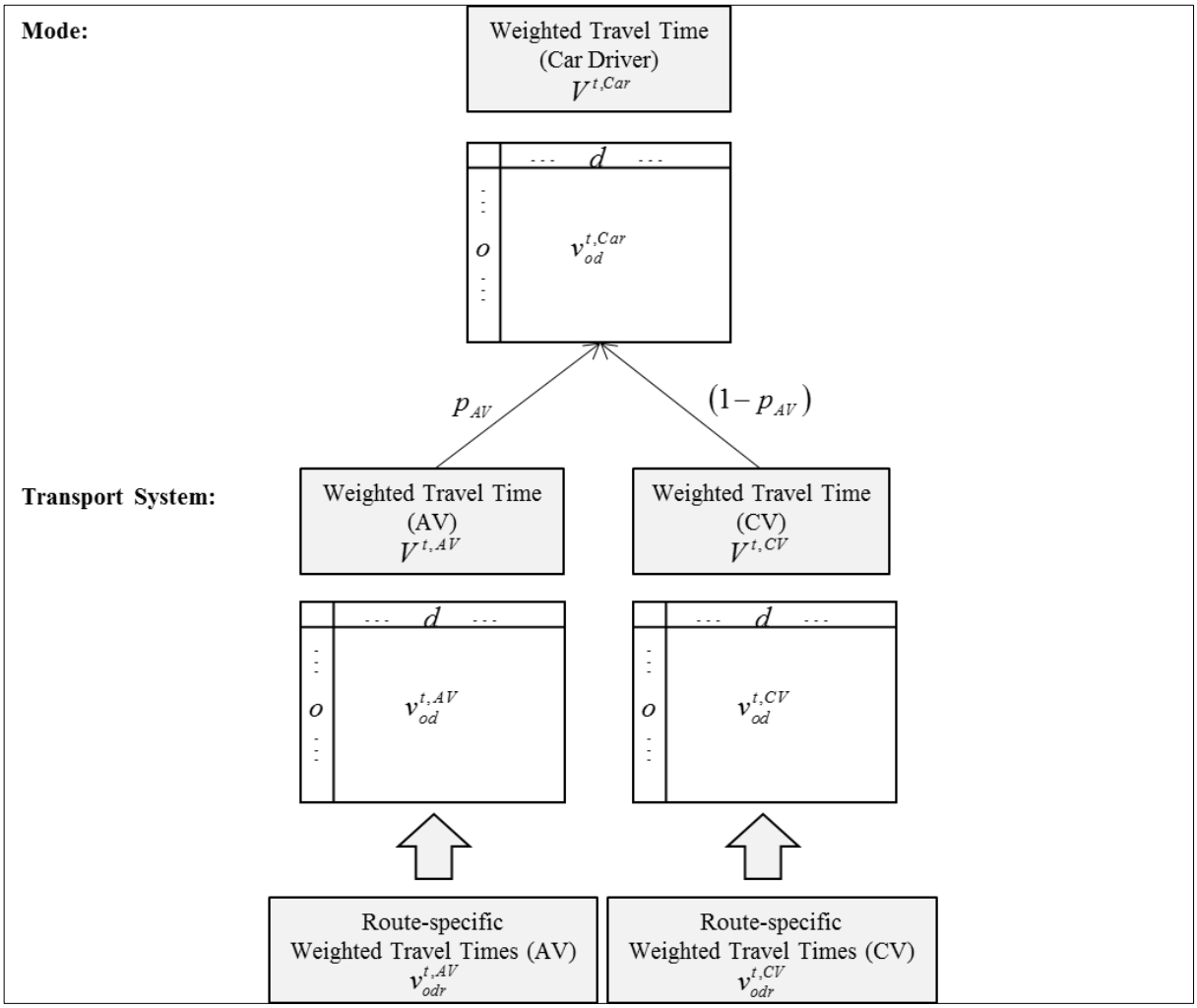

Figure 14: Derivation of the weighted travel time for the mode car driver from the transport systems AV and CV

$$v_{od}^{t,Car} = \begin{cases} \left(1-p_{AV}\right)\cdot v_{od}^{t,CV} + p_{AV}\cdot v_{od}^{t,AV} & \text{, if } t_{od}^{AV,automated} \geq t^{\varepsilon} \\ v_{od}^{t,CV} & \text{, if } t_{od}^{AV,automated} < t^{\varepsilon} \end{cases} \quad (9)$$

where

$v_{od}^{t,Car}$	weighted travel time value for the mode car driver from origin *o* to destination *d* [-]
p_{AV}	share of AV in the car fleet [-]
$v_{od}^{t,CV}$, $v_{od}^{t,AV}$	weighted travel time of CV and AV respectively from origin *o* to destination *d* [-]
$t_{od}^{AV,automated}$	part of the travel time of AV driven in automated mode on an OD-pair [min]
t^{ε}	threshold travel time to perceive an advantage for driving in automated mode [min]

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How to compute and consider the perceived automated travel time in practice?

The basic assumption for the following approach is that the transport systems (traditional) 'Car', consequently referred to as 'CV', and 'AV' are treated as part of the mode and demand segment 'Car driver'. Characteristics of trips made with one or the other both have to be taken into account for the attractiveness of the mode. To get a new skim matrix for the demand segment 'Car driver', three parts have to be considered:

- 'Normally' perceived travel time for all roads (CV)
- 'Normally' perceived travel time for roads that are not AV-ready (AV)
- Automated travel time perceived differently on AV-ready roads (AV).

Figure 15 shows how the methodology is implemented in Visum on a simplified level. Two outputs from the skim calculation of private transport are used for the further procedure: the current travel time for CV (*CV_TTC_CAR*) and the sum of the AV-ready travel time (*CX_TTC_AV-READY*). The skim matrices include aggregated values on OD-pair level according to the settings for the skim calculation, e.g. weighting of paths: "mean over path volume". The difference of the two matrices is the travel time of vehicles on roads that are not AV-ready (*CX_TTC_NOT_AV-READY*).

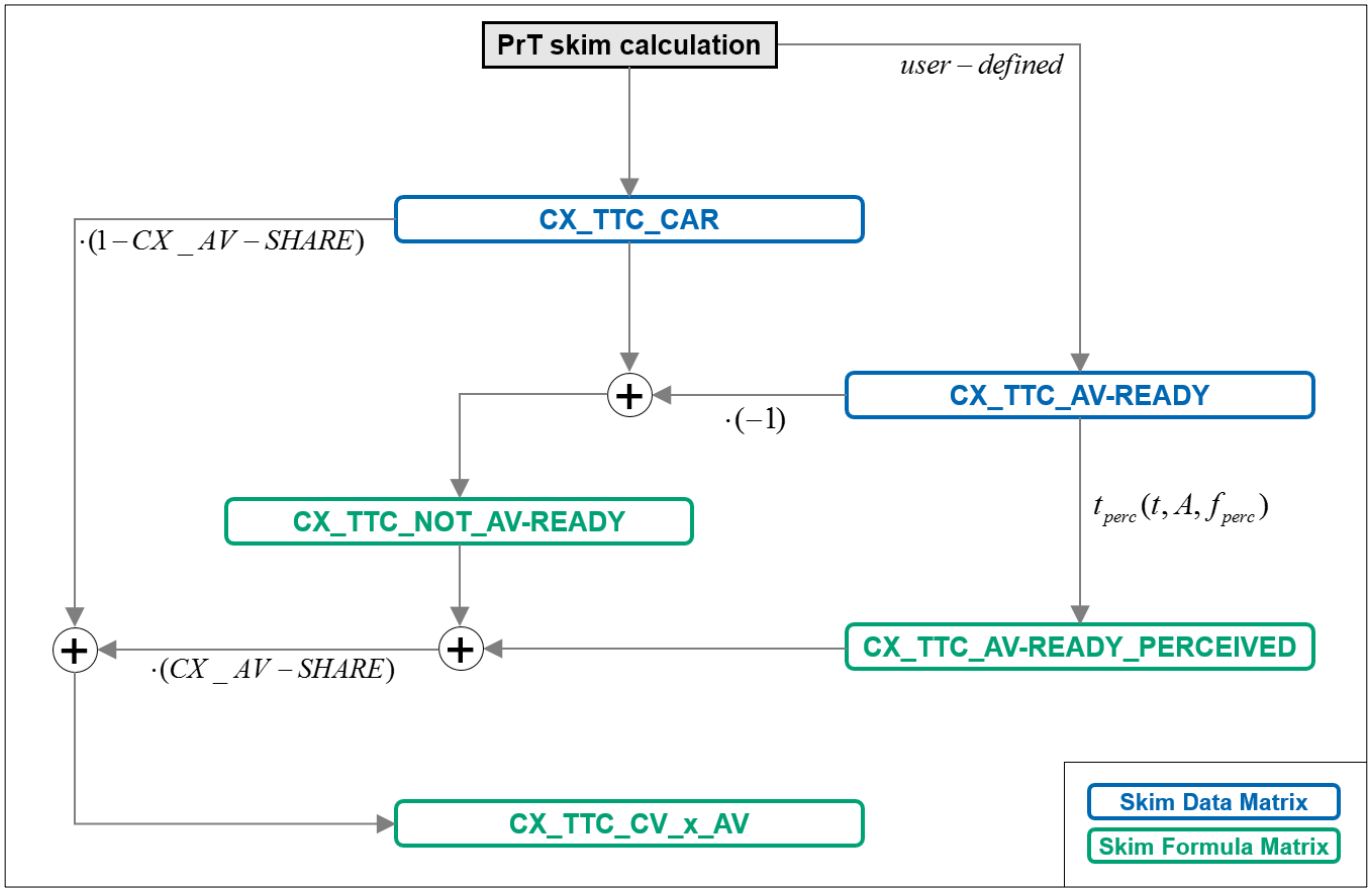

Figure 15: Approach for handling perceived automated travel time in Visum with formula matrices

The AV-ready travel time is then converted to the perceived automated travel time according to the calculation rule shown in equation (10). The modeller must decide about reasonable values for two parameters:

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- The 'ramp-up time' A, for which no reduction of the perceived time is assumed
- The factor f_{perc} that converts the travel time exceeding A to a perceived time by reducing it.

