CZECH TECHNICAL
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IN PRAGUE

MASTER OF AUTOMOTIVE
ENGINEERING

DESIGN ASSISTANCE SYSTEM APPLIED TO VEHICLES SUSPENSION DESIGN

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PREFACE

This document is the master’s thesis and a project report of “Design Assistance System applied to vehicle suspension design” major project as a part of the double-degree international Master of Automotive Engineering study program between CTU in Prague and HAN University of Applied Sciences.
As such, this document was submitted also to the Master of Automotive Systems program at HAN University of Applied Sciences in December of 2021.

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II. Master's thesis details

Master's thesis title in English:

Design Assistance System applied to vehicles suspension design

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Možnosti využití databáze DASY pro návrh zavěšení kol automobilu

Guidelines:

The objective is to study vehicle dynamics behaviour in relation to the parameters of suspension geometry and wheel alignment of different vehicles in order to define a set of relevant components to be implemented into the existing Design Assistance System (DASY) database and thusly implement vehicle dynamics subdatabase into DASY.
Activities: • Study of suspension geometry and design, preparation of methodology for acquiring relevant parameters related to suspension geometry.
• Study of Design Assistance System structure, finding out necessary parameters for vehicle dynamics description which could be used for DASY
• Define set of components which will be implemented to DASY
• Use experiments and/or simulations results for obtaining relevant information and using the results to create set of parameters, structural requirements, and files for each component

Bibliography / sources:

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Date of master's thesis assignment: **19.10.2022** Deadline for master's thesis submission: **11.01.2023**

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III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

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Date of assignment receipt

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SUMMARY

Centre of Vehicles for Sustainable Mobility's (CVUM) Design Assistance System (DASY) is a design network database system that is aimed at assisting in knowledge-based design of vehicles. Up until now, this system was used for development of vehicles' powertrains and drivetrain parts. The aim of CVUM is to further expand this system, so that it can be used in other automotive applications, such as in suspension development and vehicle dynamics behaviour testing related to it.

The goal of this project was to be a steppingstone towards this greater project at CVUM, researching how a vehicle dynamics database expansion for the existing DASY database can be made and how vehicle components and parameters related to the vehicle dynamics behaviour can be implemented into it.

This document is the project's report, in which an introduction to the topics related to this task from a literature review is given. This includes a literature review of database systems, DASY, vehicle suspension components, systems, design process, vehicle wheel alignment parameters and vehicle dynamics testing methods. In the practical part of this project report, a methodology for the vehicle dynamics database expansion through a relational database model is proposed and a component implementation procedure is shown. The model is then validated by creation of a physical model from which the database is deployed on a server and its function is demonstrated on implementation of a vehicle's component and its parameters. Further, a data acquisition method for initial closed-loop vehicle dynamic testing on a custom test track layout is shown. Finally, suggestions for future continuation of the database expansion process are given, including recommendations for improving the usability of the proposed database and other possible uses of the database.

CONTENTS

ABBREVIATIONS

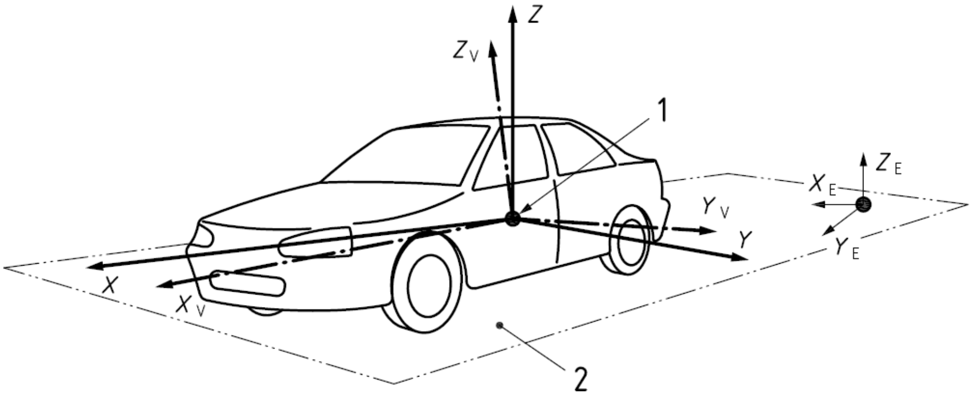
a_x	Longitudinal acceleration	[g, m/s^2]
a_y	Lateral acceleration	[g, m/s^2]
δ_H	Steering-wheel angle	[°]
δ	Steering angle	[°]
v_{δ_H}	Steering wheel rate	[°/s]
r	Yaw rate	[°/s]
ψ	Yaw angle	[°]
τ	Caster angle	[°]
σ	Kingpin inclination	[°]
r_k	Kingpin offset	[mm]
r	Scrub radius	[mm]
t_s	Sample times	[s]
n_k	Kinematic trail	[mm]
n_τ	Spindle trail	[mm]
v	Vehicle speed	[km/h]
φ_V	Vehicle roll angle	[°]
ε_V	Camber angle	[°]
ε_W	Inclination angle	[°]
X_V, Y_V, Z_V	Vehicle axis system	[-]
X_T, Y_T, Z_T	Tyre axis system	[-]
X_W, Y_W, Z_W	Wheel axis system	[-]

