PARAMETRIC MODELLING OF THE EXTERIOR DESIGN OF AUTONOMOUS SHUTTLES

Hafemann, Philipp;
Daumoser, Manuel;
Lienkamp, Markus

Technical University of Munich

ABSTRACT

Autonomous vehicles for the last mile are a promising use case for advancing autonomous driving in real-world traffic. For this purpose, traditional car manufacturers and newcomer companies develop a new vehicle concept: the autonomous shuttle. During the development, components from the automation domain, such as the sensors, must be placed and integrated into the vehicle body. The trade-offs between the functional performance of the perception and the exterior design must be evaluated early in the design process. For this purpose, a model of the vehicle exterior is needed. In this contribution, we present a method for parametric modeling of the vehicle exterior of autonomous shuttles. We define 17 input parameters and use computer-aided design to create a virtual model of the body and the wheelhouses. In the results, we validate our method by ensuring that existing shuttles can be modeled with our approach and also analyze the limitations. The model supports decision-making in the early design phase by enabling quick iterations between sensor placement and exterior design.

Keywords: Computer Aided Design (CAD), Early design phases, Virtual Engineering (VE), Exterior Design, Sensor Integration

Contact:
Hafemann, Philipp
Technical University of Munich
Germany
hafemann@ftm.mw.tum.de

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1 INTRODUCTION

Autonomous driving is one of the major trends in the automotive industry and a key technology for future transportation because it will increase safety, improve efficiency in terms of traffic flow as well as emissions, and enable greater participation in mobility (Watzenig and Horn, 2017, p. 3). Starting with research at universities at first, major car manufacturers, as well as newcomer companies, today are working towards automating the driving function.

On the one hand, this trend changes the vehicle itself. A promising new autonomous vehicle (AV) concept presented by several companies is the autonomous shuttle. It can transport multiple persons, while still being smaller than a conventional public bus. Due to their high utilization as a supplement for collective public transport, autonomous shuttles are expected to be the first vehicle type offering autonomous transportation in cities (Mira-Bonnardel, 2021, p. 103).

On the other hand, autonomous driving requires adaptions in the development process. Besides a more user-centric design for interiors, autonomous driving also requires the integration of sensors and their computing hardware into the vehicle. With higher autonomy levels, the number of sensors used will reach up to 30 sensors (Frost and Sullivan, 2018). They must be considered at an early stage in the development process because they affect the functionality of the automated driving function, and also impact other vehicle properties, like the exterior or aerodynamics. These domains all interact with the design of the vehicle body.

Therefore, a virtual model of the vehicle body is needed early in the development process. The model must account for the numerous degrees of freedom in this phase and be highly parametric. In this contribution, we present a methodology to parametrically model the vehicle body of autonomous shuttles.

2 STATE OF THE ART

In this chapter, we first work out the importance of autonomous shuttles for autonomous transportation and present existing vehicle concepts. We address the process for concept development of AVs and especially focus on the role of the vehicle body and sensor integration. In the end, we formulate the research gap for integrating sensor setup definition and vehicle body design into the development process.

2.1 Autonomous shuttles

A promising use case for autonomous shuttles is seen in the supplement or replacement of public transport in cities (Mira-Bonnardel and Attias, 2018). From the user side, people have the chance to experience autonomous technology first-hand and therefore gain trust. From the operator side, the shuttles can be used for on-demand, last-mile transportation making it easier to transport people with less amount of public transport vehicles (Bucchiarone et al., 2021).

Research from Antonialli (2019) finds a total of 92 deployments of autonomous shuttles by the end of 2019 for which shuttles from 20 different manufacturers are used. Figure 1 depicts shuttles from traditional vehicle manufacturers, such as Kamaz, Toyota, or Baidu as well as newcomers, such as Navya, Zoox, or Local Motors.

The shuttles' sensor setup and integration into the vehicle body differ, although they are all fully autonomous and are used in the same application. No publication was found explaining the process of designing sensor setup and integration into these shuttles. This shows the need for a methodology to integrate the sensor setup definition and sensor integration into the design process.

2.2 Autonomous vehicle concept development

With the absence of a driver's workplace, AVs offer new degrees of freedom in the development process. The removal of the steering wheel and the use of by-wire steering and braking systems allow for new interior concepts (Tzivanopoulos et al., 2014). New approaches are necessary to develop the vehicle concept, since no previous vehicle generations exist that could serve as starting point nor are traditional standards for vehicle packaging applicable to AVs (König et al., 2021).