The result of this conversion is the matrix *CX_TTC_AV-READY_PERCEIVED*.

$$t_{perc} = f \cdot t + c = \begin{cases} t & , t \le A,\ f = 1,\ c = 0 \\ f_{perc} \cdot (t - A) + A & , t > A,\ f = f_{perc},\ c = A - f_{perc} \cdot A \end{cases} \quad (10)$$

where

t_{perc}	perceived automated travel time between two zones
t	aggregated automated travel time between two zones
f	multiplicative factor
c	additive factor
A	threshold A for in-vehicle time perception [min]
f_{perc}	factor for perception of automated travel time

Figure 16 shows that the factor multiplied with travel time is kept to 1 until the threshold A is reached.

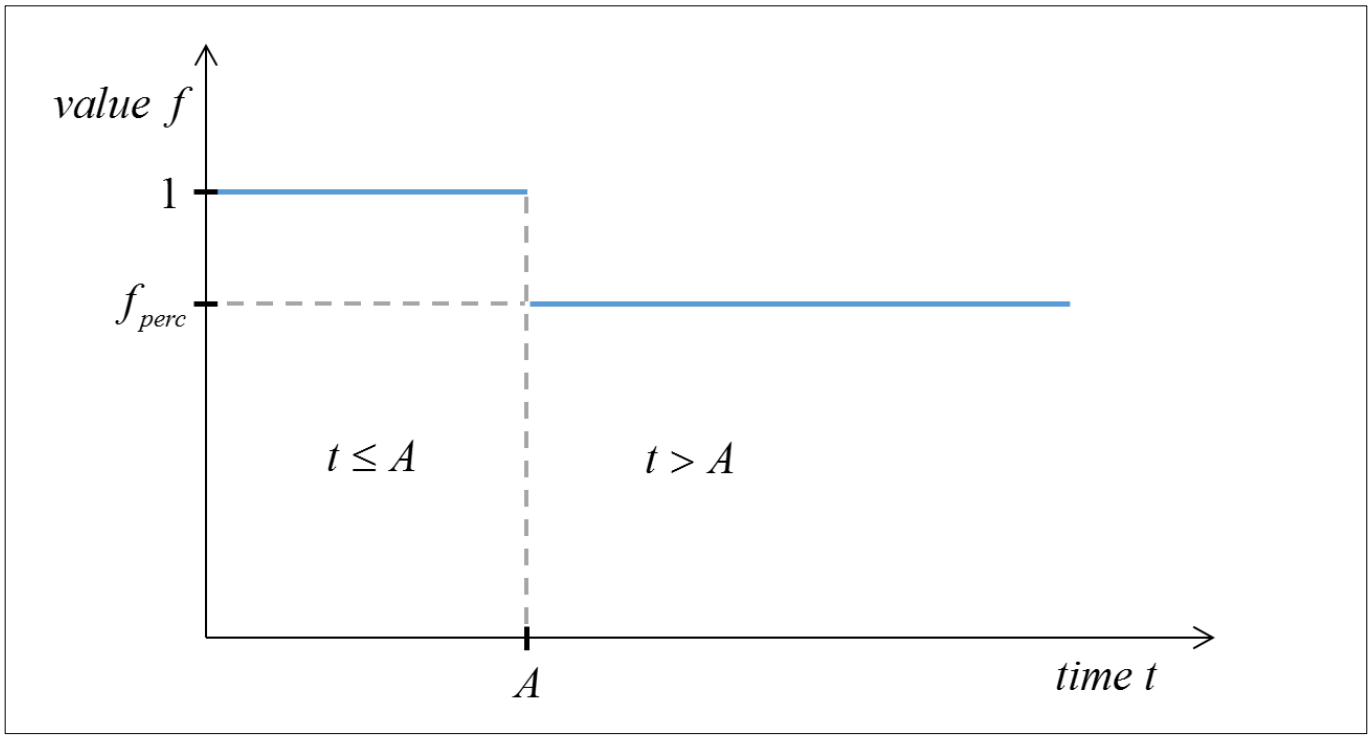

Figure 16: Course of the multiplicative perception factor for increasing travel time

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The resulting course for the perceived travel time is represented in Figure 17. Obviously, the gradient significantly changes at time A. The effect of the factor f_{perc} solely on the duration in addition to A guarantees no jump discontinuity regarding the course of perceived travel time.

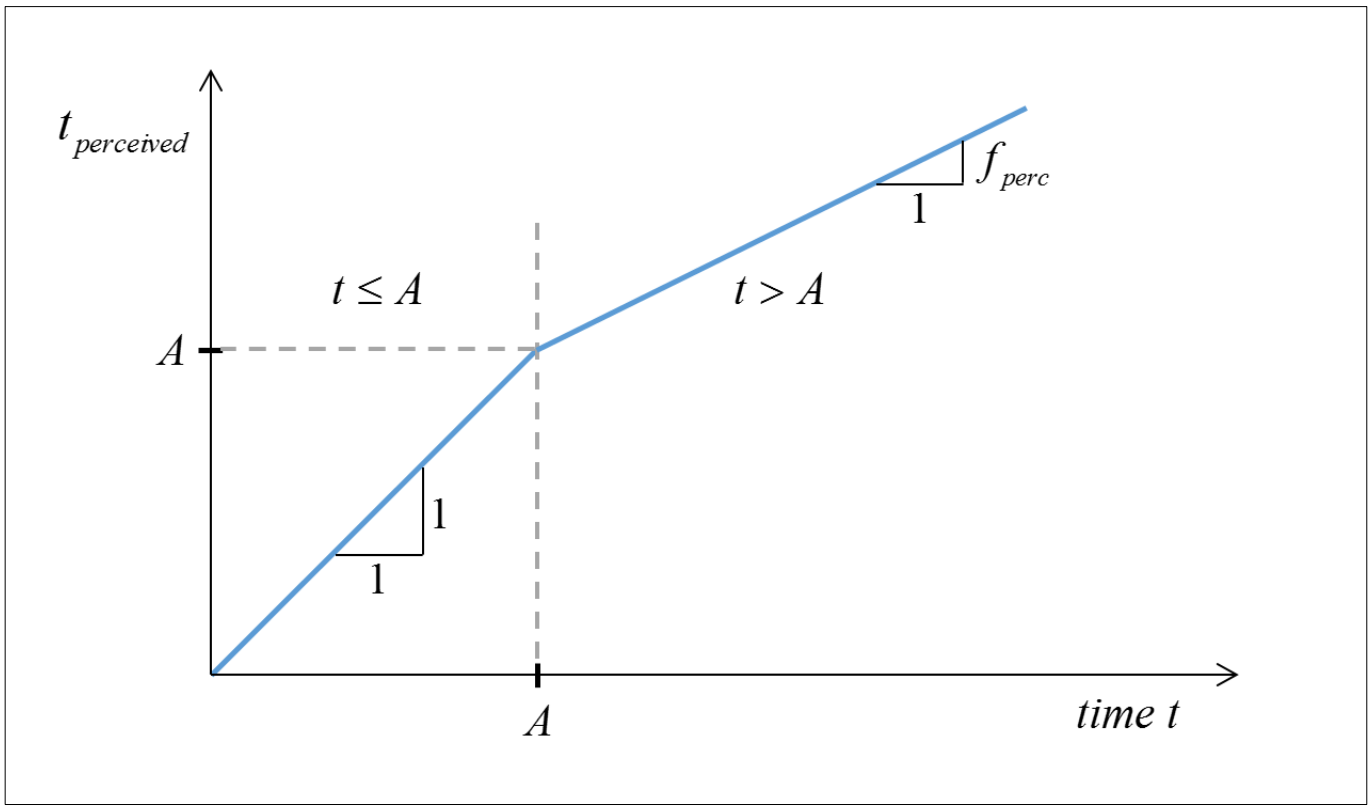

Figure 17: Perceived time in the course of increasing travel time

Merging the sum of the perceived AV-ready travel times and the not AV-ready travel times with the original travel time matrix weighted by the global AV-share *CX_AV-SHARE* results in the matrix *CX_TTC_CV_x_AV*. In the end, this matrix should be fed into trip distribution and mode choice.

Table 8 indicates the correlation between the relevant variables presented in the equation (10) and the user-defined attributes in Visum. Inserting attributes and matrices for this approach is covered in the following chapter.

Table 8: Variables used in approach and corresponding attributes in Visum

variable in approach	user-defined attribute	network element level
A	*CX_THRESHOLD_IVT_PERCEPTION_A*	network
f_{perc}	*CX_IVT-PERCEPTION_FACTOR*	network

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3.3 Instructions

This chapter comprises instructions and remarks for applying the tools provided for integrating differences regarding the perception of travel time in conventional and automated vehicles in Visum travel demand models. Some steps include the use of scripts which are available as code in deliverable D2.7, but it is also possible for the model user to do everything manually. In principle, almost everything can be done by scripts, but these depend in detail on model properties and would always have to be rewritten by other users, so the authors refrain from doing everything possible by scripts within this guide.

Prerequisites

- Travel demand model in Visum with PrT assignment and skim matrix calculation including travel time for demand segment 'Car driver' in a loop within the procedure sequence before trip distribution and mode choice are calculated.
- There is no specific requirement regarding the Visum version. The screenshots are taken out of Visum 17, but the approach was also successfully tested with older and newer software versions.

