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# Open-Source Tools for Road User Safety Assessment from the VIRTUAL Project

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## Abstract

In the assessment of road user and vehicle occupant safety, physical testing is limited to a few scenarios. Virtual testing (VT) offers an opportunity to advance transport safety by introducing additional test cases. The objective of the VIRTUAL project is to provide tools such as finite element models, guidelines and a corresponding platform to foster the uptake of VT. A VT platform, OpenVT, has been established and provides open-source human body models (HBMs) of both an average female and male, seated and standing, as well as a seat, generic vehicle and tram front models. The tool chain from virtual to physical testing has been illustrated in the low severity impact case where the seat evaluation tool was developed. The newly established organisation OVTO will run the OpenVT platform in the future and govern the evolution of the results of the VIRTUAL project after its completion.

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*Keywords:* Finite Element Human Body Models; Open Source; Road Transport; Vehicle Safety; Virtual Testing; Vulnerable Road Users.

## 1. Introduction

In the assessment of road user and vehicle occupant safety, physical testing is limited to a few scenarios. The extensive variation of road user scenarios and road user diversity should be addressed in the assessment of traffic safety. Both current and future vehicles face new challenges in maintaining the general demand for the best possible safety for all road users. For example, automated vehicles will alter passenger and driver behaviour with respect to seating positions. The driver of such a vehicle can adopt a reclined restful posture or rotate the seat sideways to interact

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easier with fellow occupants. New postures pose a challenge for occupant safety and may indeed require development of new restraint systems. Furthermore, road vehicles coexisting with vulnerable road users (VRUs) must also provide exterior protection in case of a collision. However, assessment of new safety systems will be difficult with prevailing directional-dependent crash test dummies.

In the norm for current crash safety assessment in physical testing, vehicle occupants are represented by the average male (height: 1.77 m; weight: 78 kg), although a comparison of the risk of injury between males and females reveals that females are exposed to higher injury risks among a range of different crash types (Bose et al. 2011, Forman et al. 2019, Kullgren et al. 2020). A large difference between male and female injury risk has been reported for injuries to the cervical spine, namely soft tissue neck injuries (also referred to as “whiplash injuries”). Since the mid-1960s, injury statistics show that on average, females are exposed to double the risk (ranging from 1.5 to 3 times higher) of sustaining whiplash injuries compared to males (among others: Kihlberg 1969, Morris & Thomas 1996, Richter et al. 2000, Chapline et al. 2000, Krafft et al. 2003, Jakobsson et al. 2004, Carstensen et al. 2012). Kullgren et al. (2020) found that, while vehicle crashworthiness has improved since the 1980s, the increased risk for females compared to males still remain. Virtual Testing (VT) allows a far wider range of occupant specific characteristics than is, and would ever be, viable in physical testing; including factors related to population heterogeneity, seated position and crash circumstances such as impact speed and angle to be taken into consideration in the assessment of crash safety injury protection performance.

Trams are an important pillar of modern urban mass transit, and they interact with all types of road users. With regard to unprotected road users, available accident data as well as recent efforts in standardisation indicate that the most relevant tram collision scenario involves a crossing pedestrian (Sagberg and Sætermo 1997). VT offers an opportunity for investigating such accidents in detail: i.e., considering a variation of pedestrian characteristics such as size and gender. For these simulations, a generic front model of a tram is available on VIRTUAL's open-source (OS) platform, OpenVT, which corresponds to the current geometric guidelines of the European standard TR 17420 (CEN/TR 17420, 2019) This model can be used to evaluate the weaknesses and strengths of various front geometries. Nowadays, the front design of trams is increasingly focused on pedestrian safety, and best practice in this respect would be to follow the geometry-based tramway frontage design guidelines of TR 17420 (CEN/TR 17420, 2019). Analogous to the automotive industry, computer simulations are becoming increasingly important in the development of future standards for trams, and when dealing with computer analyses, appropriate priorities must be established in the development of load cases and the evaluation of results, respectively.