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Figure 1. Autonomous shuttles from traditional car manufacturers Kamaz[1], Toyota[2], Baidu[3] (top, l.t.r) and newcomer companies Navya[4], Zoox[5], Local motors[6] (bottom, l.t.r)

As part of defining the vehicle concept, the package of the vehicle must be developed. The package includes the size and positions of all relevant components and subsystems. In literature, two "directions" for designing the package are described: from the interior design to the exterior design ("inside-to-outside") or conversely ("outside-to-inside").

Researchers in the field of AV concept development are proposing to give higher priority to the former approach where the sequence of designing the vehicle starts with the passenger, followed by the interior, and lastly the exterior definition of the vehicle (Tzivanopoulos et al., 2015; König et al., 2021; Seeger, 2014, p. 180).

In König (2022), an "inside-to-outside" method is developed to perform concept design optimization for AVs in an early design stage. The method is implemented in an open-source tool (FTM, 2022). Starting from the seating layout in the interior, they optimize the vehicle concept for given product specifications. They use dimensional chains for the interior of AVs introduced by König et al. (2021) and include detailed models of the powertrain components, wheels, suspension, and structural beams (Figure 2). After that, the base exterior dimensions are determined, and the exterior contour is modeled. They also consider the additional power consumption of environment sensors and computing units but neglect the positioning of sensors and their effect on the exterior design.

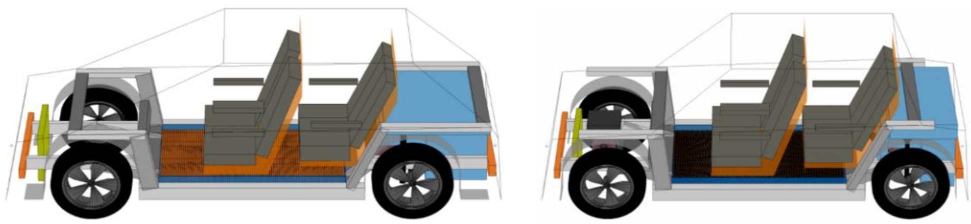

Figure 2. Concept design optimization of powertrain, package, and exterior. left: before optimization, right: after optimization of exterior and powertrain. Taken from König (2022)

Bhise et al. (2009) introduce a similar design tool including passenger packaging, ergonomics, and body structural analysis. The tool is not specifically focused on AVs, but they highlight the necessity of their tool to use the input from designers in form of exterior surfaces and assess the compatibility between the interior package and the vehicle exterior.

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1 https://www.e-autos.de/news/elektro-shuttle-ist-bei-der-wm-in-russland-autonom-unterwegs/ (accessed 30 November 2022)
2 https://global.toyota/en/newsroom/corporate/29933371.html (accessed 30 November 2022)
3 https://developer.apollo.auto/index.html (accessed 30 November 2022)
4 https://navya.tech/en/solutions/moving-people/self-driving-shuttle-for-passenger-transportation/ (accessed 30 November 2022)
5 https://zoox.com/vehicle/ (accessed 30 November 2022)
6 https://utopia.de/ratgeber/elektrobus-olli-local-motors/ (accessed 30 November 2022)

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2.3 Vehicle exterior design

Developing a suitable exterior design can be subdivided into four different phases (Wolff et al., 2021): Creative Concept Phase, 3D Development, Physical Design Models, and Color and Trim. In the creative concept phase, the vehicle's basic design characteristics and proportions are derived from the vehicle specification sheet. Traditionally, sketching different style proposals in 2D is the key method, because it best supports the explorative nature of the process (Tovey et al., 2003). In the second step, some candidate designs are translated into a 3D model for further evaluation by designers and engineers. New technologies like Virtual Reality and Artificial Intelligence are introduced to facilitate the transfer from 2D sketches to 3D models (Islas Munoz et al., 2022; Joundi et al., 2020). This second step is highly iterative and collaborative between teams from design and engineering. When creating the 3D model, requirements from different technical domains like package, ergonomics, aerodynamics, legal, safety, or manufacturing must be considered (Wolff et al., 2021; Hucho, 2013, p. 57).

The third step consists of building miniature models for a reduced number of candidate designs to further trim and detail the exterior design. In the last step, colors and materials for the interior and exterior are selected. After these four phases are finished, the design freeze milestone is reached.