Disclaimer: This document has been updated to provide guidance for Visum 2020 users as well. Therefore, instructions are available separately for Visum 2020 in chapter 3.3.2. Besides some changes in scripts that are necessary due to structural changes of the software, some other steps have been revised compared to the counterpart of older Visum software versions in chapter 3.3.1. Based on the experience of the last two years in modeling AV, the updated instructions for Visum 2020 represent the approach that the authors would currently recommend.

3.3.1 Visum 18 or lower

It is recommended to comply the instructions in the following order. The tools are partly based on each other. Any other sequence or differing names can cause errors or additional subsequent effort for the model user.

- Go to menu *Demand – TSys/Modes/DSeg* and create a transport system for AV *CX_AV* as shown in Figure 2 in chapter 2.3.
- Transfer the network attributes like speed and authorization for using links etc. from CV for AV.
- Create mode and demand segment with the same name automatically (see also Figure 3 in Chapter 2.3).
- Run the script file "CoEXist_Create_User-Defined_Attributes_-_Extension_for_perceived_automated_travel_time_impacts.vbs" to create seven new attributes.
- Compare the list of user-defined attributes to Figure 18 and Table 9 to check if the script worked properly.
- Load the procedure parameter file "CoEXist_Procedure_Parameters_-_Extension_for_perceived_automated_travel_time_impacts.xml" and insert the operations to the desired place in the procedure sequence, e.g. after initializing other attributes or assignments as shown in Figure 19.

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Table 9: Overview on user-defined attributes added by the script

attribute	object	origin	description
CX_AV_READY	link type	by user	0: link type is not AV-ready, 1: link type is AV-ready
CX_AV_READY	link	by user	0: link is not AV-ready, 1: link is AV-ready
CX_AV-SHARE	network	by user	fixed AV share as a percentage for splitting the demand
CX_ID	matrix	by user	CoEXist-unique identifier for working with formula matrices
CX_IVT_PERCEPTION_FACTOR	network	by user	Factor for the perception of in-vehicle time in automated driving mode
CX_THRESHOLD_IVT-PERCEPTION_A	network	by user	Threshold A for the perception of in-vehicle time in automated driving mode [min]
CX_TTC_AV-READY	link	formula	Current travel time on AV-ready links [min]

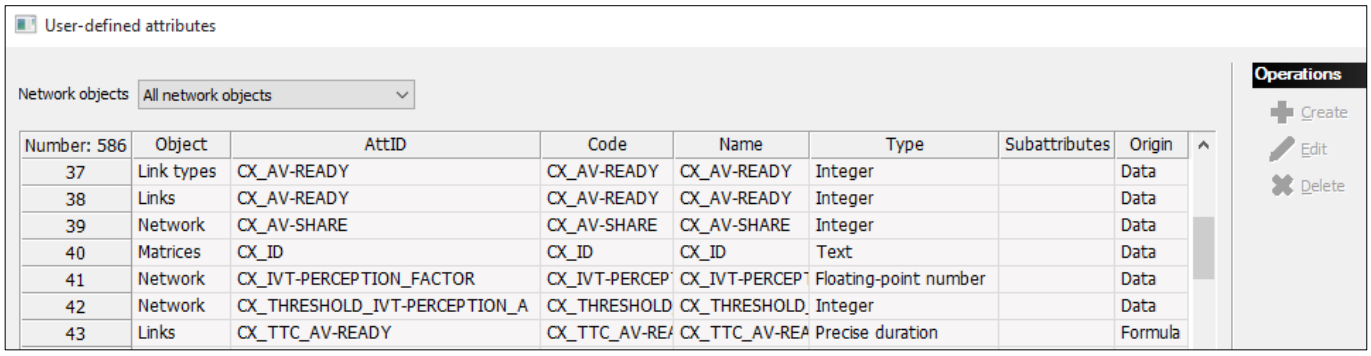

Figure 18: User-defined attributes that should be added by running the script

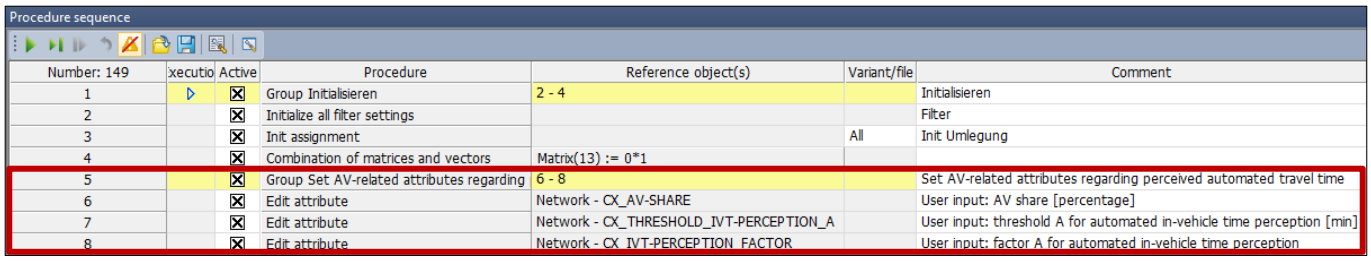

Figure 19: Added group of operations for setting the relevant attribute values

- The group of procedures contains operations to set values for attributes needed.
- Add the operation *Calculate PrT skim matrix* for *CX_AV* right after the already existing *Calculate PrT skim matrix* for 'Car' / 'Car driver' and activate the calculation for the skim *User-defined* as shown in Figure 20. All other possible skims have to be deactivated.

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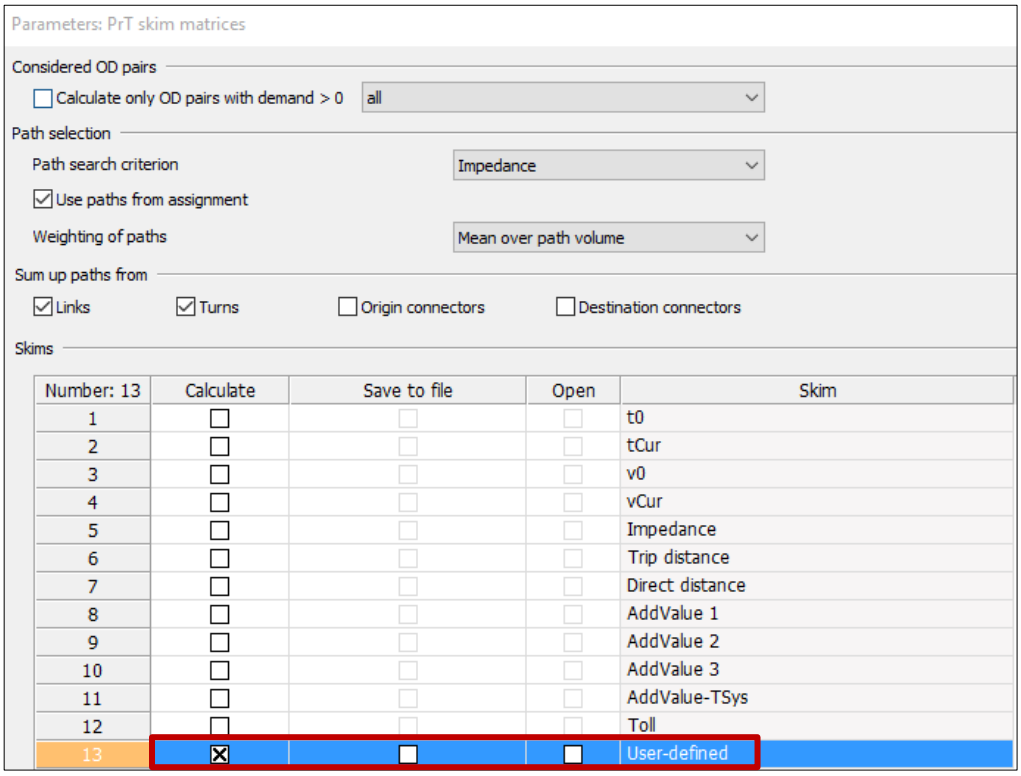

Figure 20: Activate user-defined skim calculation for CX_AV

- Set the Code for the user-defined skim to *CX_TTC_AV-READY* by selecting *General procedure settings – PrT settings – Skims – User-defined* (see Figure 21). Decide about reasonable values for the other editable settings (e.g. decimal places) according to the other skims included in your model.
- Edit the parameters of the user-defined skim by selecting *Parameters* in the box at the bottom (see also Figure 21). On link level, choose *CX_TTC_AV-READY* divided by 60 to get minutes as unit instead of seconds (default unit for data type *precise duration* of the link attribute *CX_TTC_AV-READY* is seconds) as shown in Figure 22.
- Execute the new PrT skim calculation procedure once: It is enough to start the execution and abort it after a few seconds to get Visum to create the new user-defined skim matrix automatically with the assigned code.
- Identify this new skim matrix and set the value for the attribute *CX_ID* to *CX_TTC_AV-READY*.
- Identify the skim matrix for the current travel time (TTC) of 'Car' / 'Car driver' and set its *CX_ID* to *CX_TTC_CAR*.
- Identify the demand matrix for 'Car driver' as calculated by the travel demand model and set its *CX_ID* to *CX_CAR_DEMAND*
- Run the script "CoEXist_Create_Formula_Matrices_-_Extension_for_perceived_automated_travel_time_impacts.vbs" to incorporate the prepared formula matrices.