The aims of the VIRTUAL project have been to provide tools and models suitable for VT and to initiate an open platform that will foster the uptake of VT. Multiple Road traffic users have been considered: vehicle occupants, pedestrians, cyclists, and public transport passengers. The objective of this paper is to present the OS tools, their usability and how to further develop and foster an OS VT community for road user safety assessment.

## 2. Method

The aims were to create a global hub for OS VT, freely accessible on the internet, and to demonstrate its success in traffic safety assessment. In addition, finite element OS Human Body Models (HBMs) of both men and women were developed in a scalable format of car occupants and pedestrians, cyclists and standing passengers on public transport, in addition to the tools and methods needed to use the HBMs for VT.

### 2.1. The OpenVT platform

Open Source (OS), i.e., a software coming with human readable source code and not only as binary, and open access, i.e., scientific content being accessible free of charge to any interested person or institution, are core principles of the VIRTUAL project, not only to make results created with public funds available free of charge, but also to maximise the impact of the project in the long term. The developed OpenVT platform is the infrastructure for these

principles: a combined collaboration and dissemination platform, where the project results will remain available and alive after the project duration.

The OpenVT platform relies on the OS software Gitlab (<https://gitlab.com/gitlab-org/gitlab>), which is based on the git version control framework (<https://git-scm.com/>) and is intended for collaborative software development. Since the HBMs represent core content and come as ASCII based LS-DYNA input code, Git is perfectly suited for HBM development and greatly facilitates project management in collaborative development. To encourage user self-administration, a user and content administration concept has been implemented based on the basic Gitlab infrastructure, while still ensuring that publicly available content meets VIRTUAL's dissemination standards. Keeping results available, active and useful after the end of the project has been proven challenging in many publicly funded projects. The OpenVT Organisation (OVTO) is VIRTUAL's answer to this problem. The not-for profit organisation OVTO as a legal entity will, at the end of the VIRTUAL project, take over the project results, run the OpenVT platform and safeguard sustainable development of the VIVA+ HBMs (see below) and other content developed within VIRTUAL.

## 2.2. The Human Body Models VIVA+ and Seat Evaluation Tools (SET)

Scalable OS HBMs of an average female and an average male, the VIVA+ 50F and 50M models, have been created (John et al. 2022). The VIVA+ models represent seated occupants, pedestrians, cyclists and standing passengers on public transport. The VIVA+ seated 50F is used as the “base-model”, on which all model development is carried out. The geometry for this model has partly been based on statistical shape models representing the outer skin, ribcage, pelvis, femur and the tibia, and partly based on the shape of an individual female which provided the geometry for the ViVA model (Östh et al. 2017). The stature for the female is 162 cm and the weight 63 kg, corresponding to the average female defined in the same data source as crash test dummies are based on (Schneider et al. 1983). The target age is 50 years old, corresponding to the average adult age in the European Union<sup>2</sup>. Based on the base-model, derivative models can be created using mesh morphing. Currently, morphing codes are available to generate the standing average female and the seated average male. For seated vehicle occupants in low severity rear impact crashes, physical models of both an average female and an average male, the Seat Evaluation Tool (SET) 50F and 50M, have been developed. The SET 50F and 50M have the same geometry and similar weight and height as the VIVA+ 50F and 50M models.

## 2.3. Occupant protection: rear impact virtual testing and reclined seating positions

Rear impact simulations of both the VIVA+ 50F and 50M were conducted to demonstrate the benefits of VT for physical testing and that both sexes should be considered in consumer test protocols. Two different studies with two different seats were simulated. The first comprised of three different pulse severities based on the European New Car Assessment Programme whiplash test protocol (Euro NCAP (2019, low and medium – 16 km/h, high – 24 km/h)), simulated using an OS Toyota Auris driver's seat model that was developed in the VIRTUAL project. Secondly, reclined seating positions expected for automated driving (AD) vehicles were studied with two Faurecia seat models. Since the dummy used in these tests, the BioRID, is limited to a seat back angle of 20-30°, one seat model representing an actual vehicle seat with only the lower belt anchorages attached to the seat frame and one with an integrated restraint system designed to be moved to potential novel seating positions. Seat back angles of up to 55° were studied for both sexes using the VIVA+ 50F and 50M, with heads upright or resting on the head restraint.