2.4 Sensor setup and integration

For AVs, the domain of sensor setup and sensor integration needs to be considered with their influence on the design and aerodynamics. Sensor housings are often protruding the vehicle body and therefore impact the aerodynamics. Although no study specifically analyzed the effects of sensors, research about the impact of taxi signs shows an increase in the aerodynamic drag by up to 5% (Chowdhury et al., 2012).

Similarly, the sensor setup has an impact on the exterior design. Placing sensors outside the vehicle body increases their functional performance since their field-of-view becomes larger, but it also alters the vehicle's appearance. Therefore, the sensor placement and integration strategy must be part of the vehicle design process. Hartstern et al. (2020) propose a method for evaluating different sensor setups in an early design phase. However, in their approach, the vehicle body is not modeled. Liu et al. (2019) optimize the sensor placement of an existing production vehicle using a detailed body model.

Fischer et al. (2021) analyzed 18 different passenger cars including research and concept vehicles for their sensors and the integration strategy. They distinguish between an additive and an integrative design strategy. The additive strategy sees the sensor integration as a step following the design of the vehicle, whereas the integrative strategy seeks to include the sensor integration as part of the design process. They conclude that the integrative strategy leads to a more harmonic design, but the implementation of this strategy requires consideration of the functionality and positions of the sensors at an early stage in development.

2.5 Research gap

Since autonomous shuttles are a new vehicle type, the development of these vehicles cannot be based on previous knowledge, processes, or standards. Existing approaches for adapting the development process for AVs are based on an "inside-to-outside" approach, where the vehicle exterior is defined last. These approaches do not consider new domains, like the sensor setup definition and integration into the vehicle exterior. Contrary, research that deals with sensor setup definition is focused on optimizing the performance of the perception task and does not consider the vehicle exterior or the development process. The exterior in this research is either neglected or an existing car's exterior is used. Designing a complex system like an autonomous shuttle requires modeling both the vehicle exterior and sensor setup at an early stage with a sufficient level of detail. The sensor setup impacts the design and at the same time, the design might impair the field of view of the sensors. Therefore, a methodological approach to co-design the sensor setup and exterior before the design freeze in the development process is still missing. To identify a conflict of objectives between these domains, it is important to have a virtual vehicle exterior as early as possible. Therefore an approach to quickly model the vehicle body as a 3D representation, either from scratch or based on a 2D sketch is needed.

In this article, we present an approach to parametrically model the exterior which is suitable for usage in early vehicle design stages. In Chapter 3 we describe the approach and give a detailed description of the model. Chapter 4 demonstrates the capabilities of the model by validating its result against already presented real-world shuttles.

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3 METHODOLOGY

In the first step, the requirements for the model are derived and presented in the following:

1. It must apply to autonomous shuttles.
2. It must be usable in the early design phase, in which the number of possible designs is large.
3. The parametric model should require a minimum number of parameters to be able to quickly iterate and create different design proposals.
4. The model must generate a high-quality surface. There should be no sharp bends, creases, or non-continuous areas on the surface.

For the first requirement, the current vehicles from Figure 1 were analyzed. The presented shuttles can be characterized as vehicles with a One-box design and symmetry along both the longitudinal and transversal axis. The symmetry between the front and rear also underlines the ability of some of the shuttles to operate bi-directionally. Considering the symmetry, the modeling approach can be reduced to a quarter vehicle and mirrored later in the process.

The second and third requirement determines the required level of detail. Our approach should enable the conversion of a 2D sketch to a 3D representation. Detailed styling elements, such as lights or radiator grills, are not necessary to be included, but the general shape must be represented. According to findings from Tovey et al. (2003), the form lines are key descriptors when sketching automotive shapes. Their finding also emphasizes the importance of wheels and wheelhouses. Consequently, our approach focuses on the centerline, the shoulder contour, the wheelhouses, and the wheels. Given the symmetry assumption, our approach should model the shape along one centerline and one shoulder line. Further parameters are needed for the position and size of wheel components. The trade-off between the level of detail and complexity of the parametric model must be balanced.

The fourth requirement implies that the contour lines must have a continuous curvature and different segments of the line must merge tangentially.

From the requirements, we derived the method for creating the virtual vehicle body. The whole process is depicted in Figure 3, and the parameters we derived as input parameters are sshown in Table 1.