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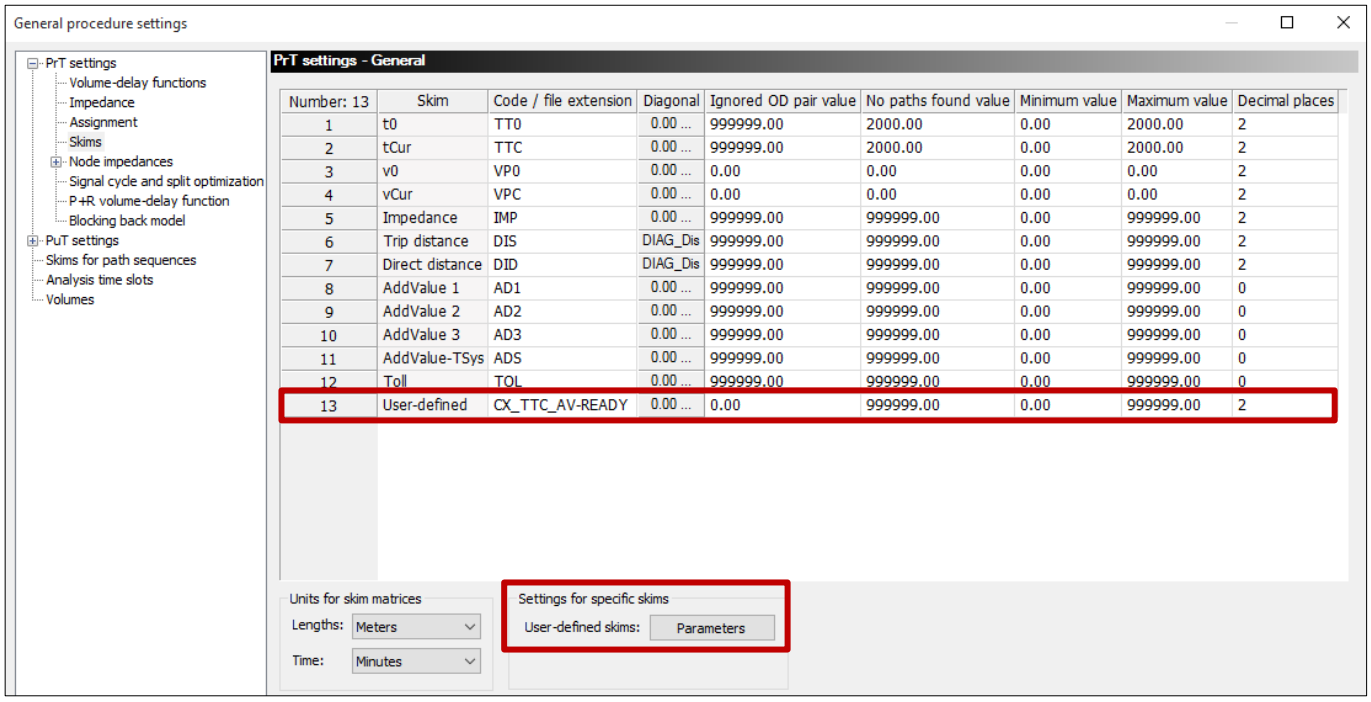

Figure 21: Overview on private transport skims in general procedure settings

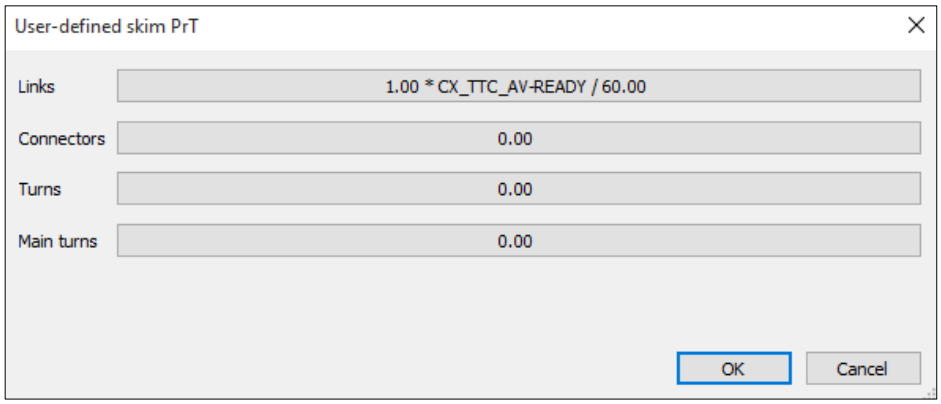

Figure 22: Setting parameters for user-defined skim

- As a result, there should be two new demand matrices to which the demand is divided in proportion to the AV share set by the user. Also, three additional formula skim matrices are added by the script. Open the list of matrices and compare to the list shown in Figure 23. Check, if the five formula matrices have been added. The matrices' numbering is not relevant for any further steps. The script identifies the next numbers available. The model use is free to modify the matrices' numbers afterwards.

No	Code	MatrixType	ObjectTypeRef	CX_ID	DataSourceType
1100	CX_TTC_AV-READY	Skim	Zone	CX_TTC_AV-READY	Data
1101	CX_TTC_NOT_AV-READY	Skim	Zone	CX_TTC_NOT_AV-READY	Formula
1102	CX_TTC_AV-READY_PERCEIVED	Skim	Zone	CX_TTC_AV-READY_PERCEIVED	Formula
1103	CX_TTC_CV_x_AV	Skim	Zone	CX_TTC_CV_x_AV	Formula
1104	CX_CV_DEMAND	OD demand	Zone	CX_CV_DEMAND	Formula
1105	CX_AV_DEMAND	OD demand	Zone	CX_AV_DEMAND	Formula

Figure 23: List of matrices including the new formula matrices

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- Choose the new demand formula matrices as input for the demand segments *CX_AV* and the one already in usage for CV under *Demand – Demand data – Demand segments* as shown in Figure 7 in Chapter 2.3.
- Finally, the matrix *CX_TTC_CV_x_AV* should now be used as replacement for the matrix of the current travel time 'TTC' in all utility functions affected within trip distribution and mode choice. For example, in the Stuttgart Region model, four operations *Tour-based model - Combined trip distribution / mode choice* need to be modified. A dialogue opens up: Choose *Mode choice utility* and replace the matrices within the *Utility function* for each relevant row, e.g. with the help of a spreadsheet software and copy & paste.

3.3.2 Visum 2020

It is recommended to comply the instructions in the following order. The tools are partly based on each other. Any other sequence or differing names can cause errors or additional subsequent effort for the model user.

- Go to menu *Demand – TSys/Modes/DSeg* and create a transport system for AV *CX_AV*.
- Transfer the network attributes like speed and authorization for using links etc. from CV for AV.
- Create mode and demand segment with the same name automatically.
- Run the script file "CoEXist_Create_User-Defined_Attributes_-_Extension_for_perceived_automated_travel_time_impacts_Visum2020.vbs" to create six new attributes.
- Compare the list of user-defined attributes to Table 10 to check if the script worked properly.

Table 10: Overview on user-defined attributes added by the script

attribute	object	origin	description
CX_AV_READY	link	by user	0: link is not AV-ready, 1: link is AV-ready
CX_AV-SHARE	network	by user	fixed AV share as a percentage for splitting the demand
CX_ID	matrix	by user	CoEXist-unique identifier for working with formula matrices
CX_IVT_PERCEPTION_FACTOR	network	by user	Factor for the perception of in-vehicle time in automated driving mode
CX_THRESHOLD_IVT-PERCEPTION	network	by user	Threshold A for the perception of in-vehicle time in automated driving mode [min]
CX_TTC_AV-READY	link	formula	Current travel time on AV-ready links [min]

- Load the procedure parameter file "CoEXist_Procedure_Parameters_-_Extension_for_perceived_automated_travel_time_impacts_Visum2020.xml" and insert the operations to the desired place in the procedure sequence, e.g. after initializing other attributes or assignments.
- The group of procedures contains operations to set values for attributes needed.

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- Add the operation *Calculate PrT skim matrix* for *CX_AV* right after the already existing *Calculate PrT skim matrix* for 'Car' / 'Car driver' and activate the calculation for the skim *User-defined* as shown. All other possible skims have to be deactivated. The model user could duplicate the corresponding operation for CV to adopt all the other settings accordingly and only modify the demand segment and skim selection.
- Set the Code for the user-defined skim to *CX_TTC_AV-READY* by selecting *General procedure settings – PrT settings – Skims – User-defined* (Figure 21). Decide about reasonable values for the other editable settings (e.g. decimal places) according to the other skims included in your model.
- Edit the parameters of the user-defined skim by selecting *Parameters* in the box at the bottom. On link level, choose *CX_TTC_AV-READY* divided by 60 to get minutes as unit instead of seconds (default unit for data type *precise duration* of the link attribute *CX_TTC_AV-READY* is seconds).
- Execute the new PrT skim calculation procedure once: It is enough to start the execution and abort it after a few seconds to get Visum to create the new user-defined skim matrix automatically with the assigned code.
- Identify this new skim matrix and set the value for the attribute *CX_ID* to *CX_TTC_AV-READY*.
- Identify the skim matrix for the current travel time (TTC) of 'Car' / 'Car driver' and set its *CX_ID* to *CX_TTC_CAR*.
- Identify the demand matrix for 'Car driver' as calculated by the travel demand model and set its *CX_ID* to *CX_CAR_DEMAND.*
- Run the script "CoEXist_Create_Formula_Matrices_-_Extension_for_perceived_automated_travel_time_impacts_Visum2020.vbs" to incorporate the prepared formula matrices.
- As a result, there should be two new demand matrices to which the demand is divided in proportion to the AV share set by the user. Also, three additional formula skim matrices are added by the script. Check, if the five formula matrices have been added. The matrices' numbering is not relevant for any further steps. The script identifies the next numbers available. The model use is free to modify the matrices' numbers afterwards.
- Choose the new demand formula matrices as input for the demand segments *CX_AV* and the one already in usage for CV under *Demand – Demand data – Demand segments*.
- Finally, the matrix *CX_TTC_CV_x_AV* should now be used as replacement for the matrix of the current travel time 'TTC' in all utility functions affected within trip distribution and mode choice. For example, in the Stuttgart Region model, four operations *Tour-based model - Combined trip distribution / mode choice* need to be modified. A dialogue opens up: Choose *Mode choice utility* and replace the matrices within the *Utility function* for each relevant row, e.g. with the help of a spreadsheet software and copy & paste.