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<sup>2</sup> <https://vivaplus.readthedocs.io/en/latest/model/anthro/>

#### 2.4. Integrated virtual assessment of pedestrian and cyclist protection: example tram-pedestrian

An integrated assessment of both active and passive safety measures was developed. VT scenarios were derived based on real-world accident data. The effect of active safety systems on the outcome of these scenarios was evaluated before the remaining injury risk was processed. As such, the change in injury risk can be assessed for multiple cases to obtain robust countermeasures optimised for a variety of scenarios. The simulation results can then be used for a cost-benefit analysis, enabling objective evaluation of concepts for novel safety measures. In this paper, the effect of an exemplary improvement of a generic tram-front on pedestrian injury risk is presented, however the tool chain is also applicable to car safety evaluation and cyclist protection. A generic tram front was developed based on the geometric guidelines provided in TR 17420 (CEN/TR 17420, 2019). Following these guidelines, the most essential parameters that describe the tram front include an angle alpha which describes the dullness and an angle beta, which defines the steepness, respectively. To investigate the influence of these parameters, morphed tram front shapes were compared in terms of the Head Injury Criterion (HIC), rotational acceleration of the head and also the overall kinematics after impact, respectively. The HBM's trajectory subsequent to the impact is important to ensure that the person is not subsequently run over by the tram.

### 3. Results

#### 3.1. The OpenVT platform

The OpenVT platform, which has already become an important online platform for HBM modelling and virtual testing, has been operational since December 2018 and can be accessed at <https://openvt.eu>. The OpenVT Organisation (OVTO) was founded in November 2021 in Zürich, Switzerland, as an association adhering to the Swiss civil code, which will run the OpenVT platform in the future and govern the evolution of the results of the VIRTUAL project after its completion. The transition process of the OpenVT platform and the VIRTUAL project results from the VIRTUAL participant organisations to OVTO is currently taking place and is scheduled to be completed by the end of 2022.

#### 3.2. The VIVA+ 50F and 50M and the SET v0.1 50F and 50M

The baseline model is the seated average female (VIVA+ 50F), which has been morphed to a seated average male (VIVA+ 50M) as well as respective standing models. Particular attention was paid to developing robust models with a mesh pattern suitable for morphing to various postures and anthropometries, while maintaining an acceptable mesh quality. The model comes with openly accessible documentation, user manual, as well as pre- and post-processing metafiles. All models were validated using appropriate validation load cases. The first level of validation is on the component level, i.e., a single rib or an isolated femur. The second level of validation is on the whole-body level. So called “injury detection systems” consisting of nodal sensors, have been included on anatomic landmarks. The nodal time histories, acceleration, velocities, trajectories and rotations can be evaluated, and certain sensors are also used as input for the calculation of injury criteria, e.g., HIC.

Metafiles for harmonised postprocessing for the open-source tool Dynasaur have been developed, and calculation procedures for the injury criteria (kinematic and strain-based) have been implemented. A list of the recommended injury criteria and the “level of trust” is available as part of the model documentation (<https://vivaplus.readthedocs.io/en/latest/model/injury-assessment>). Web-based open documentation has been implemented for the VIVA+ models, supporting continuous updating along with model releases. The documentation has been implemented with the open-source Python-based MkDocs library and is hosted on ReadTheDocs (<https://vivaplus.readthedocs.io/>). The documentation intends to provide tutorials, how-to guides, and technical references for the VIVA+ models. The sections include Model Documentation, User Guide, and Contributor

Handbook. The User Guide and Contributor Handbook sections are intended as learning resources for new users and future contributors, respectively.

The SET models are based on the design concept of the BioRID, which has been further developed, as well as the body geometry, height, and weight of the VIVA+ models. The spine of the SET is, in addition to the sagittal plane motion of the BioRID, able to rotate along the vertical axis. Furthermore, the SET has a newly designed flexible shoulder segment. The first version, SET v0.1 has been constructed, the VIVA+ 50F and 50 M and the SET v0.1 50F are shown in Fig. 1.

