D2.9 Built-in AV-ready macroscopic tool

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1 Brief description

The example demonstrates step by step how autonomous vehicles can be considered in macroscopic models, more precisely in PrT assignments.

2 Requirements

PTV Visum 2020 module: Simulation-based dynamic assignment (SBA).

3 Important note

This deliverable completes the tools developed by the University of Stuttgart within the project. They can be found in deliverable D2.7 *AV-ready macroscopic modelling tool* and D2.8 *Guide for the simulation of AVs with a macroscopic modelling tool*, both available in the resources section of the CoEXist Website[1].

4 Objective

The example shows how autonomous vehicles can be modelled in a macroscopic model and how their properties can be taken into account in a PrT assignment. This example consists of two parts: the first part shows how autonomous vehicles are mapped for static PrT assignments, the second part models autonomous vehicles for simulation-based dynamic assignment (SBA). The example begins with a brief introduction to the special characteristics of autonomous vehicles.

Note: Fictitious assumptions were made in the example to model autonomous driving, i.e. the results do not permit any generally valid conclusions. At the end of the example, a section briefly outlining the influencing factors of various parameters in the investigation of autonomous driving for the transfer to actual use cases can be found.

5 Introduction

Autonomous vehicles play an increasing role. Consequently, their consideration in macroscopic models is important. Under current conditions, it can be assumed that autonomous vehicles will exist alongside conventional vehicles over a longer period of time. The driving behaviour of autonomous vehicles is essentially determined by the capabilities (levels of driving automation) and the existence of a special infrastructure. On sections where C2C (car to car) or C2X (car to infrastructure) communication is supported, autonomous vehicles can communicate with each other and drive at a

[1] https://www.h2020-coexist.eu/resources/

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fixed distance or form platoons. On sections where this is not possible, autonomous vehicles behave like conventional vehicles. There are two requirements for the modelling:

- The equipment of the infrastructure must be mapped in the network. Network objects equipped for C2C or C2X are referred to below as 'AV-ready'.
- The driving behaviour of autonomous vehicles must be modelled depending on the infrastructure.

The second requirement distinguishes autonomous vehicles from conventional modelling, which assumes that vehicles of a transport system show the same behaviour across the network.

In this example, the focus is on the effect of autonomous vehicles in terms of traffic flow, i.e. capacity, travel time and route selection. Other aspects such as safety, legal regulations or environmental influences are partly related to this but are not further elaborated in this example.

6 Modelling of autonomous vehicles in static PrT assignments

In static assignments, the travel time is calculated using VD functions. Input variables are volumes, the capacity, and the speed in the unloaded network, from which t0 results directly. The volumes of a link or a turn are determined across all transport systems in passenger car units (PCU). The PCU factors applicable to the transport system are defined as an attribute of the transport system. The total passenger car units are compared with the capacity to determine the volume, which finally results in the travel time or speed according to the VD function in the loaded network.

The assumption that autonomous vehicles will behave differently on 'AV-ready' links than on others must be reflected in the factor for PCU. In the simplest case, it is assumed that the factor is fixed on 'AV-ready' links but differs from the default value at the transport system. If autonomous vehicles keep a smaller distance on 'AV-ready' links, a factor smaller than 1 is assumed. If the distance is larger, e.g. due to safety-relevant aspects, the factor can be larger than 1.

In order to consider different factors for PCU depending on 'AV-ready', a user-defined VD function is required that calculates the total volume of a link using link attributes.

The user-defined VD function provided with the example includes a BPR function that calculates the volume as shown in the figure below.

$$t_{cur}(sat) = t_0 * (1 + a * sat^b)$$

$$sat = \frac{q_{HGV} * f_{HGV}^{PCU} + q_{car} * f_{car}^{PCU} + q_{AV1} * f_{AV1}^{PCU} + q_{AV2} * f_{AV2}^{PCU}}{q_{max}}$$

$$if\ CX\_AV - ready = 1, \quad f_{AV_{1,2}}^{PCU} = CX\_PCU\_AV_{1,2}\,, \quad else\ f_{AV_{1,2}}^{PCU} = CX\_PCU\_AV_{1,2}\_\text{Default}$$

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with

a, b	Parameters of the volume-delay function
sat	Volume/capacity ratio
q_{TSys}	Volume by transport system
CX_AV-ready	Link UDA with value 1 for AV-ready, otherwise 0
$CX\_PCU\_AV_{1,2}$	Link UDA PCU factor for transport system AV1 and AV2
$CX\_PCU\_AV_{1,2}\_Default$	PCU factor for transport system AV1 and AV2 (default)

This user-defined VD function can be applied to models that meet the following requirements:

- Maximum of four transport systems with the codes HGV, CAR, AV1 and AV2
- IDs of the user-defined attributes (UDA) for links:

CX_PCU_AV1 of the type floating-point number with the factor for PCU for AV1
CX_PCU_AV2 of the type floating-point number with the factor for PCU for AV2
CX_AV-ready of the type 'bool' with 1 = AV-ready, otherwise 0

Note: Before proceeding with the example, make sure that the .DLL contained in the subdirectory \USERDEFINED_VDF\ is copied to the directory %APPDATA%\PTVVISION\PTV VISUM 2020\USERVDF-DLLS\. The .DLL must be in this directory when starting the program.