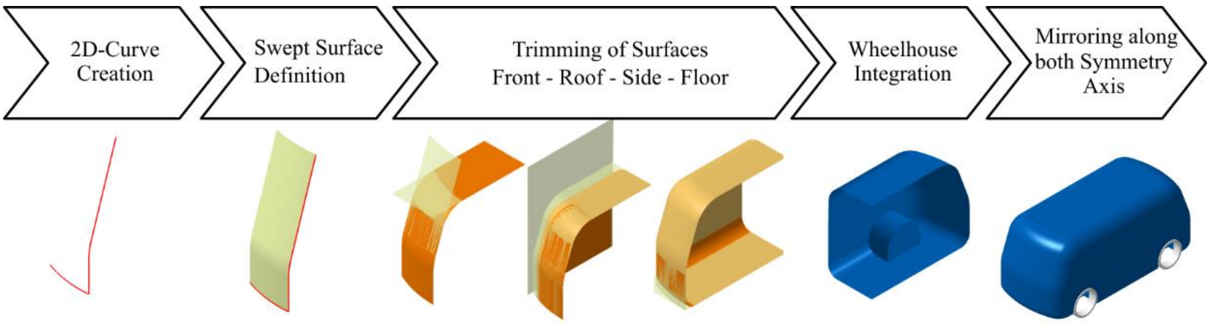

Figure 3. The process to model the exterior design of autonomous shuttles

We use 17 input parameters belonging to three distinct groups. The first group consists of the vehicle base parameters that define the vehicle length, height, width, and ground clearance. Geometrically, they define the base shape of the vehicle as a rectangular box. The second set of parameters contains the design parameters that refine the rectangular shape. The last set of parameters describes the wheelhouse and wheel parameters and are used later in the process.

Table 1. Parameter sets for autonomous shuttle exterior design

Base Parameters	**Design Parameters**	**Wheel Parameters**
Vehicle Length (VL) Vehicle Width (VW) Vehicle Height (VH) Ground Clearance (GC)	Rounding Vehicle Front (RF) Rounding Vehicle Front to Roof (RFR) Rounding Vehicle Side to Roof (RSR) Rounding Vehicle Front to Floor (RFF) Rounding Vehicle Side to Floor (RSF) Front Inclination (FI) Side Inclination (SI) Height of Start of Inclination (HSI) Rounding Vertical to Inclination (RVI)	Wheelbase (WB) Trackwidth (TrW) Tire Diameter (TD) Tire Width (TiW)

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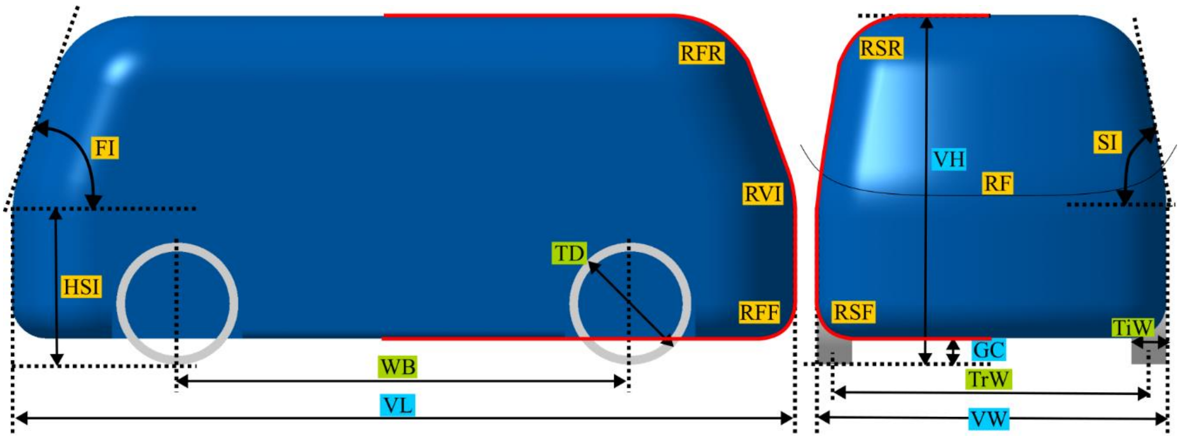

Figure 4. Definition of the parameters (base blue, design yellow, wheel green) and contour lines (red) for the side and front view

The first step of our process includes creating the contour lines on planes representing the side, front, roof, and bottom of the vehicle, respectively. The position and size of the planes are defined by the base parameters. The course of each polyline is modeled using the design parameters.