ACRONYMS

HAN	Hogeschool van Arnhem en Nijmegen
CTU	Czech Technical University in Prague
CVUM	Centre of Vehicles for Sustainable Mobility
DASY	Design Assistance System
ID	Identifier
SQL	Structured Query Language
RDBMS	Relational Database Management System
PK	Primary key
FK	Foreign key
FEM	Finite Element Method
IC	Internal combustion
CAD	Computer aided design
3D	Three dimensional
MBS	Multi body simulation
CoG	Centre of gravity
DoF	Degree(s) of freedom
DCC	Dynamic Chassis Control
LKPC	Aerodrome Panenský Týnec ICAO code
ICAO	International Civil Aviation Organization
HD	High-definition
LED	Light-emitting diode
CCD	Charge-coupled device
GUI	Graphic user interface
ETL	Extract, transform, load function
GPS	Global Positioning System
CAN	Controller Area Network
ABS	Anti-lock braking system
ISO	International Organization for Standardization

COORDINATE SYSTEM

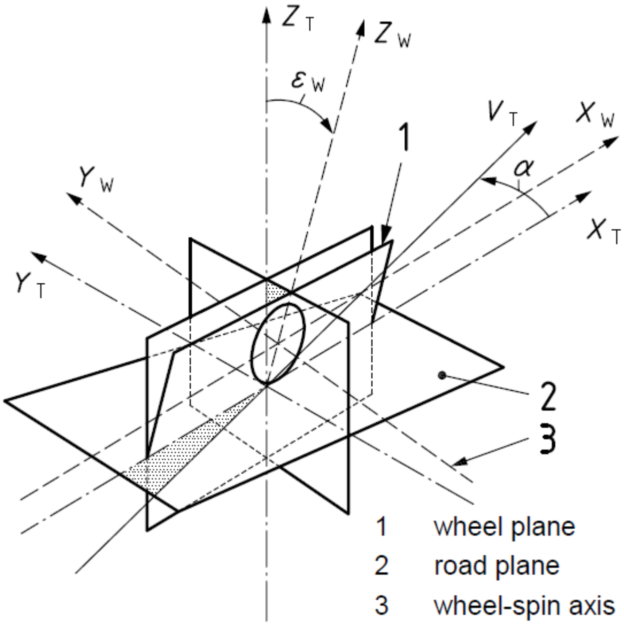
ISO axis coordinate system is being used in the notation of this project, as shown below from ISO 8855-2011[7], Section 2 – Axis system.



Key

1 vehicle reference point

2 ground plane



1 wheel plane

2 road plane

3 wheel-spin axis

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1 INTRODUCTION

1.1 Background

Centre of Vehicles for Sustainable Mobility's (CVUM) Design Assistance System (DASY) is a design network database system that is aimed at assisting in knowledge-based design of vehicles. Its main tasks are representation of different structures with parameters at different levels and evaluation of design network parameters linked by methods.

It generally stores all the models and components in one database with the ability to reuse any of these in new projects. Supporting information can also be stored in the database. Currently, DASY is used as a tool mainly focused on development of internal combustion engines. The system is continuously being developed and expanded at the Centre of Vehicles for Sustainable Mobility. [1]

1.2 Problem definition

As the vehicle dynamics behaviour is crucial to the design process of vehicles, CVUM is looking to expand the DASY database to also include vehicle dynamics.