6.1 Step of the example for static assignments

The example for the use in static assignment includes steps for the modelling of autonomous vehicles as well as some evaluation possibilities.

6.1.1 Prerequisites for modelling with autonomous vehicles

In a first step, the model is extended by two transport systems of autonomous vehicles that can have different characteristics. To do so, proceed as follows:

1. Set all project directories to the subfolder of the example \STATIC\.
2. Open the STATIC.VER version file.
3. From the **Demand** menu, choose **TSys/Modes/Demand Segments**.
4. In the dialog, add two transport systems AV1 and AV2, for which you also create modes and demand segments with the same codes. When inserting both transport systems, activate the **Transfer network attributes from: CAR** option. In the dialog that opens next, create a mode and demand segment with the same code and name. The transport systems AV1 and AV2 are thus permitted on the same network objects as CAR.
5. In the next step, import the required user-defined attributes (UDA). To do this, select **Open** > **Network** from the **File** menu, open the CX_UDA_STATIC.NET file and confirm all dialogs that open.
6. Open the **Attributes** list and use the drop-down list to restrict it to **Only user-defined**. The list contains 11 new UDA for links and 5 for the network. 10 link UDA are defined by formulas. The UDA **CX_AV-Ready** is an input attribute that you absolutely need in addition to the UDA **CX_PCU_AV1** and **CX_PCU_AV2** for modelling autonomous vehicles. For the latter

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two attributes, the entry is made using the network UDA of the same name to which the formula of the link UDA refers. The following table gives an overview of the UDA. Only the bold UDA are necessary, all others offer additional evaluations or simplify further modelling.

Network object	AttrID	Formula	Use
Link	**CX_AV-READY**	No	Input: Modelling AV-ready links; AV-ready = 1, otherwise = 0
Link	**CX_PCU_AV1**	Yes	Is calculated: PCU factor on AV-ready links for AV1
Link	CX_PCU_AV1_DEFAULT	Yes	Is calculated: PCU factor of the TSys AV1
Link	CX_CALCPCU_AV1	Yes	Is calculated: PCU factor used on the link for AV1
Link	**CX_PCU_AV2**	Yes	Is calculated: PCU factor on AV-ready links for AV2
Link	CX_PCU_AV2_DEFAULT	Yes	Is calculated: PCU factor of the TSys AV2
Link	CX_CALCPCU_AV2	Yes	Is calculated: PCU factor used on the link for AV2
Link	CX_VOL_PCU_AV1	Yes	Is calculated: Volume in PCU AV1 (1)
Link	CX_VOL_PCU_AV2	Yes	Is calculated: Volume in PCU AV2 (1)
Link	CX_VOL_VEH_AV	Yes	Is calculated: Volume in vehicle AV1 and AV2
Link	CX_VOL_PCU_TOTAL	Yes	Is calculated: Total volume in PCU (1)
Network	CX_PCU_AV1	No	Input: Value for link UDA CX_PCU_AV1
Network	CX_PCU_AV2	No	Input: Value for link UDA CX_PCU_AV2
Network	CX_Share_AV1	No	Input: Share from matrix no. 1 for demand AV1
Network	CX_Share_AV2	No	Input: Share from matrix no. 1 for demand AV2
Network	CX_Share_CAR	Yes	Is calculated: Matrix no. 1 minus demand for AV1 and AV2

(1) Note that the attributes available in Visum with calculated volumes in PCU are always based on the default value at the transport system.

7. Next, create 3 formula matrices. In the example, the demand for the existing matrix is divided between the three demand segments CAR, AV1, and AV2 using formulas.
   - Open the **Matrices** list via the **Lists** > **Demand** menu.
   - Use the **Create** button to create three matrices of the **Formula matrix** type in the list. If you create the three matrices in one step by setting the number of matrices to be inserted on the tab Set of matrices to 3, first specify matrix no. 1 under **Edit formula**. Factors can be edited later in the Formula column of the list.
8. After creating the matrices, change the code, the name, and the demand segment in the list to the respective codes of the transport systems CAR, AV1, and AV2 and edit the formula by multiplying matrix no. 1 with an associated network UDA for the share. Alternatively, after creating the three matrices, import the file CX_MATRIX_STATIC.DMD. Under conflict handling, change the entry to **Overwrite attributes**.
   The **DSegCode** column references the matrices as assignment matrices.
   After this step, the entries in the matrix list look like this:

Number: 4	No	Code	Name	MatrixType	ObjectTypeRef	Sum	DSegCode	DataSourceType	Formula
1	1	C	Car total	OD demand	Zone	11848.680		Data	
2	2	CAR	CAR	OD demand	Zone	11848.680	CAR	Formula	Matrix([NO] = 1)*[CX_SHARE_CAR]
3	3	AV1	AV1	OD demand	Zone	0.000	AV1	Formula	Matrix([NO] = 1)*[CX_SHARE_AV1]
4	4	AV2	AV2	OD demand	Zone	0.000	AV2	Formula	Matrix([NO] = 1)*[CX_SHARE_AV2]

9. Change the two user-defined network attributes for the shares (Menu **Network** > **Network settings** > **User-defined attributes** tab) by entering 0.3 for CX_Share_AV1 and 0.1 for CX_Share_AV2.
   The remaining demand is automatically assigned to the demand segment CAR.
10. Assign the user-defined VD function to all links. Via the menu **Calculate** > **General procedure settings** > **PrT settings** > **Links VD functions**, you can create a new VD function with the number 2. From the drop-down list for the type, select the user-defined function with the name CX_AV_2TSYS_PCU_CONST_BPR. For parameter b, enter the value 4. Assign VD function number 2 to all link types in the upper part of the dialog.