In the second step, a *swept surface transformation* is applied for each plane respectively, meaning that one polyline is extruded using the other polyline as a guidance path (Catiadoc, 2012b, 2012c). This transformation yields a three-dimensional surface. The step is done for each of the four vehicle planes resulting in four surfaces. In the third step, these surfaces are intersected and trimmed using a *bitangent shape fillet* (Catiadoc, 2012a). This operation removes surfaces outside the intersection and allows to define a radius for the fillet between the two surfaces. By defining the radius parameters from Table 1, the rounding of the edges is created in this transformation (Figure 5). The order of intersecting the surfaces is defined in descending order of priority: first, the front surface is intersected with the roof surface. The result is then intersected with the side surface, and last, the intersection with the floor surface is performed.

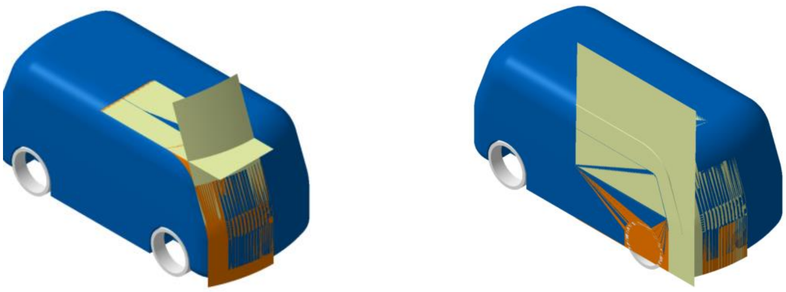

Figure 5. Trimming of the front with the roof (left) and the front-roof with the side (right)

After these steps, the wheelhouse is integrated into the quarter vehicle. The dimensions and positions are calculated using the wheel parameters. Given the tire width *TiW* and diameter *TD*, the wheelhouse length l_{wh} is given by

$$l_{wh} = \sqrt{TiW^2 + TD^2} \tag{1}$$

and the wheelhouse width w_{wh} can be derived with the maximum steering angle δ_{max} by the formula given by Nicoletti et al. (2020):

$$w_{wh} = 0.5 \cdot TiW \cdot \cos(\delta_{max}) + 0.5 \cdot TD \cdot \sin(\delta_{max}) + 0.5 \cdot TiW \tag{2}$$

For our model, the maximum steering angle value is set to a fixed value of 50°, which is a maximum value feasible in today's passenger cars (Pfeffer and Harrer, 2011, p. 56). The positioning of the wheelhouse is defined by the wheelbase and trackwidth and is integrated by trimming the surface of the previous steps once more. As the last step, the quarter vehicle model is mirrored twice to receive the final vehicle exterior model.

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4 RESULTS

For the validation of this model, the three autonomous shuttles from the top of Figure 1 are chosen to be modeled by our approach. The first step is to obtain three 2D views for each vehicle: one for the front, the side, and the top. This is done by researching images, where these vehicles are shown in either of these three perspectives. The images found are then pre-processed. This step includes removing any background and tracing the contour of the vehicle manually to retrieve a planar sketch representation. The sketch representations from each side are set in scale with each other. The results are used as a reference for comparison with the model derived from our approach.
As a next step, the three vehicles need to be modeled by the means of our parametric approach. Therefore, the parameters of the model must be determined. The parameters are obtained using different sources:

1. Manufacturer information. If the manufacturer has provided the information publicly, the values can be taken over directly.
2. Derived parameters. Parameters that are not published are derived through calculation or visual analysis of the reference sketches. When the reference sketches are set in scale and one (reference) dimension is known, it is possible to calculate missing dimensions by measuring the dimension in the image and then scaling it. In some cases, the sensor attachments are enlarging the vehicle, i.e., the manufacturer information is corrected to account for the parameters of the base vehicle without the parts necessary to attach the sensor. Another example of derivation are the radii of the model, which are derived from the true-to-scale reference sketches. The information about the wheel parameters is sparse and therefore derived from the reference sketch.