3.4 Recommendations

The model user needs to set two values within the added group of procedures:

- The threshold A (*CX_IVT_PERCEPTION_FACTOR)* that represents a ramp-up time, for which no effects on perceived travel time are considered.
- The factor f_{perc} to convert the time exceeding the treshold into a perceived automated travel time.

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Of course, these parameters can be set freely by the modeller to serve a certain purpose or to investigate sensitivity of the travel demand.

There are not many research studies published that identify typical values for the parameters of the proposed approach since a complex/extensive stated preference survey is necessary.

Cyganski et al. (2018) suggest the following:

- $f_{perc} = 0.87$ for trip distances smaller or equal to 10 km and
- $f_{perc} = 0.79$ for trip distances longer than 10 km

They assume no anticipated time saving within the first five minutes, therefore a threshold is set to 5 minutes. ($A = 5\,\mathrm{min}$).

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4 Ridematching

4.1 Purpose

Fleets of CAV level 5 can provide unmanned ridesharing (or ride-hailing) services as a stand-alone service or as last-mile service in combination with public transport. Ridesharing services pool person trips with a similar temporal and spatial pattern to one vehicle trip. This section explains how person trips can be pooled to vehicle trips using a ridematching algorithm, which is suitable for macroscopic travel demand models.

4.2 Approach

The algorithm works likewise with integer demand, which is typical for agent-based microscopic models and with non-integer demand occurring in travel demand matrices of a macroscopic model. Considering non-integer demand the algorithm also assumes non-integer vehicles. The vehicles' capacity is set according to the first proportion of demand as Figure 24 exemplary indicates: 0.8 persons get in a vehicle causing a capacity of 6x0.8=4.8 persons and a 0.8 vehicle trip.

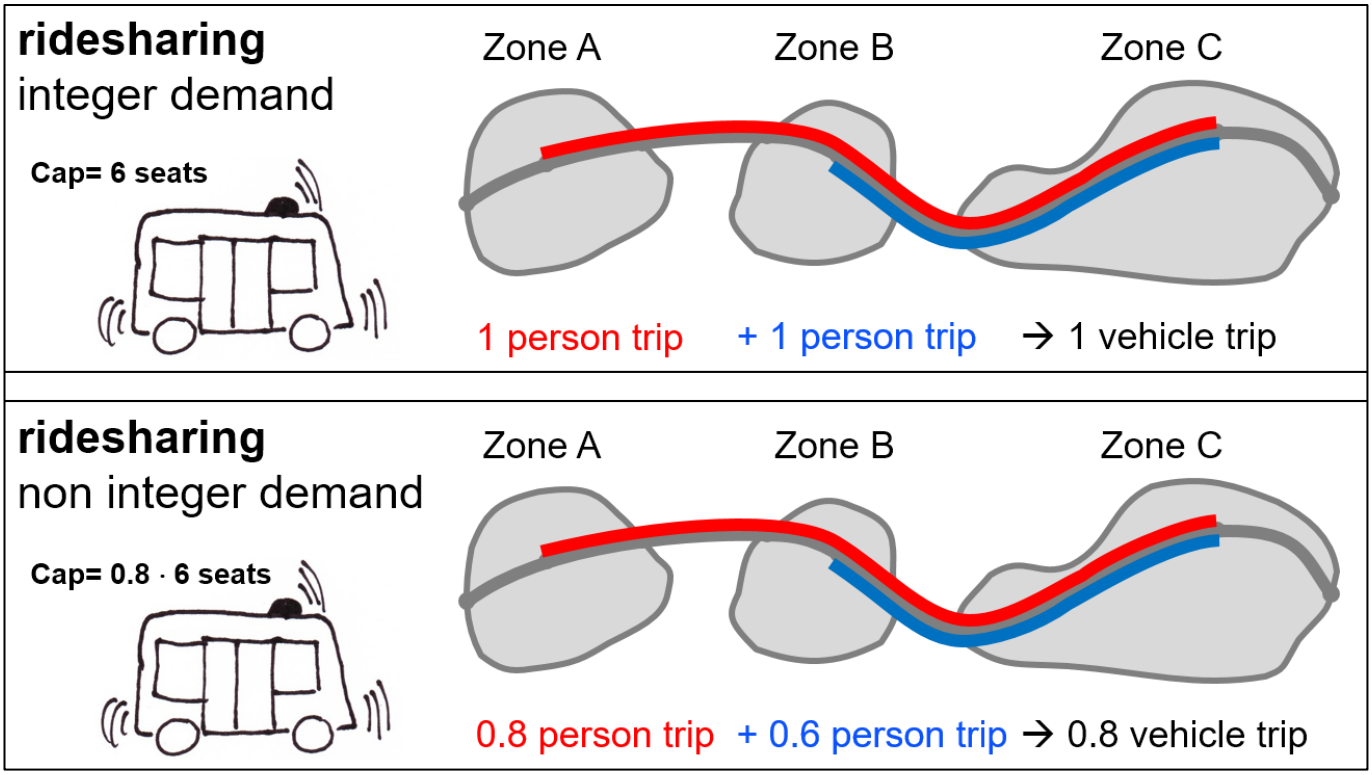

Figure 24: Ridesharing with integer and non-integer demand

- First, each road link or node is assigned to one zone (see Figure 25).

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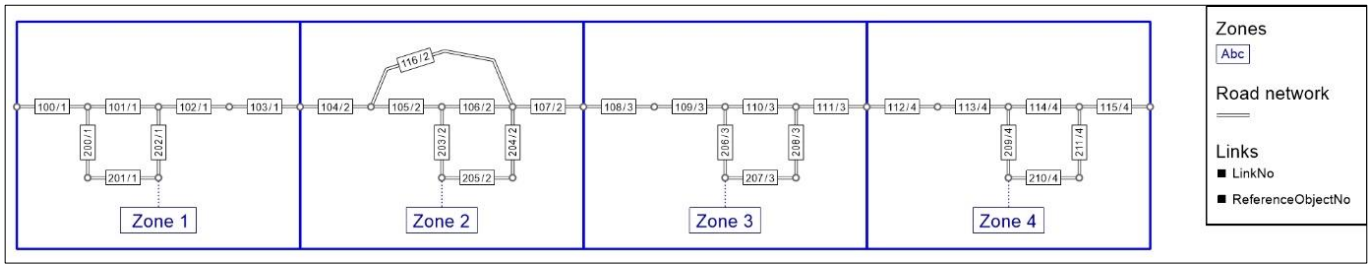

Figure 25: Road links and related zones in a network

- For each OD-pair, a path is computed depending on an assignment method or on the shortest path as shown in Figure 26.

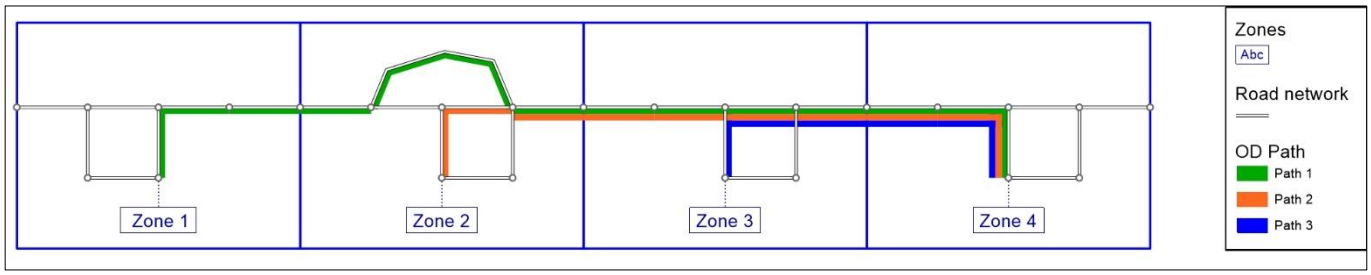

Figure 26: Path representation in the network

- The representation of a path in the road network is reduced from a sequence of links or nodes to a sequence of zones (see Table 11).
- The zones act as a buffer along the path, where demanders can be picked up. This means, that the exact positions of demanders are not considered for matching trips.

Table 11: Conversion from sequence of links or nodes to sequence of zones

path	from	to	sequence of links (or nodes)	sequence of reference objects (= zones)	
				complete	without duplicates
1	1	4	202,102,103,104,116,107,108,109, 110,111,112,113,209	1,1,1,2,2,2,3,3,3,3,4,4,4	1,2,3,4
2	2	4	203,106,107,108,109, 110,111,112,113,209	2,2,2,3,3,3,3,4,4,4	2,3,4

- The algorithm basically compares two simplified path sets of suppliers and demanders.
- Desired trips are first sorted by length and then the algorithm tries to match trips together that show a large overlapping of their respective zone sequences. By doing this, vehicle capacity is utilized to a higher extent.
- For each boarding procedure, an additional time fee/surcharge is added to travel time.

4.3 Instructions

The instructions refer to the tool available on the website of USTUTT.

The provided tool comprises one time interval with a suggested demand. The model user may modify the demand as desired and start the simulation by running the procedure sequence. Please note that the

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included algorithm works only for small networks, since no search engine is included. For bigger networks, an updated version of the tool should be used which is currently not available on the website of USTUTT. Previous studies (e.g. Friedrich et al., 2018, Friedrich and Hartl, 2016) successfully applied the extended tool incorporating a search engine for the Stuttgart Region travel demand model. If you are interested, please contact USTUTT. The tool as available on the website so far has only been applied within Visum 18 or lower.