The steps above complete all the prerequisites for modeling with AV. Now you just need to define 'AV-ready' links in order to take into account the characteristics of autonomous vehicles in the context of an assignment. First, an assignment is carried out in this state and then a scenario with 'AV-ready' links is calculated and compared. As long as no 'AV-ready' links are defined in the network, the vehicles of the transport systems AV1 and AV2 behave like conventional vehicles, i.e. they are taken into account with a PCU factor of 1.0 in the entire network.

6.1.2 Calculating an assignment with autonomous vehicles

1. Switch to the procedure sequence and change the reference objects so that the demand of all transport systems is assigned.
2. Execute the procedure sequence and then load the graphic parameters file RESULT_STATIC.GPA using the list box in the menu of the network editor.
3. Save the version as STATIC_NOAV.VER.
4. Switch to the link list **Links: Inputs**.
   In this list, a column filter is active for the attribute 'AddVal2'. First import the list layout LINKS_INPUT.LLA. Values must be defined for the three UDA highlighted in color. Set the 'CX_AV-ready' attribute to True for all 135 filtered links. For these links, a PCU factor must be defined for AV1 and AV2.
5. To define the values for the attributes 'CX_PCU_AV1' and 'CX_PCU_AV2', set the network UDA of the same name to the values 0.8 for AV1 and 0.9 for AV2. Make this change under **Network** > **Network settings** > in the **User-defined attributes** tab. The assumption underlying these values is that autonomous vehicles can travel on 'AV-ready' links at shorter distances and that this fact differs again for the vehicles of the two AV transport systems.
6. Rerun the assignment.

In the example, we are particularly interested in two changes: the change in the volumes in PCU and the changes in the volumes of CAR.
The changes are examined on the basis of a version comparison.

6.1.3 Comparing versions with and without autonomous vehicles

1. From the **File** menu, choose **Compare and transfer networks** > **Version comparisons**.
2. Click **Add** and select the **Load comparison network in the background** option.
3. Select the version file STATIC_NOAV.VER and enter the code 'noAV'.

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4. Confirm with **OK**.

You can analyze both changes by loading the graphic parameters files VERSCOMPARISON_STATIC_NOAV_PCU.GPA (changes to volumes in PCU) and VERSCOMPARISON_STATIC_NOAV_CAR.GPA (changes to volumes in demand of CAR).

You can find the result of the comparison with the differences for CAR in the version STATIC_COMPARISON.VER.

You will find that, as expected, the volumes in PCU are reduced on almost all links. With CAR (conventional vehicles), volume shifts in favor of 'AV-ready' links can be observed. This effect results from the fact that autonomous vehicles have an influence on capacity, i.e. with the same number of vehicles the travel time on a link is reduced and can therefore result in shifts from other routes.

In addition to a comparison of evaluation attributes, the influence of autonomous vehicles (AV) can also be examined with regard to total indicators such as total vehicle kilometres or total vehicle hours. For future scenarios, certain assumptions can be implied and their effects analyzed. For example, we vary the assumptions regarding the PCU factor on 'AV-ready' links and the share of AV in total demand for such an analysis. You can use scenario management for such an analysis since you can compare indicators directly after calculating the scenarios.

6.1.4 Comparison of different scenarios

From the version STATIC_NOAV.VER the base version of a scenario management project is created, where we limit ourselves to one transport system for AV (AV1).

1. Open this version and make the following changes:
    - Initialize the assignment.
    - Set the value of the network UDA for CX_PCU_AV1 to 1.00.
    - Set the value of the network UDA for CX_Share_AV2 to 0.00.
    - In the link list, load the layout LINK_INPUTS.LLA and set the value of the attribute 'CX_AV-ready' to True for the filtered 135 links.
    - Change the reference objects in the PrT assignment procedure: Remove the demand segment AV2.
2. Save this version as STATIC_BASE.VER.
   With these changes we get a base version where the demand of AV1 behaves like that of CAR, i.e. the PCU factor is 1.0 in the whole network.
3. Use the STATIC_BASE.VER version to create a scenario management project 'Static_AV', for which you create \STATIC_AV\ in a subfolder.
4. Create 5 modifications in which you vary the values of the network UDA 'CX_PCU_AV1' from 0.7 to 1.2 with a step size of 0.1. A value of 1.0 corresponds to the state of the base version and requires no modification.
5. On the **Basic settings** tab, create scenario indicators. Use the relation to the PrT assignment quality data (last iteration, all DSeg).
   In the following list of the selected indicators you will find the used name of the alias in brackets:
    - Max:PrT quality data(last iteration, all DSeg)\Iteration (Iter)
    - Sum:PrT assignment quality data)last iteration, all DSeg)\Vehicle miles traveled PrT (VMT)
    - Sum:PrT assignment quality data(last iteration, all DSeg)\Vehicle hours traveled tCur (VHT)
    - Min:PrT assignment quality data(last iteration, all DSeg)\Gap (minGap)
    - Max:PrT assignment quality data(last iteration, all DSeg)\Gap (maxGap)

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6. Create 6 scenarios in which the base version is combined with a modification and a base version without a modification is calculated.