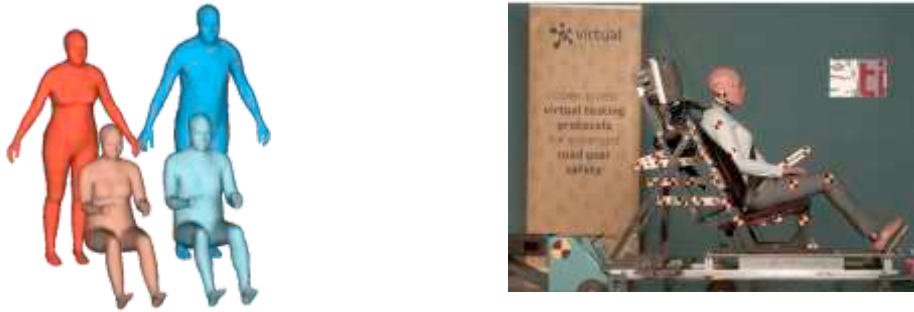


Fig. 1. The VIVA+ 50F and 50 M as seated and standing models (left) and the SET v0.1 50F (right).

### 3.3. Occupant protection: rear impact virtual testing and reclined seating positions

The Euro NCAP rear impact simulations show that the response differed between the VIVA+ 50F and 50M. Comparing the response of the VIVA+ 50F and 50M for the mid-severity pulse, the 50M reached higher peak values for the head and T1 x- and angular displacement and head x-acceleration while the 50F reached higher peak T1 x-acceleration as shown in Fig. 2.

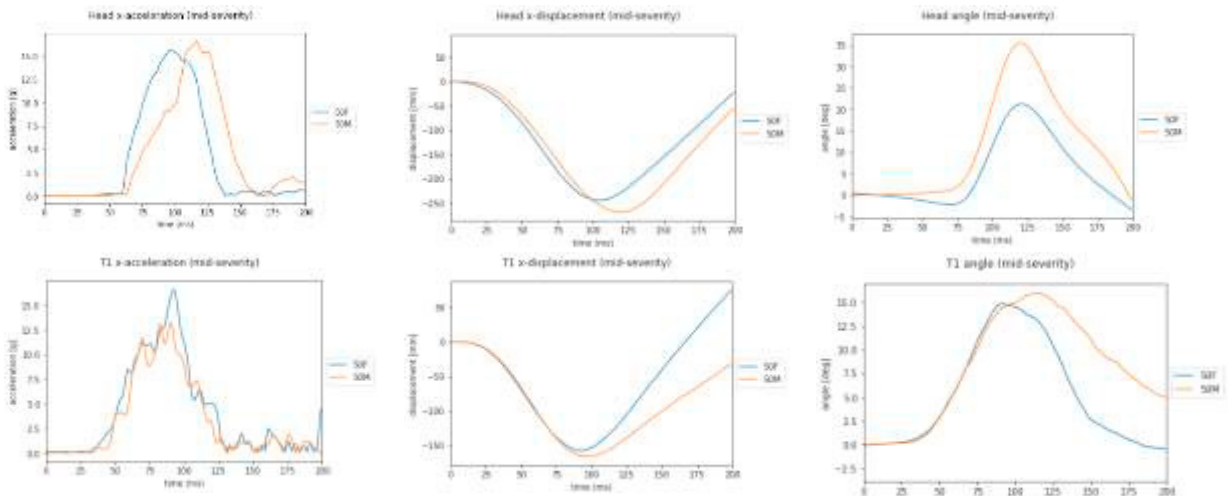


Fig. 2. The simulation results with the VIVA+ 50F and 50M in the Euro NCAP mid-severity pulse in the OS Toyota Auris seat, the head and T1 angular and horizontal (x) displacement and horizontal acceleration.