4.4 Recommendations

The model requires a temporal distribution of the travel demand in form of time-dependent matrices. A temporal resolution with 96 intervals of 15 minutes (96x15 min = 1440 min = 24 hours) is recommendable.

The quality of the macroscopic ridematching algorithm depends on the size of the traffic zones. If the traffic zones are too large, the algorithm will overestimate the potential of ridesharing. Ideally zone size does not exceed 0.25 km² and 2000 inhabitants.

The algorithm uses a travel time matrix to determine the travel times between OD-pairs for loaded and empty runs. It is recommended, that this travel time corresponds to the peak hour travel time.

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5 Vehicle scheduling

5.1 Purpose

Fleets of CAV level 5 can provide unmanned ridesharing or carsharing services. To minimize the number of required vehicles, empty vehicles need to be reallocated to places with current demand. This requires a vehicle scheduling (or vehicle blocking) process simulating the dispatching of shared vehicle fleets. This section explains how vehicle trips can be concatenated to tours in a macroscopic travel demand model. The vehicle scheduling algorithms determines the number of required vehicles and the origins, destinations and times of empty vehicle trips.

5.2 Approach

The difficulty for vehicle scheduling in macroscopic travel demand models is the fact that demand is non-integer. Figure 27 shows an example for the problem. Vehicles must be split further into non-integer units related to the demand requesting a trip.

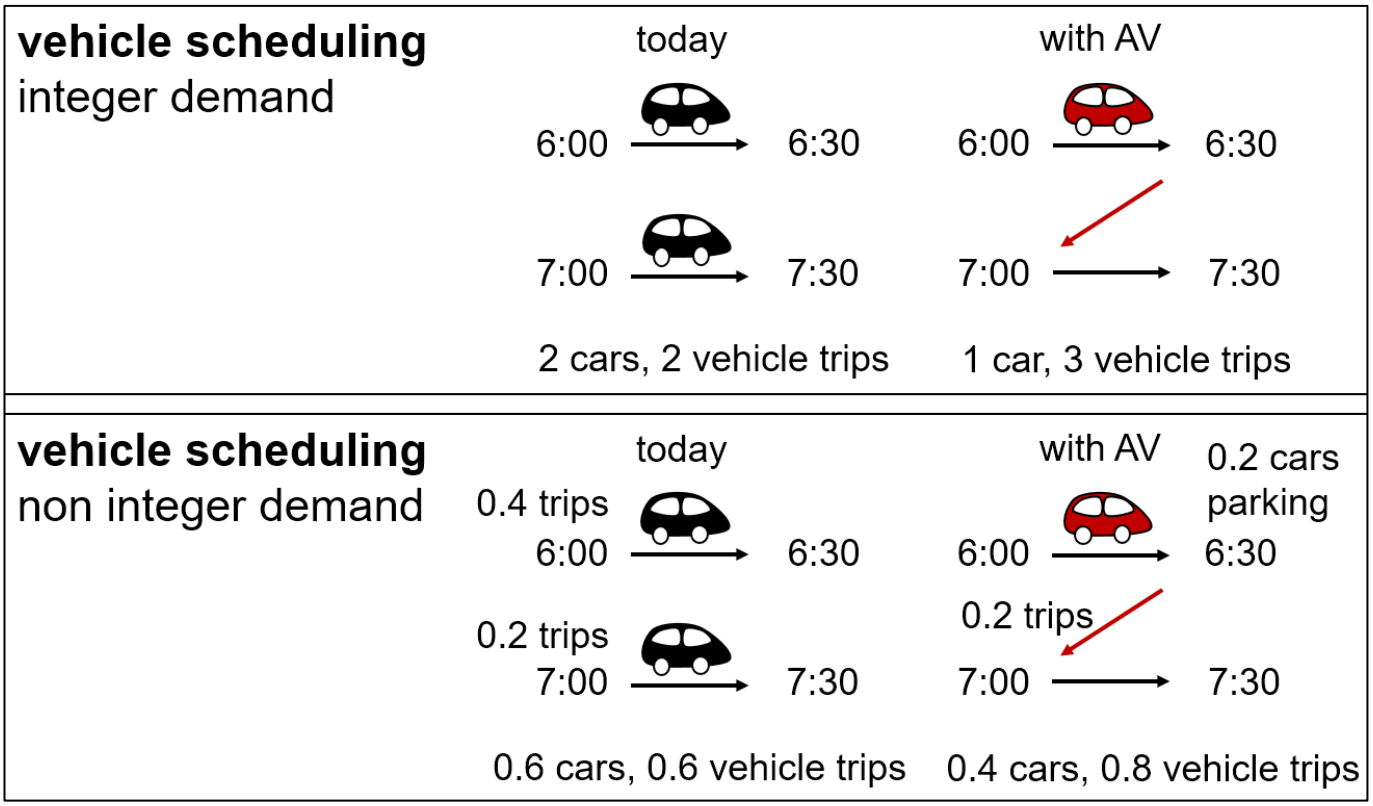

Figure 27: Concept of vehicle scheduling with integer and non-integer demand

The algorithm uses a linear optimization program to minimize the fleet size as indicated in Figure 28. It does not consider timetables as a basis, but needs a vehicle trip matrix for each time interval as an input. Furthermore, one matrix including the temporal distance in time intervals serves as impedance for possible relocation operations of empty vehicles.

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$$\min \quad \sum_{(s \in S)} z_s$$

$$\text{s.t.} \quad z_s \geq \sum_{t \in S} y_{(s,t,i)} \qquad \forall s \in S$$

$$\sum_{\substack{t \in S: \\ i-d(t,s) \geq 1}} y_{(t,s,i-d(t,s))} = \sum_{t \in S} y_{(s,t,i)} \qquad \forall s \in S,\ \forall i \in I$$

$$y_{(s,t,i)} \geq x_{(s,t,i)} \qquad \forall s, t \in S,\ \forall i \in I$$

$$y_{(s,t,i)} \in \mathbb{R}_+ \qquad \forall s, t \in S,\ \forall i \in I$$

$$z_s \in \mathbb{R}_+ \qquad \forall s \in S$$

Input:

S	Set of zones
I	Set of time intervals
$d(s,t)$	Time intervals needed from zone s to zone t
$x_{(s,t,i)}$	Nr. of vehicles needed to drive from zone s to zone t starting in time interval i

Output/Variables:

z_s	Nr. of vehicles starting in zone s (Fleet size)
$y_{(s,t,i)}$	Nr. of vehicles driving from zone s to zone t starting in time interval i (Vehicle flow)

Figure 28: Linear program integrated in the vehicle scheduling tool

The optimization problem can be interpreted as a flow problem. The algorithm compares the vehicle trip matrices for each time interval, computing for each zone the outgoing and incoming vehicles. For the latter, trips that started in another zone in one of the previous intervals have to be considered. In any case, there will be a lack of vehicles in a zone, when the number of outgoing vehicles exceeds the number of incoming vehicles. There are three possibilities to deal with the shortage of vehicles, applied in the following order:

1) Use parked vehicles, already 'waiting' within the zone.
2) Use relocated vehicles (=vehicles parking in another zone in a previous time interval).
3) Insert new vehicles into the zone.

Depending on the need, the algorithm utilizes one or more of these options to balance the number of vehicles for each zone and each time interval. Figure 29 represents the different in- and outputs of vehicles for an exemplary zone. The basic condition for all time intervals is that the sum of all vehicle inputs equals the sum of all vehicle outputs.

The sum of all vehicles inserted into the network through the course of the modelled time represents the required fleet size to fulfil the desired ride- or carsharing trips for all time intervals.

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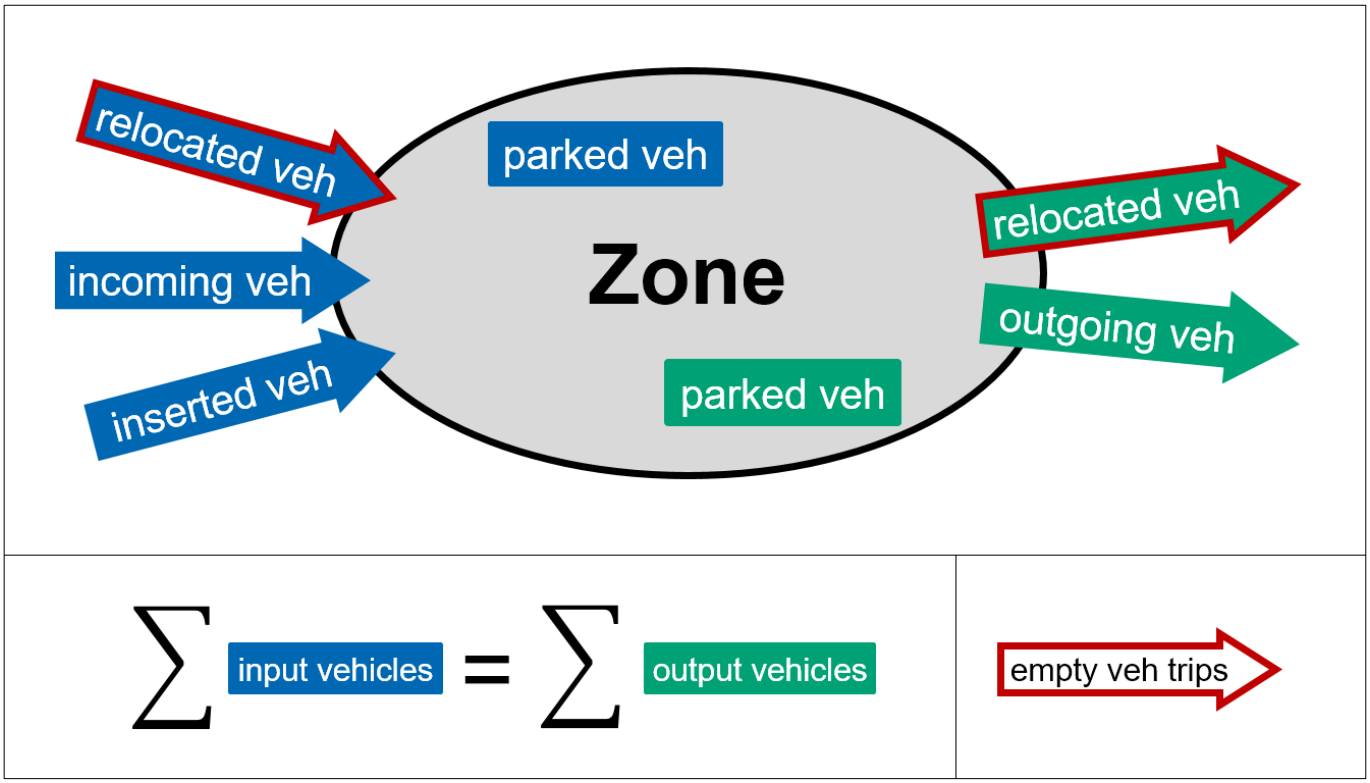