The view of the 6 scenarios is as follows:

Edit project

Basic settings | Scenarios | Modifications | Procedure parameter sets | Global layouts | Comparison patterns | User-def. attributes | Distributed computing | Multi-user mode

Number: 6	Active	Number	Code	Description	Procedure parameter set	Modifications	Calculation state	Compute node	Iter	VMT	VHT	minGap	maxGap
1	☒	1	PCU	0,7	0 from base version	1	Not calculated	localhost					
2	☒	2	PCU	0,8	0 from base version	2	Not calculated	localhost					
3	☒	3	PCU	0,9	0 from base version	3	Not calculated	localhost					
4	☒	4	PCU	1	0 from base version	...	Not calculated	localhost					
5	☒	5	PCU	1,1	0 from base version	4	Not calculated	localhost					
6	☒	6	PCU	1,2	0 from base version	5	Not calculated	localhost					

You can find the uncalculated state of this project in the subdirectory \STATIC_AV\.

6.1.5 Further analyses

The following steps provide further instructions on how to proceed with the project but are not part of the delivered example.

1. Perform the calculations for all scenarios.
   You can use the calculated scenario indicators to investigate how changes affect the assumptions about driving behaviour.
2. Expand the project by varying the share of demand in the AV1 segment. With the network UDA 'CX_Share_AV1' you can do this in the same simple way as with the factor for PCU before. Use one of the previously created modifications in which the value of the network UDA 'CX_PCU_AV1' is not equal to 1, for example modification 2 with a PCU factor of 0.8. If you do not use such a modification, the demand of AV1 behaves like conventional vehicles of the demand segment CAR and the variation of the share has no effect.

With the results that you obtain from the scenarios, you can test the influence of autonomous vehicles or the underlying assumptions about driving behavior. In the example we can see how the total vehicle kilometers (VMT - Vehicle Miles Traveled) or hours (VHT - Vehicle Hours Traveled) change with the PCU factor or the share of autonomous vehicles in total demand. The following diagrams illustrate this for this example.

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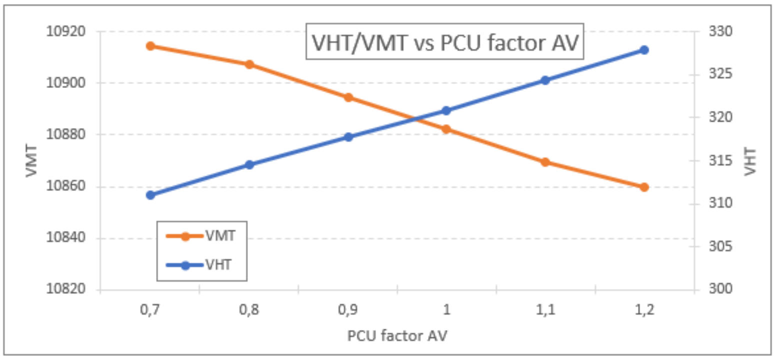
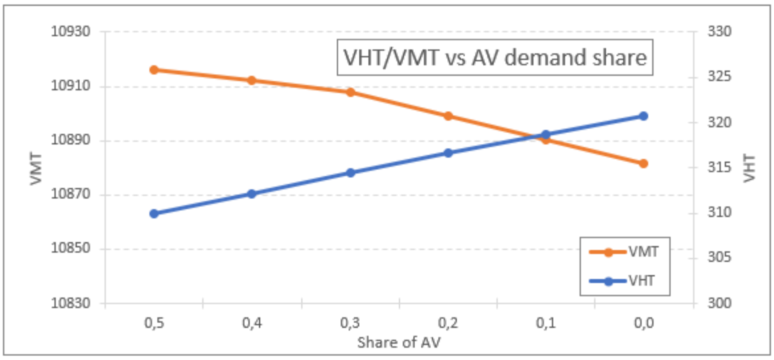


Test	AV1 - PCU	CAR - PCU
1	0.7	1.0
2	0.8	1.0
3	0.9	1.0
4	1.0	1.0
5	1.1	1.0
6	1.2	1.0



Test	AV1 - share	CAR - share
1	0.5	0.5
2	0.4	0.6
3	0.3	0.7
4	0.2	0.8
5	0.1	0.9
6	0.0	1.0

The tests highlighted in grey represent variants in which there are either no autonomous vehicles in the network or their driving behavior does not differ from that of conventional vehicles.

6.2 User-defined VD function

The .DLL and the source code of the user-defined VD function used in this example can be found in the subfolder \USERDEFINED_VDF\.
The calculation of the total volume in PCU assumes that autonomous vehicles (transport systems AV1 and AV2) on 'AV-ready' links have a fixed value for the PCU factor. This is defined in a link UDA. Otherwise, the value defined at the transport system applies to PCU.
With a user-defined VD function you can also make other assumptions about autonomous vehicles, for example the effect, i.e. the factor for PCU, can also depend on the share of autonomous vehicles on an 'AV-ready' link.
More information on creating the .DLL and the contents of the code can be found in the manual and in the comments of the *.CPP and *.H files.
corresponding values, you must define user-defined attributes with corresponding formulas.