The current project is the starting point of this future expansion. As the vehicle's suspension geometry and wheel alignment are crucial parameters that affect vehicle dynamics in terms of stability and safety, CVUM currently aims to expand the DASY database by the related components, parameters, and data sets. To do so, a methodology of selecting the most relevant parameters and obtaining the data needs to be established and validated.

In the future, the database will be further expanded to include the effects of the powertrain and steering system design, but that exceeds the scope of this current project. The current goal is the implementation of components, parameters and data sets related to suspension design into DASY. Using knowledge from the expanded DASY database about the effect of powertrain and suspension design on vehicle dynamics will in future reduce the time and costs of development activities.

1.3 Objective and the research question

1.3.1 Project objective

The objective of this project is to prepare implementation of components and parameters related to vehicle dynamics behaviour (specifically to the vehicle's suspension geometry and wheel alignment) into Design Assistance System (DASY) environment by obtaining a set of parameters, structural requirements, and files, acquired and validated by experiments and/or simulations.

1.3.2 Research question

The main research question of this project is:

How can a vehicle dynamics database be added to the DASY database system?

To find an answer to the main question, the following sub questions are defined:

- *Which of the available test vehicles are the most suitable to perform the tests with?*
- *Which input and output parameters can be measured on the available test vehicles that are deemed useful for creating the database?*
- *What parameters are most relevant in assessing the effects of vehicle's suspension geometry and wheel alignment?*
- *How can the different parameters be measured on the test vehicles?*
- *What test manoeuvrers should be considered to obtain data for the database?*
- *What are the simplifications considered?*
- *What future actions can be taken to implement vehicle dynamics database to DASY?*

2 LITERATURE REVIEW

2.1 Database and Database Systems

To understand the following introduction into DASY (Chapter 2.2), and to complete the objective of this project, some introduction to the topic of databases is needed. This introduction shall be kept to a necessary minimum required for this project, for any reader interested in this topic it would be recommended to follow the listed literature [17; 18; 19], where this topic is discussed in greater detail.

2.1.1 Terminology

To introduce the basic terminology, data are formalised and physically recorded findings, experience, knowledge, and results of observations of processes, manifestations, activities, and elements of the world. Information is a logical interpretation of data. Integrated, computer processed, and organised sum of persistent data is called a database. Database management system is a set of software resources that allows for the creation of database, the use of database (data manipulation) and the database management and administration. When combined, database and database management system, create a database system. [17; 18, p.3-16; 19, p.3-6]

To understand why a database system is used, it is important to understand its advantages. The main advantage being the speed at which the data is accessible, because a correctly set-up database allows for a fast search of the required data as well as enabling the possibility to easily share the stored data. It is a compact solution – as all of the data are present in one system; that also allows for any redundancy to be reduced. Furthermore, the data can be updated as needed, while a greater security is also offered, as the data can be protected against loss and unauthorised access. [18, p.16-20]

2.1.2 Database systems

There are many different types of database systems, just to name a few: hierarchical, network relational, object oriented, NoSQL. One of the most common systems in use is a relational database. It is a system, where the entities are connected together with some relation. A relational database management system (RDBMS) is a software product that stores relational databases, provides security and manages user access to the databases. They also have functions for management of databases - functions such as backup and restoration of data, index management and data loading utilities. SQL (structured query language) programming language is used for programming RDBMS and managing the data inside of the database. [18, p.3-11, p.26-28; 19, p.3-6]

Several RDBMS products are available, such as either freeware open-source products such as MySQL, or enterprise-oriented systems like Oracle, Microsoft SQL Server and others. The selection of a particular system depends on the requirements placed upon the system and the environment in which it is being used. [18, p.3-11, p.28; 19, p.5-6]

2.1.3 Database models

To create a database system, a database model is necessary – it is used to determine how to store digitalised information in a structured database. The importance of data model lies in saving of time and prevention of mistakes when building the database structure at a later stage of the database creation process. It also provides data consistency and scalability of the database for future expansion. [19, p.6-14]