Figure 29: Vehicles (veh) to, from and in a zone

5.3 Instructions

The way the vehicle scheduling tool is currently implemented, it only works for the Stuttgart Region travel demand model. It is not yet applicable for any other model. An updated, generalized version is in development. A detailed guidance would not be helpful and is therefore not provided. Nevertheless, some rough clues are given on how the tool is applied at present:

- Insert prepared procedure parameters at a point within the procedure sequence, where the demand matrices for car- or ridesharing for all time intervals are already calculated.
- Choose ride- or carsharing by editing an attribute.
- Decide about desired settings by editing a configuration file.
- Execute the operations related to the tool.

Required paths are set automatically. The basic framework of the tool works as follows:

- Export relevant demand matrices and the impedance matrix to a specific folder accessible for the optimization program.
- The algorithm processes the given data and computes a valid solution in form of matrices with vehicle trips.
- These matrices are imported to Visum together with a NET file containing the final outcome (e.g. fleet size).

Regarding computational time, the Stuttgart model with 1175 zones and 96 time intervals requires approximately 5 to 10 minutes for applying the vehicle scheduling tool.

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5.4 Recommendations

The only setting that the model user currently may adapt is the number of decimal places the algorithm considers for the output matrices. Naturally, the precision of the input demand matrices should at least be equal or even higher than the set number. Setting a higher precision for the output as for the input makes no sense.

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6 Next steps

Besides finishing the development of the tools and continuing with literature review, the aim is to finally apply the tools on use cases to be able to run the simulations defined in the Experimental Design in D3.1.

There are three macroscopic use cases for which the tools are used as Table 12 indicates. Whereas use cases 2 of Gothenburg and 7 of Stuttgart focus on impacts of AV on capacity and network performance, the second use case of Stuttgart concentrates on new mobility services like ridesharing, integrated into or competing with public transport.

Table 12: Overview on macroscopic use cases incorporating a selection of the presented tools

use case title (use case number)	partner city	applied tools (chapter)	results available
Accessibility during long-term construction works (2)	Gothenburg	Capacity and network performance (2)	latest March 2020
Impacts of CAV on travel time and mode choice on a network level (7)	Stuttgart	Capacity and network performance (2) Perception of automated travel time (3)	latest March 2020
Impacts of driverless car- and ridesharing services (8)	Stuttgart	Capacity and network performance (2) Perception of automated travel time (3) Ridematching (4) Vehicle Scheduling (5)	latest March 2020

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7 Literature

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8 Appendix

8.1 How to create user-defined volume-delay functions

This chapter deals with the creation of user-defined volume-delay functions and provides general and software-specific remarks, tips and instructions for the user.

- Software needed: Microsoft Visual Studio Community 2017, Microsoft .NET Framework and other installed products within Visual Studio as shown in Figure 30. Programming itself is done in C++.

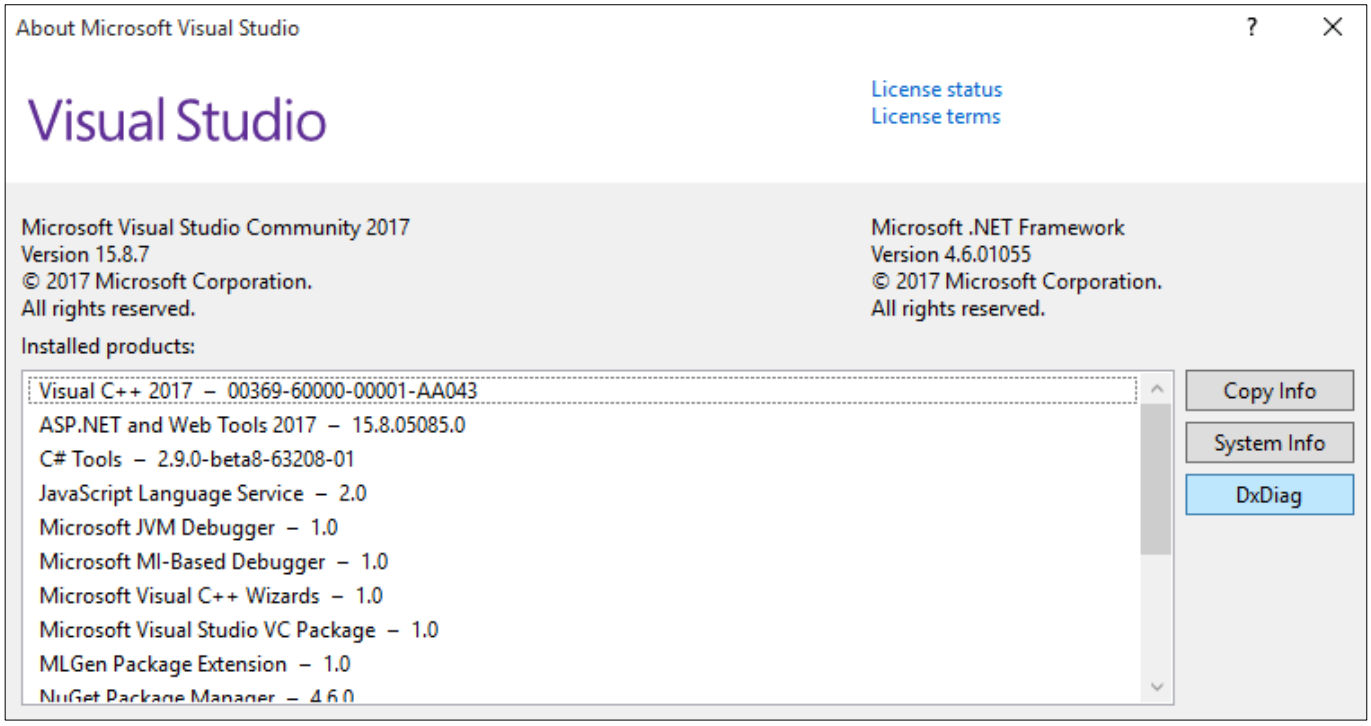

Figure 30: Information on Visual Studio and other software used

- Copy the files from the folder “C:\Program Files\PTV Vision\PTV Visum 17\Data\UserDefVDF“ to another local directory of your choice. The examples provided in the installation of Visum serve as template. Please note that if you use another software version of Visum, you need to navigate to the related folder.
- Open the solution *UserDefVDF.sln* in Visual Studio that includes some projects by default.
- The programming of a VDF is done in a CPP file.
- It is recommended to create a new CPP file for every new function, so that the corresponding code does not get lost. The DLL files are not readable by any text editors. The content is only accessible through the CPP code.
- After adding a CPP file, copy the code from an example provided by Visum or provided in the appendix of Deliverable 2.7 into the new file for guidance. Especially the example functions for including impacts of AV on network performance from D2.7 are recommended, because they contain helpful comments throughout the code.

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- Edit the code so it fits your purposes. Do not forget to set unique names for *VDFName* and *VDFID*, otherwise Visum may not identify the functions properly.
- It is possible to include and exclude CPP files at all times to and from the current project. This means there is no need to create a new project for each new VDF.
- But care must be taken when building a DLL. A project must contain only one CPP file, which will be compiled to a DLL in the end.
- Check the related configuration for building DLL under *Build – Configuration Manager…* and select the settings as shown in Figure 31.

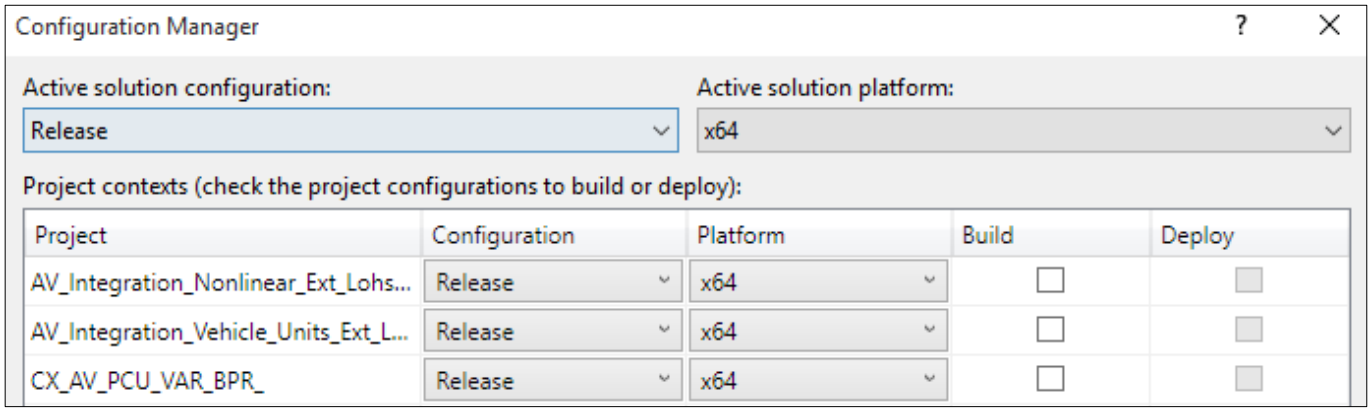

Figure 31: Build configuration for all projects in Visual Studio

- The name for the DLL comprises three parts: a prefix *VisumVDF_*, the name of the current project and a suffix *x64*. Prefix and suffix are mandatory for Visum to be able to detect the functions. The name of the CPP is irrelevant. For better readability, include a "_" at the end of the projects name. However, it is also possible to modify the way the name is going to be created (see Figure 34 below).
- To create a DLL, select *Build – Build *projectname** (see Figure 32).