While taking over parameters from manufacturer information is done easily, deriving parameters from calculations or visual analysis results in inaccuracies. With the determined parameters, the 3D model for each vehicle is generated with the methodology described in the previous chapter. Finally, the original vehicles and our 3D model are compared by overlaying our model's front, top, and side views with the reference sketches. For each of the reference vehicles, a parameter configuration was found that models the vehicle, accordingly, see Table 2. The difference between the reference sketch and the result from our model is depicted in Figure 6.

Table 2. Determined parameters of the three reference shuttles. Superscript 1 denotes a parameter taken directly from the manufacturer's specification

	ZOOX	Navya	Local Motors
Base Parameters			
Vehicle Length / mm	3630[1]	4600[1]	3920[1]
Vehicle Width / mm	1800	2100[1]	2050[1]
Vehicle Height / mm	1936[1]	2500[1]	2500[1]
Ground Clearance / mm	170	200[1]	150
Design Parameters			
Rounding Vehicle Front / mm	4000	4000	4000
Rounding Vehicle Front to Roof / mm	500	1000	600
Rounding Vehicle Side to Roof / mm	400	150	350
Rounding Vehicle Front to Floor / mm	50	50	170
Rounding Vehicle Side to Floor / mm	20	10	10
Front Inclination / deg	75	68	75
Side Inclination / deg	85	82	85
Height of Start of Inclination / mm	600	1100	2500
Rounding Vertical and Inclination / mm	1000	1000	1000
Wheel Parameters			
Wheelbase / mm	2980	2950	2526[1]
Trackwidth / mm	1650	1885	1835
Tire Diameter / mm	800	690[1]	647[1]
Tire Width / mm	215	215[1]	215[1]

For the Zoox, not many parameters were given and needed to be derived. The special shape of the Zoox with its protruding tires is handled well. Differences appear with add-on parts such as the mudguards for

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the wheels, the sensor attachments, and the lower middle of the vehicle, in which radar sensors and lights, are integrated.

For the Navya Autonom Shuttle Evo, there are differences where the sensor housings are present at the lower front of the vehicle. The shape of these sensor integration parts is not represented by our model. The front view shows that the shuttle has a distinct shoulder line, where the vehicle is wider below and less wide above. This design feature is too detailed to be modeled by our approach and above the shoulder, our model is therefore too wide. In the top view perspective, the vehicle rounding from side to front shows that the corner of our model is protruding from the actual rounding from the real vehicle.

The Olli from Local Motors can be reproduced well. Only in the side view, there are differences in the rounding from front to floor. The front-to-floor transition of Olli is distinct because the rounding intersects with the wheelhouses at a height greater than the ground clearance. Our model assumes a ground clearance constant over the length of the vehicle and therefore shows a deviation in this part.