Note: Please note that the factors underlying the VD function are only used to calculate the travel time in the loaded network (tCur). In particular, they have no effect on calculated attributes from the assignment, such as volumes in PCU. To output or display corresponding values, you must define user-defined attributes with corresponding formulas.

7 Modelling of autonomous vehicles in SBA

In simulation-based dynamic assignment (SBA), the concept of using passenger car units does not exist. The loading of the network is carried out by a simulation with a simplified car following model.

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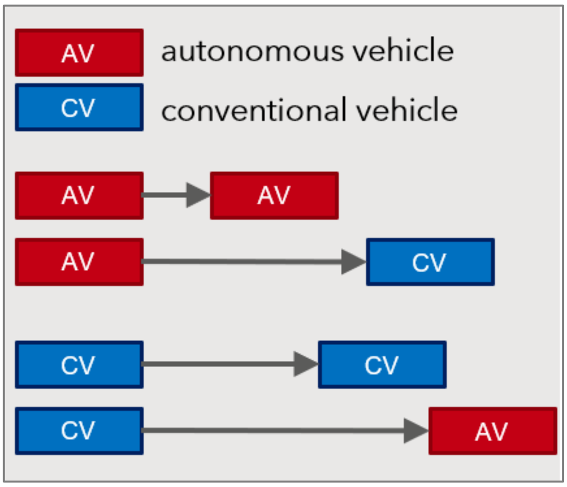
In order to represent different driving behaviour of autonomous vehicles, the following behaviour must be influenced. Basically, this possibility is given by the link attribute 'SBA reaction time factor'. However, this factor is applied universally to the reaction times of all vehicles on the link. Moreover, in the case of autonomous vehicles, it is assumed that the following behaviour also depends on the vehicle in front. If, for example, this is an autonomous vehicle, i.e. one AV follows another AV, the distance may be smaller than if the front vehicle was a conventional vehicle. In order to map the behaviour of autonomous vehicles in the simulation, the reaction time factor must depend on the transport system of the vehicle itself and on the transport system of the vehicle in front. These extended setting options for the transport system-dependent factors of the reaction time are permitted by the attribute 'SBA is reaction time factor transport system dependent'. If this attribute is not activated, the 'SBA reaction time factor' attribute by default applies to all vehicles on the link. With this logic, 'AV-ready' can be mapped on a link by activating the attribute 'SBA is reaction time factor transport system dependent'. Only after activating the attribute you can enter factors for possible combinations of transport systems. The following figure outlines combinations for two transport systems AV and CV on 'AV-ready' links.



7.1 Steps of the example for SBA

The example for the use in SBA includes steps for the modelling of autonomous vehicles as well as some evaluation possibilities.

7.1.1 Prerequisites for modelling with autonomous vehicles

In a first step, the model will be extended to include a transport system of autonomous vehicles. To do so, proceed as follows:

1. Set all project directories to the subfolder of the example \SBA\.
2. Open the SBA.VER version file.
3. From the **Demand** menu, choose **TSys/Modes/Demand Segments**.
4. Add a transport system AV1, for which you also create modes and demand segments with the same code. When inserting the transport system, activate the **Transfer network attributes from: CAR** option. In the dialog that opens next, create a mode and demand segment with the same code and name.
   The transport system AV1 is thus permitted on the same network objects as CAR.
5. In the next step, import the user-defined attributes (UDA). To do this, select **Open** > **Network** from the **File** menu, open the CX_UDA_SBA.NET file and confirm all dialogs that open.

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6. Open the **Attributes** list and use the drop-down list to restrict it to **Only user-defined**.
   The list contains a calculated UDA for links. The UDA is not required but allows the display of the actual factor used for the SBA reaction time for AV1. The two network UDA serve to determine the share of demand for AV1.
   For links, the factor of the reaction time depends on whether a link was modelled as 'AV-ready'. In SBA, a link is considered 'AV-ready' if it allows the use of the transport system dependent factor. This is done by setting the attribute 'SBA is reaction time factor transport system dependent' to True. In this case, factors can be defined for all combinations of vehicles of the transport systems. In the example, we limit ourselves to changing the factor for a vehicle of the transport system AV1 that follows another AV1, i.e. we only change the attribute 'SBA reaction time factor PrTSys-PrTSys (AV1,AV1)'. The calculated attribute indicates this value on 'AV-ready' links, otherwise the value of the attribute 'SBA reaction time factor' applies. The following table gives an overview of the user-defined attributes.

Network object	AttrID	Formula	Use
Link	CX_SBAFactor_AV-AV	Yes	Is calculated: used factor for the reaction time depending on AV-ready links
Network	CX_Share_AV1	No	Input: Share from matrix no. 1 for demand AV1
Network	CX_Share_CAR	Yes	Is calculated: Matrix no. 1 minus demand for AV1 and AV2

7. Next, create 2 formula matrices. In the example, the demand of the existing matrix is divided between the demand segments to be assigned CAR and AV1 using formulas.
   - Open the **Matrices** list via the **Lists > Demand** menu.
   - Use the **Create** button to create two matrices of the **Formula matrix** type in the list. If you create the two matrices in one step by setting the number of matrices to be inserted to 2, first specify matrix no. 1 under **Edit formula**. After creating the two matrices, import the file CX_MATRIX_SBA.DMD. Under conflict handling, change the entry to **Overwrite attributes**.