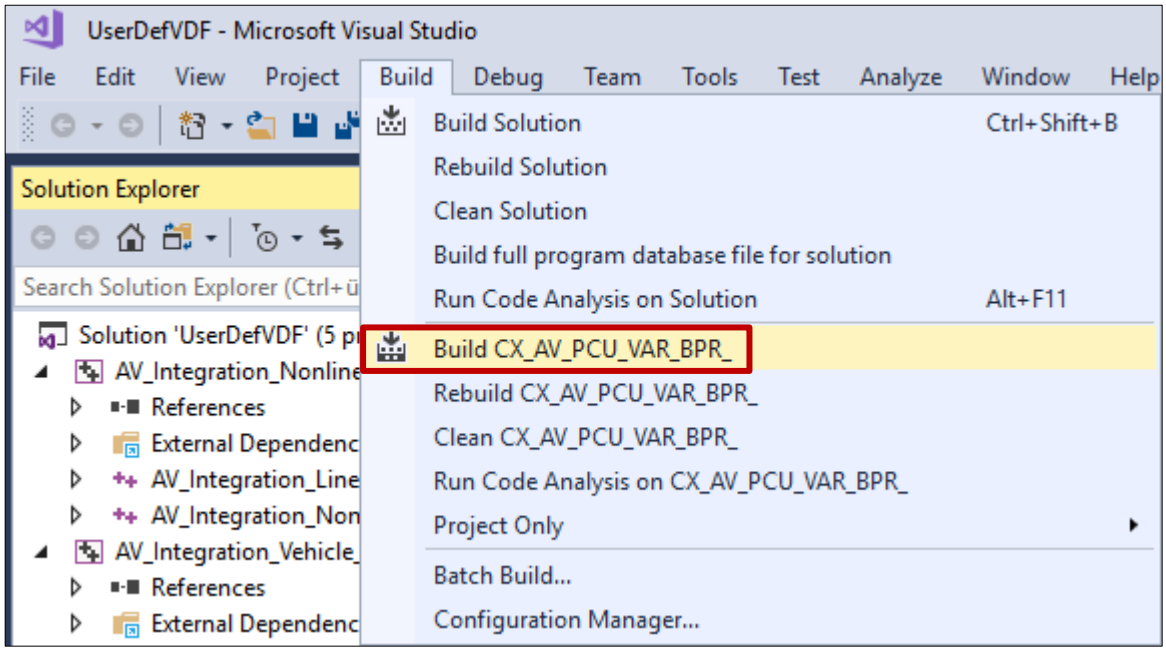

Figure 32: Create the DLL by building the code of the CPP-file of the current project

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- Built DLL files are located in “\x64\Release” starting from the directory where the user placed the copied CPP files before

Troubleshooting

- DLL file cannot be created, error message appears
- The reason is maybe a wrong setting in the project’s properties
- Please check the settings in *Project – Properties – Configuration Properties – General*. Refer to Figure 33 for guidance

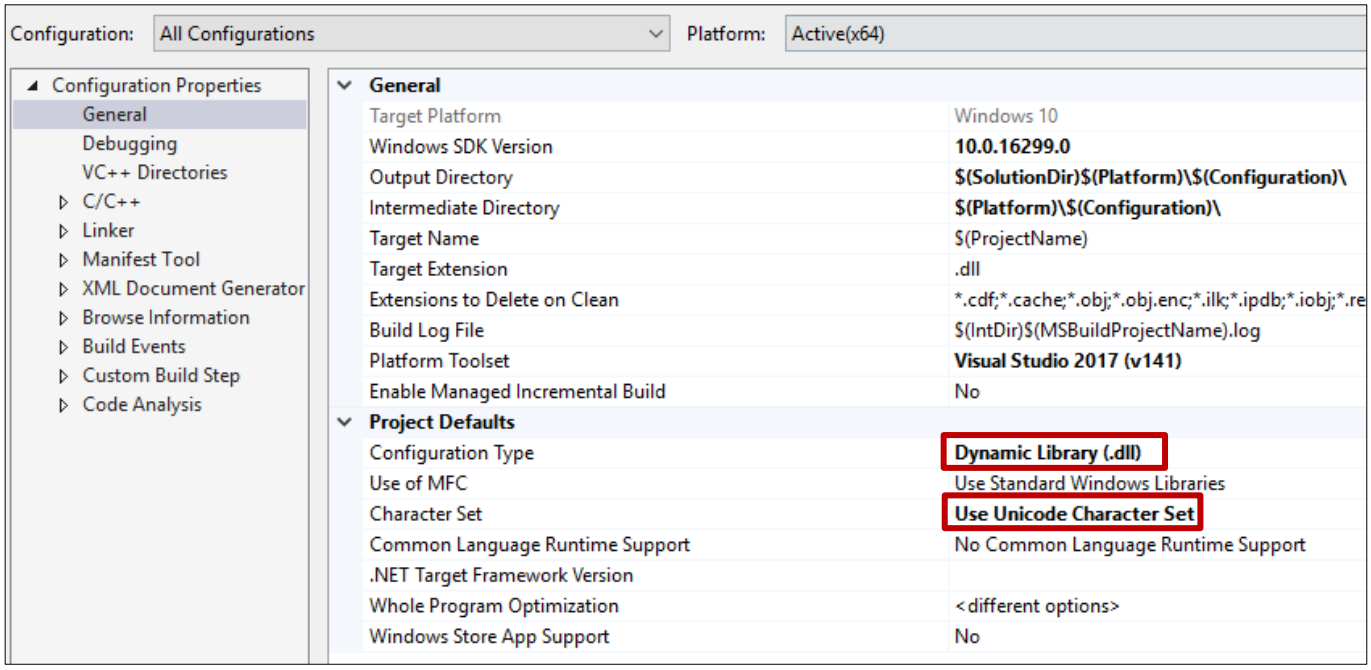

Figure 33: Project properties general settings in Visual Studio

- Successfully built DLL, but the file is not named properly as described with prefix and suffix
- Check the settings in *Project – Properties – Configuration Properties – Linker – Output File*. Refer to Figure 34 for the syntax.

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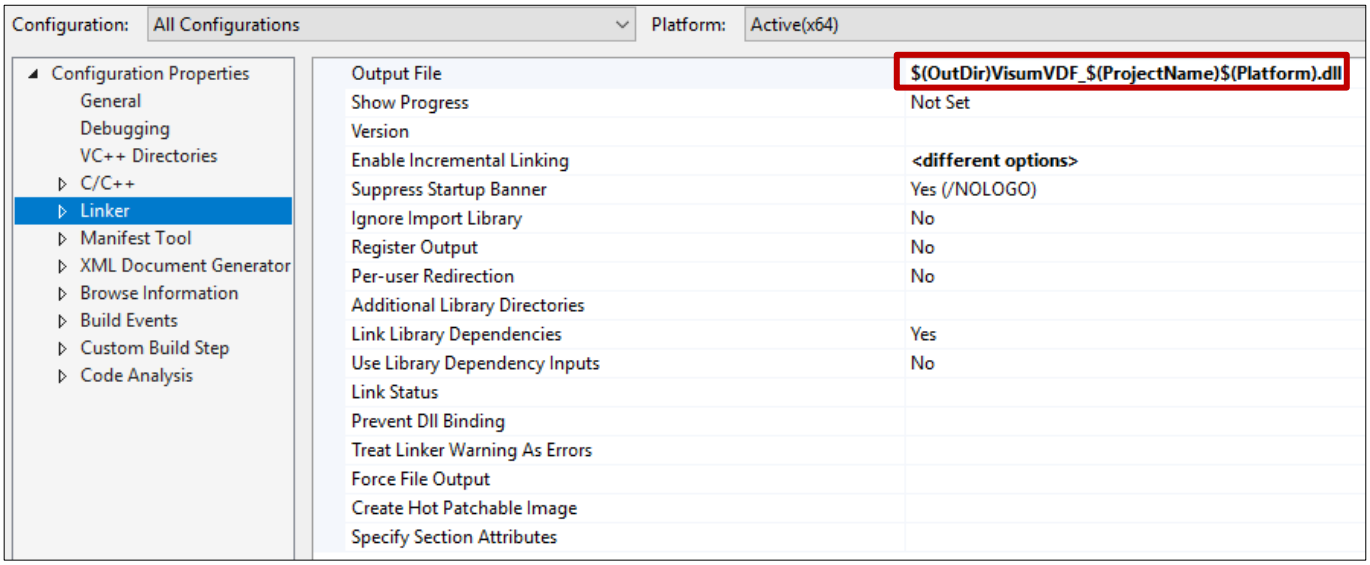

Figure 34: Setting for name the output file

For further guidance please check the PTV Visum 17 Manual Chapters “6.4.4 User-defined VD functions” and “19.2.1.6 Applying user-defined volume-delay functions”. If you use another software version of Visum, the chapter numbers can deviate.

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