Database models can be divided into different categories according to the level of detail the model offers. In a high-level conceptual database model, only the basic structure proposition is present –

it provides the main "bones", creates a list of necessary entities and the desired basic function of the database. [19, p.15-16; 18, p.33-37]

Record based logical model is representative of the data as a road map for physical implementation. The main elements of a logical model are entities, attributes, and relationships. Entities are logical groupings of data (tables). Attributes are pieces of information that make up entities (cell content). Relationships describe how entities are related. Logical model's elements describe the groupings of data as they might appear to be in the real word. [19, p.15]

The physical model of a database expands on the logical model previously created, it is also created by using various elements – tables where data is stored, columns containing information about the data in the table rows; primary and foreign keys, that define the relationships between two tables – the physical elements store data in a database, so they represent the real database working structure. [19, p.15-16]

2.1.4 Entities, attributes, and relationships

As already mentioned, entities represent the logical groupings of data, they represent how data is sorted and aligned in the database. Instance is the record, or row in a table, that represents occurrences of a single type of information. Entities contain multiple instances. Each logical entity may be represented by multiple physical tables. The information describing entities makes up the attributes. For a model construction, a definition of a collection of attributes that stores data for each entity is necessary. The definition is made of a name, description, purpose, and data type. [19, p.23-25]

Primary key (PK) is an attribute that uniquely identifies each instance in an entity, sometimes also called identities. A foreign key is similar to a PK, but instead of being a unique value, it references to other instance, or is based on PK of other entity. [19, p.30-31]

Logical relationships between entities and attributes can be differentiated into three categories of cardinality – one-to-one, one-to-many, and many-to-many. As the names suggest, it refers to a number of connections at each end of the relationship chain – one entity record can be connected to one, or more than one, other record in the other entity. Most common type of relationship in database is one-to-many as the second entity can, for example, as a whole be related to one record in the first entity. [19, p.35-40]

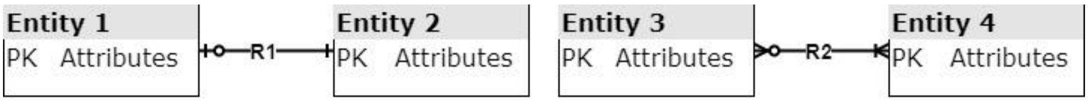


Figure 1 - Relationships between objects - notation in a database model

Relationships between entities in a database model are noted using Barker's notation, in the case of the shown example in Figure 1, a so called "*Crow's foot*" type. Barker's notation describes the cardinality and obligation of a relationship. Relationship "*R1*" shows that Entity 1 has to be connected to one attribute from Entity 2, but Entity 2 can be connected to one, or none, of the Entity 1 attributes. Relationship "*R2*" shows that Entity 3 must be connected to one, or many, attributes of Entity 4, while Entity 4 can be connected to many, or none, of the Entity 3 attributes. This type of notation gives both the obligation and cardinality of the relationship in one notation. [24]

2.2 Design Assistance System (DASY)

Centre of Vehicles for Sustainable Mobility's (CVUM) Design Assistance System (DASY) is a design network database system that is aimed at assisting in knowledge-based design of vehicles. It is based on an object-relational database management system. As such, its main tasks are representation of different structures with parameters at different levels and evaluation of design network parameters linked by so called methods. It stores all the models and components for the relevant projects in one database with the ability to reuse any of them in new projects. Any supporting information can be also stored in the database, giving an opportunity for the database to be further expanded. Currently, DASY is used as a tool mainly focused on the development of internal combustion engines, but the goal of this, and future CVUM projects, is to further expand and develop this system to be useful in other sectors of automotive industry. [1]

2.2.1 DASY structure

The model (assembly) in DASY is represented as a set of components and subassemblies - in each model there are stored components that are a part of this main structure. To each component, parameters can be added. Each component has a set of structural requirements and files related to it. Components can have their own subcomponents and subassemblies. All the components are stored in the related library and can be further divided into classes. [1]