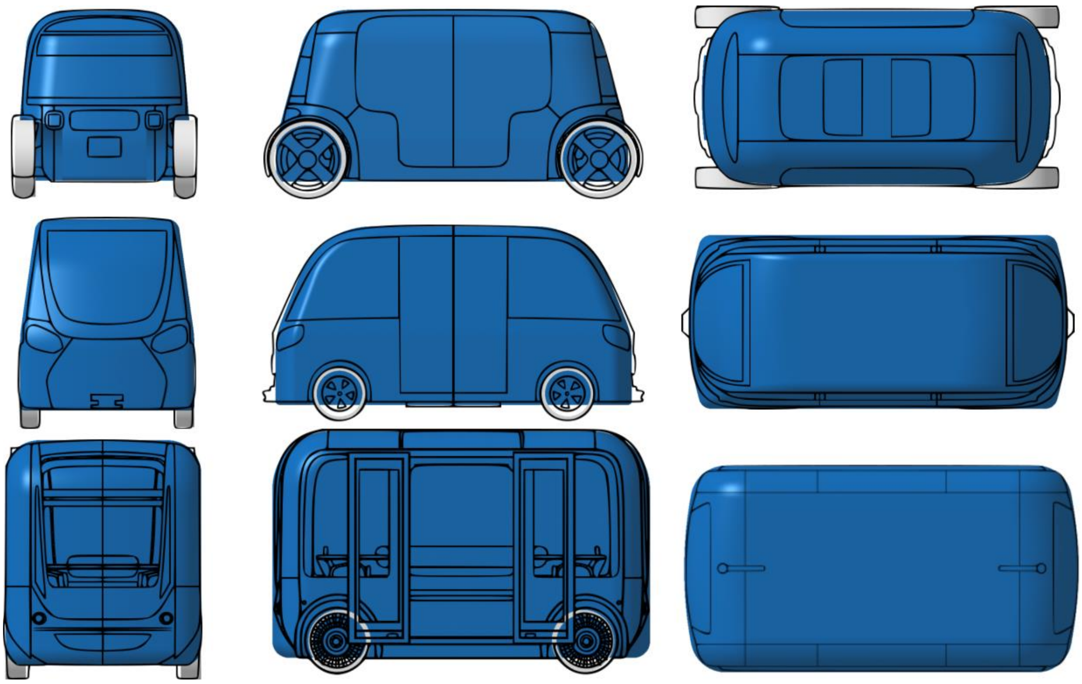

Figure 6. True-to-scale reference sketches of the ZOOX (top), Navya (middle), and local motors (bottom) in comparison with the model from our approach (blue)

The surface quality is checked by using highlight illuminations in the CAD environment. With this virtual lightning, the surface can be checked for both potential defects, such as holes or undercuts, and smoothness. Despite their different body shapes, there are no irregularities on the surface of our three exemplary vehicles (Figure 7). Therefore, a very good surface quality is achieved.

Figure 7. The surface quality of the Navya (left) and local motors (right) under highlight illumination.

In a further step, we investigated the limitations of our modeling approach. As presented in Figure 3, the process consists of a sequence of surface trims with fillets in all main dimensions. Therefore, separate dimensional chains for height, width, and length are used. Since the surface must be tangentially continuous, boundary conditions and limitations can be derived. The value of the parameters must be greater than 0 mm, and the angles parameter α_k must be greater than 0 deg and less

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than 90 deg. For edge cases of 0 deg or 90 deg, the dimensional chains are not defined, i.e., to model a straight vertical plane, an approximation must be used, e.g., 89.9 deg instead of 90 deg.
Another limiting factor is the integration of the wheelhouse. To allow its integration into our body model, the trackwidth must be greater than the width of the two wheelhouses and the wheelbase must be greater than two times the wheelhouse length. At the same time, the wheelbase must be less than the overall vehicle length. At the boundary of the two conditions, the vehicle looks as depicted in Figure 8.

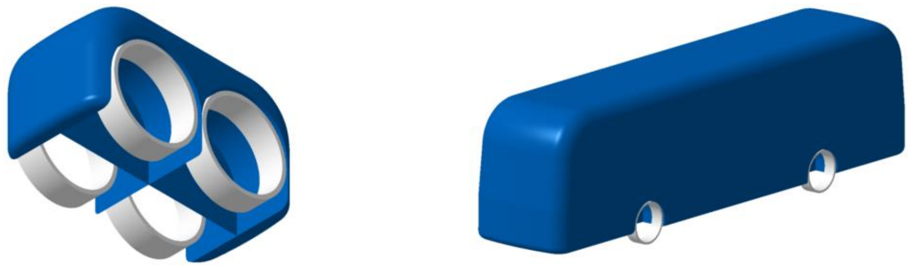

Figure 8. Limitations of the parametric model for narrow (left) or long vehicle variants (right)

5 DISCUSSION AND OUTLOOK

In this paper, we present an approach to model the exterior shape of autonomous shuttles. The approach is fully parametric based on 17 parameters. Our model can be used in the early design phase by relevant stakeholders from design and engineering disciplines. It allows for a quick transfer of 2D sketches into a 3D representation of sufficient detail for the engineering activities, without limiting the creative freedom of the designers. The applicability of the model was shown using three reference shuttles that could well be remodeled by our approach. As long as the vehicle to be modeled is of One-Box-Design, like shuttles or buses, our model is applicable in a wide range.
Using this model early phase of the design helps to uncover potential conflicts between different domains, e.g. between sensor positioning and design. Using our model, different sensor positions and integration strategies can be assessed and analyzed. Since the placement is usually close to the vehicle body, the vehicle's exterior shape should not impair the environment perception of the autonomous driving function. For this purpose, we aim to refine the proposed model by including windows and that further limit the space for sensor placement. In the next step, we will also investigate concepts for sensor integration that will then allow for iterative optimization of both the sensor positions and the design influences of the sensor integration.
Further research can focus on linking our exterior model with existing "inside-to-outside" approaches, that consider the vehicle interior layout, the vehicle package, and the structural components of the vehicle. Combined with the proposed exterior model and consideration of design, sensor integration, and aerodynamics, a more holistic approach is established.

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