   The DSegCode column references the matrices as assignment matrices.
8. Change the network UDA for the share of the demand AV1 (menu **Network > Network settings**) by entering the value 0.3 for CX_Share_AV1.
   The remaining demand is automatically assigned to the demand segment CAR.

The steps above complete all the prerequisites for modelling with AV. Now you just need to define 'AV-ready' links in order to take into account the characteristics of autonomous vehicles in the context of a simulation-based assignment (SBA). First, an assignment is carried out in this state and then a scenario with 'AV-ready' links is calculated and compared. As long as no 'AV-ready' links are defined in the network, the vehicles of the AV1 transport system behave like conventional vehicles, i.e. the SBA reaction time factor applies, which is independent of the transport system of the preceding vehicle.

7.1.2 Calculating an assignment with autonomous vehicles

1. Switch to the procedure sequence and change the reference objects so that the demand of all transport systems is assigned. Execute the procedure sequence and then load the graphic parameters file RESULT_SBA.GPA using the list box in the menu of the network editor. Save the version as SBA_NOAV.VER.

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2. Switch to the link list **List (Links)**.
   In this list, a column filter is active for the attribute 'AddVal2'. First import the list layout SBA_LINKS_INPUT.LLA. Set the attribute 'SBA is reaction time factor transport system dependent' to True for all 135 filtered links. Then the values for the attribute 'SBA reaction time factor-PrTSys-PrTSys (AV1,AV1)' must be defined. For the scenario, we set this value to 0.8. The assumption underlying this value is that autonomous vehicles on 'AV-ready' links travel at a shorter distance when they follow another autonomous vehicle. The driving behaviour does not change if an autonomous vehicle follows a vehicle of the transport system CAR.
3. Rerun the assignment.

In the example, it is primarily interesting to see how the volumes of CAR change throughout the analysis period. The changes are examined on the basis of a version comparison.

7.1.3 Comparing versions with and without autonomous vehicles

1. From the **File** menu, choose **Compare and transfer networks** > **Version comparisons**.
2. Click **Add** and select the **Load comparison network in the background** option.
3. Select the version file SBA_NOAV.VER and enter the code 'noAV'.
4. Confirm with **OK**.

You can analyse the changes by loading the graphic parameters file VERSCOMPARISON_SBA_NOAV_CAR.GPA (changes to volumes in demand of CAR in vehicles).
You can find the results of the comparison with the differences for CAR in the version SBA_COMPARISON.VER. The display compares values for the analysis period but can be transferred to analysis time intervals.
For reasons of simplification, we have refrained from comparing the results of several assignments with different random seeds that are necessary for a valid statement.
In SBA, the influence of autonomous vehicles (AV) can be examined with regard to key indicators such as total vehicle kilometres or total vehicle hours. For future scenarios, certain assumptions can be implied, and their effects analysed. For example, we vary the assumptions regarding the SBA reaction time factor PrTSys-PrTSys on 'AV-ready' links and the share of AV in total demand for such an analysis. You can use scenario management for such an analysis since you can compare indicators directly after calculating the scenarios. The following steps provide further guidance on how to proceed with the project for such an analysis. The delivered example contains a scenario management project in which the scenarios have not yet been calculated.

7.1.4 Comparison of different scenarios

The base version of a scenario management project is created from the version SBA_NOAV.VER.

1. Open this version and make the following changes:
   - Initialize the assignment.
   - In the link list, load the layout SBA_LINK_INPUTS.LLA and set the value of the attribute 'SBA reaction time factor transport system dependent' to True for the filtered 135 links. We vary the values for the attribute 'SBA reaction time factor-PrTSys-PrTSys (AV1,AV1)' in the modifications.

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2. Save this version as SBA_BASE.VER. With these changes, we get a base version where the demand of AV1 behaves like that of CAR, i.e. the factor for SBA reaction time is 1.0 in the whole network.
3. Use the SBA_BASE.VER version to create a scenario management project 'SBA_AV', for which you create \SBA_AV\ in a subfolder.
4. Create 5 modifications in which you vary the values of the link attribute 'SBA reaction time factor-PrTSys-PrTSys (AV1,AV1)' for the 135 filtered links of the open link list from 0.7 to 1.2 with a step size of 0.1. A value of 1.0 corresponds to the state of the base version and requires no modification.
5. Create a procedure parameter set based on the procedure parameters of the base version. Create a procedure variable 'RS' with a procedure reference 'Simulation-based dynamic assignment SBA\Base\Random seed'. This allows you to define multiple scenarios with the same modification, but which uses a different random seed for the assignment. You can average the ratios of these scenarios to obtain statistically validated results.
6. On the **Basic settings** tab, create scenario indicators. Use the relation to the Simulation-based dynamic assignment (SBA) quality data (last iteration).