When reclining the back of the concept seat with integrated seat belt, the backset (distance head-to-head restraint) increased more for the male than for the female when the occupants kept their head in an upright position. The reason

for the difference is due to the adjustment position of the head restraint being mid-height for the male and in the lowest position for the female, as well as the direction between the two head restraint positions when reclining rearwards resulting in both Neck Injury Criterion (NIC) and Aldman pressure increased for both the female and the male.

Table 1. The simulations with the VIVA+ models in different reclined seating positions in a seat with integrated seat belt.

Cushion angle	Seat back angle	Shoulder adjustment (forward rot)	Head restraint	Head	Occupant	THRC (ms)	Head acc (g)	T1 acc (g)	NIC (m <sup>2</sup> /s <sup>2</sup> )	maximum vertebrae Cx versus T1 angle (°)	vertebrae Cx with highest rotation	Aldmann pressure (kPa)	backset (mm)
base	25	0	mid	upright	50M	46ms	18,6	19,6	13,9	36°	C2	-30	26
base	25	0	low	upright	50F	48ms	22	23	15,9	40°	C1	-30	32
base	35	0	mid	leaning	50M	0ms	13,8	21,2	21,9	42°	C2	-55	0
base	35	0	low	leaning	50F	0ms	14,9	21	22,3	41°	C2	-35	0
base	35	0	mid	upright	50M	54ms	19,2	17,8	13,9	32°	C2	-30	43
base	35	0	low	upright	50F	51ms	23,7	23,2	17	32°	C2	-35	37
base	45	1	mid	leaning	50M	0ms	14,5	21,3	26,3	42°	C2	NA	0
base	45	1	low	leaning	50F	0ms	16,8	19,6	21,9	45°	C4	-80	0
base	45	1	mid	upright	50M	63ms	20,4	16,1	18,6	25°	C2	-40	63
base	45	1	low	upright	50F	60ms	24,4	16,8	20	30°	C2	-55	47
base	55	10	mid	leaning	50M	0ms	17,9	15,8	30	37°	C4	NA	0
base	55	10	low	leaning	50F	0ms	17,2	12,2	21,7	45°	C3	-100	0
base+10°	45	0	mid	leaning	50M	0ms	13,1	21,3	36,2	42°	C2	-45	0
base+10°	45	0	low	leaning	50F	0ms	15,3	29,6	42	44°	C3	NA	0
base+10°	55	1	mid	leaning	50M	0ms	12,3	16,9	26,2	44°	C2	NA	0
base+10°	55	3	low	leaning	50F	0ms	15,6	21,1	34	45°	C4	NA	0
base+20°	45	1	mid	leaning	50M	0ms	13	22,8	30,6	38°	C2	-40	0
base+20°	45	3	low	leaning	50F	0ms	16,4	30,2	36,4	38°	C3	NA	0

Load cases with leaning head-on-head restraint showed higher whiplash injury risks than keeping the head in an upright position not touching the head restraint, observed for all seat back positions. This difference is visible for the NIC value, the relative rotation of the vertebrae and in the Aldman pressure. This effect was present for both males and females and is caused by a lower head acceleration when the head is leaning on the head restraint, which creates a higher difference between the upper neck and lower neck accelerations.

Based on NIC values, some load cases showed higher values for males than females, but no clear advantage was observed for male or female injury risk. When observing the relative rotation of vertebrae, the highest relative rotation versus T1 was observed for the C3 or C4 vertebrae for females, whereas the maximum values were observed for C2 vertebrae for males. The mean value of these rotations is higher for females than for males. Therefore, it is worth studying the relative rotation of each vertebra of males and females in closer detail. Since the classic head restraint used with the adjustment up and down, is not very favourable at higher reclined angles, it would be interesting to study emerging head restraint concepts for novelty seats further.

### 3.4. Integrated virtual assessment of pedestrian and cyclist protection: example tram-pedestrian

Figure 3 exemplarily shows two tram-pedestrian impact scenarios: on the left side there is a baseline generic tram model in accordance with TR17420 and on the right side a morphed tram model with a steeper front, both with the VIVA+ 50<sup>th</sup> percentile female (Version 0.1.6) in front of them. On the left side the HBM has been positioned at 15% and on the right side at 50% of the half tram width, respectively. Such impact analyses were also performed with a duller tram front and a combination of a duller and steeper design. Following TR17420 the most important criteria is the HIC value and the lateral deflection of the HBM, respectively, that is required to be at least 800 mm and is determined by assuming a trajectory parabola from the point of impact with the initial direction of the velocity vector at the HBM's centre of gravity (COG). Although the TR17420 does not require the evaluation of any further injury criteria, the rotational head acceleration is also considered as comparative value. In addition, in Figure 3 the QR code of Siemens "Assisted and Driverless Train Operation" is found.



Fig. 3. Generic tram model in compliance with TR17420 with VIVA+ 50F at 15% tram width (left) and steeper front shape at 50% tram width (right) and the QR code of Siemens "Assisted and Driverless Train Operation".

Table 2 and Table 3 exemplarily show tram pedestrian impact simulation results for differently shaped tram fronts. From the HIC values alone almost no head injury would be expected. This is mostly due to the front screen that is geometrically set back and therefore almost prevents direct head impact onto the glass (at least in the 50F case considered here).

Table 2. VIVA+ 50F Model at 15% half tram width.

	Baseline <b>B</b>	Steeper front <b>S</b>	Duller front <b>D</b>	Steeper+duller front <b>SD</b>
HIC <sub>15</sub>	32	104	36	160
Max linear acc. COG Head (g)	24,6	61,7	27	73,3
Max rot. Acc. COG Head (rad/s <sup>2</sup> )	5407	4774	5291	4777

Table 3. VIVA+ 50F Model at 50% half tram width.

	Baseline <b>B</b>	Steeper front <b>S</b>	Duller front <b>D</b>	Steeper+duller front <b>SD</b>
HIC <sub>15</sub>	102	197	88	365
Max linear acc. COG Head (m/s <sup>2</sup> )	45,1	68,3	38,3	113,6
Max rot acc. COG Head (rad/s <sup>2</sup> )	5587	5498	6145	6390
Lateral Deflection (mm)	1207	957	783	1160

Figure 4 presents the translational acceleration response of the head COG due to its impact with the tram front. These graphs indicate that an actual impact of the head was only detected for the S/SD shapes at 15% half the tram width, whereas no impacts happened for the B and D shapes, respectively. At 50% half the tram width, a head impact was noticed for all four shapes but again the acceleration response was significantly stronger for the steeper S/SD designs reaching almost 120g in case of the SD shape.

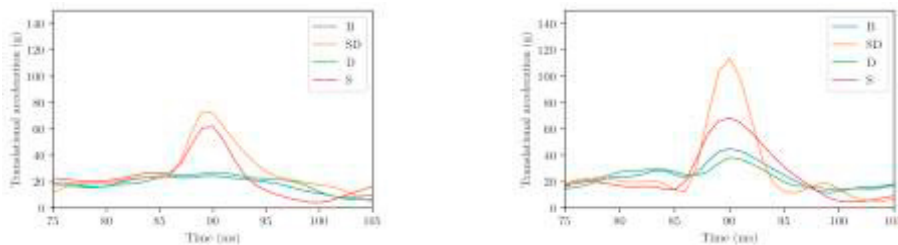


Fig. 4. Translational head COG acceleration of VIVA+ 50F model (Version 0.1.6) at 15% width (left) and at 50% width (right), respectively.



#### 4. Conclusion and future work

The results of VIRTUAL foster the uptake of VT. The contributions include the OpenVT platform, OVTO, seated and standing VIVA+ 50F and 50M, as well as the integrated assessment chain and more found at: [https://virtual.openvt.eu/users/sign\\_in](https://virtual.openvt.eu/users/sign_in). The developed VIVA+ models are provided as both female and male average road users. In future, the models could be used to represent all different ages and sizes. The OpenVT platform, OS-HBMs and tools for simulation of road user safety and cost benefit analysis, will be further developed by the open global user and research community.

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