In the following list of the selected indicators you will find the used name of the alias in brackets:

- PrT Simulation-based dynamic assignment quality data (last iteration)\Iteration (Iter)
- PrT Simulation-based dynamic assignment quality data (last iteration)\Gap (AP) (GAP)
- PrT Simulation-based dynamic assignment quality data (last iteration)\Vehicle miles travelled PrT (VMT)
- PrT Simulation-based dynamic assignment quality data (last iteration)\Vehicle hours tCur (VHT)

7. For the base version and each modification, create 5 scenarios to which you assign the procedure parameter set 1. Vary the random seed in column RS, e.g. from 10 to 50 with a step size of 10.

The view of the 30 scenarios is as follows:

Basic settings | Scenarios | Modifications | Procedure parameter sets | Global layouts | Comparison patterns | User-def. attributes | Distributed computing | Multi-user mode

Number: 30	Active	Number	Code	Description	Procedure parameter set	Modifications	Calculation state	Compute node	RS	Iter	GAP	VMT	VHT
1	☒	2	AV-AV_10	0.7	1 RS	1	Not calculated	localhost	10				
2	☒	3	AV-AV_20	0.7	1 RS	1	Not calculated	localhost	20				
3	☒	4	AV-AV_30	0.7	1 RS	1	Not calculated	localhost	30				
4	☒	5	AV-AV_40	0.7	1 RS	1	Not calculated	localhost	40				
5	☒	6	AV-AV_50	0.7	1 RS	1	Not calculated	localhost	50				
6	☒	7	AV-AV_10	0.8	1 RS	2	Not calculated	localhost	10				
7	☒	8	AV-AV_20	0.8	1 RS	2	Not calculated	localhost	20				
8	☒	9	AV-AV_30	0.8	1 RS	2	Not calculated	localhost	30				
9	☒	10	AV-AV_40	0.8	1 RS	2	Not calculated	localhost	40				
10	☒	11	AV-AV_50	0.8	1 RS	2	Not calculated	localhost	50				
11	☒	12	AV-AV_10	0,9	1 RS	3	Not calculated	localhost	10				
12	☒	13	AV-AV_20	0,9	1 RS	3	Not calculated	localhost	20				
13	☒	14	AV-AV_30	0,9	1 RS	3	Not calculated	localhost	30				
14	☒	15	AV-AV_40	0,9	1 RS	3	Not calculated	localhost	40				
15	☒	16	AV-AV_50	0,9	1 RS	3	Not calculated	localhost	50				
16	☒	17	AV-AV_10	1.0	1 RS	...	Not calculated	localhost	10				
17	☒	18	AV-AV_20	1.0	1 RS	...	Not calculated	localhost	20				
18	☒	19	AV-AV_30	1.0	1 RS	...	Not calculated	localhost	30				
19	☒	20	AV-AV_40	1.0	1 RS	...	Not calculated	localhost	40				
20	☒	21	AV-AV_50	1.0	1 RS	...	Not calculated	localhost	50				
21	☒	22	AV-AV_10	1.1	1 RS	4	Not calculated	localhost	10				
22	☒	23	AV-AV_20	1.1	1 RS	4	Not calculated	localhost	20				
23	☒	24	AV-AV_30	1.1	1 RS	4	Not calculated	localhost	30				
24	☒	25	AV-AV_40	1.1	1 RS	4	Not calculated	localhost	40				
25	☒	26	AV-AV_50	1.1	1 RS	4	Not calculated	localhost	50				
26	☒	27	AV-AV_10	1.2	1 RS	5	Not calculated	localhost	10				
27	☒	28	AV-AV_20	1.2	1 RS	5	Not calculated	localhost	20				
28	☒	29	AV-AV_30	1.2	1 RS	5	Not calculated	localhost	30				
29	☒	30	AV-AV_40	1.2	1 RS	5	Not calculated	localhost	40				
30	☒	31	AV-AV_50	1.2	1 RS	5	Not calculated	localhost	50				

8. Perform the calculations of all scenarios and average the numbers from the calculations with different random seeds.

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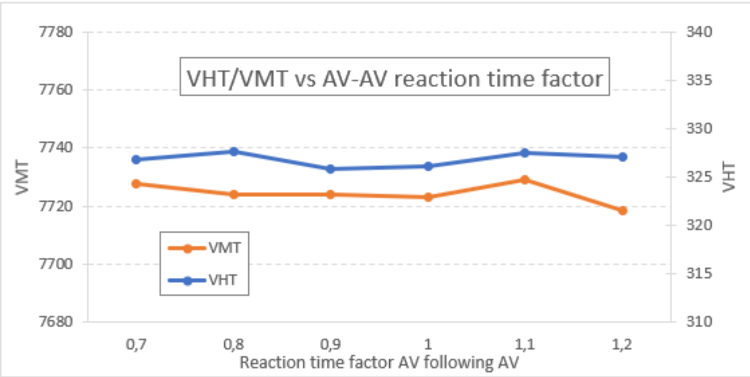
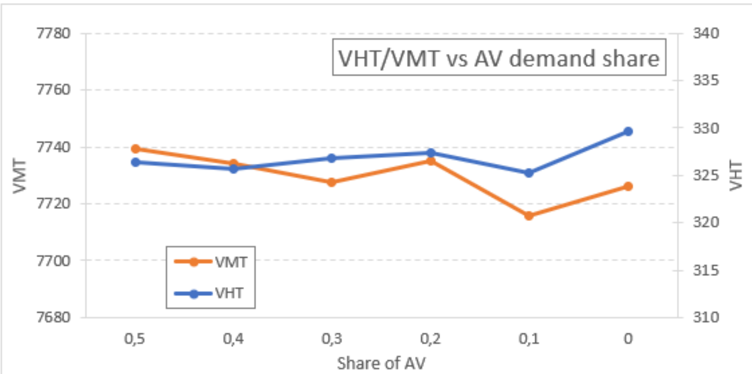
You can use the results to evaluate how changes in the assumptions about driving behaviour affect the indicators.

9. Expand the project by varying the share of the demand in the AV1 segment. Based on a modification of driving behaviour assumptions, e.g. modification 1 with a factor of 0.7 for the reaction time between two vehicles of the transport system AV1.
10. Create 5 modifications in which you vary the share, i.e. set the value of the network UDA 'CX_Share_AV1' to 0.5, 0.4, 0.2, 0.1 or 0. A share of 0.3 is covered by the definition in the base version.
11. As before, create 5 scenarios with different random seeds for each of these modifications. The results for a share of 30% demand AV1 are already available and therefore no additional scenarios are needed for this case. In total, the project contains 60 scenarios: 30 with a variation of the reaction time factor AV-AV and 30 with a variation of the AV share of demand.
12. Also, perform the calculations of all scenarios and average the results from the scenarios with different random seeds.

With the results that you obtain from the scenarios, you can test the influence of autonomous vehicles or the underlying assumptions about driving behaviour. In the example, we can see how the total vehicle kilometres (VMT - Vehicle Miles Travelled) or total vehicle hours (VHT - Vehicle Hours Travelled) change with the PCU factor or the share of autonomous vehicles in total demand. The following diagrams illustrate this for this example.



Test	AV1 - AV1	Others	AV1 - share
1	0.7	1.0	0.3
2	0.8	1.0	0.3
3	0.9	1.0	0.3
4	1.0	1.0	0.3
5	1.1	1.0	0.3
6	1.2	1.0	0.3



Test	AV1 - share	CV - share	AV1 - AV1
1	0.5	0.5	0.7
2	0.4	0.6	0.7
3	0.3	0.7	0.7
4	0.2	0.8	0.7
5	0.1	0.9	0.7
6	0.0	1.0	0.7

The tests highlighted in grey represent variants in which there are either no autonomous vehicles in the network or their driving behaviour does not differ from that of conventional vehicles.

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8 Influencing factors in the analysis of autonomous vehicles

In the example, we have deliberately refrained from a detailed interpretation of the results, as this is an example with fictitious assumptions.
In the following, we describe factors that influence the results of such an analysis. For the explanations, we use the present example.

8.1 Assumptions about AV

- Static: To the VD function used here applies: every AV on an 'AV-ready' link has an influence on the capacity – and consequently on the travel time.
- SBA: In SBA, the influence is limited to cases where a deviating vehicle behaviour has been defined. In this example, this applies to autonomous vehicles that follow other autonomous vehicles. The following behaviour of autonomous vehicles does not change if they follow conventional vehicles on a link.

Also note that the influence of the changed following behaviour is less direct than in static assignment. The changed following behaviour as such does not lead to a change in the travel time: The following vehicle drives at the same speed yet at a different distance behind the vehicle in front. However, as a consequence of the changed following behaviour - in the case of a factor smaller than 1 - more vehicles can pass over a link in one hour before queues form. The wait time of the congestion influences the subsequent travel time and route choice

8.2 Network structure

In this example, a dense road network with a large number of alternative routes is considered. Autonomous vehicles do not have an additional incentive to use 'AV-ready' links in the present network, nor are they limited to these.

8.3 AV-ready infrastructure

In most studies, the choice of links equipped for AV will be limited to predefined network components, e.g. highways. Nevertheless, the number of links and their importance in the network have an influence on the results.

8.4 Node impedances

In SBA, junction control and geometry play a crucial role for delays in the network. In static assignments, this influence is either neglected or only partially recorded. In dense networks with many signal controls, the travel time gain on links can be cancelled out by wait times at nodes. This is also influenced by the coordination of signal controls.

8.5 Impedances (and VD functions)

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The impedance definition (and VD function in static assignments) determines how sensitively drivers react to changes. If, for example, the travel time in the impedance is provided with a relatively high coefficient compared to other impedance components, longer but faster routes may be chosen.

8.6 Level of demand

In addition to a variation of driving behaviour parameters of autonomous vehicles and the share of AV in demand, the level of total demand over a range can also be investigated. In static assignment, the effect of a single AV on travel time depends on the VD curve. VD curves typically rise steeper with increasing occupancy, i.e. the effect on the travel time of the PCU factor also changes with occupancy. In SBA, the advantages of e.g. denser driving become clearer when the probability of congestion increases.

9 Additional source of information

The built-in functionalities have also been presented in a webinar that is available on the CoEXist YouTube channel under this link: https://www.youtube.com/watch?v=PHDeRbvpfkw

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