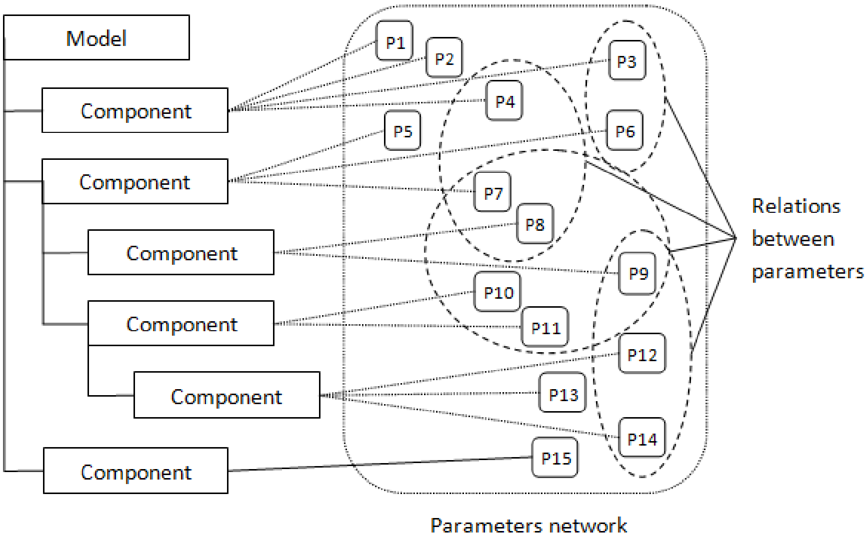


Figure 2 - DASY model, component and parameter structure [1]

The associated parameters are used to store the data related to the different components. If there are some parameters where some relation that connects them can be determined, this relation can be added in the form of "methods". [1]

These methods may be elaborated at different levels - methods can be computational, design based or experimental – they can be simple formulas, complex analogies, or unknowns that have some effect on the parameters or the components there are part of. The deeper to the substance of phenomena description the method is extended, the more data are usually called for as input parameters. Input and output parameters for one method should be distinguished, but output of one method can be an input for another. [1]

As the DASY database is used in knowledge-based design, it does not have to include the solutions and the methods to still be useful. DASY is a "well of wisdom" that can provide valuable information from previous experiments and designs.

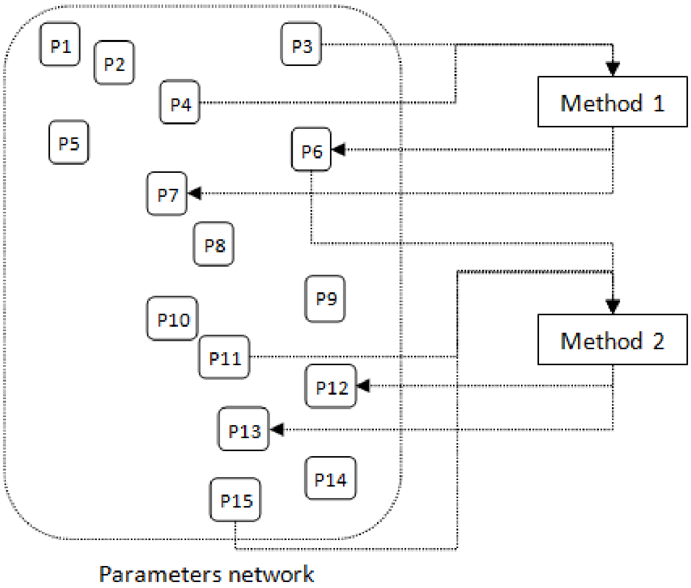


Figure 3 - Parameters network and connecting methods [1]

The methods connected to certain parameters can be fed with data included in those parameters or external data from ‘modules’ can be used. Modules can be the measuring methods used to obtain the data, experiments, the evaluation methods to process the measured data, or the data source itself (simulation results). In any case the modules function as external data source that can be used in conjunction with DASY database and in some cases can also be stored in DASY as accompanying data to methods. [1]

It can generally be said that the more modules, the better, as more measuring and evaluation methods allow for a comparison of the studied subject on a greater scale.

Flexibility of DASY’s construction approach is sufficiently high so that any structure can be changed, removed, or added in case a new concept, or project, requires it. Flexible plugins systems allow to extend DASY functionality to any field of application. The optimization capabilities make DASY usable in real industrial applications with ability to include external software in an optimization loop. [1]

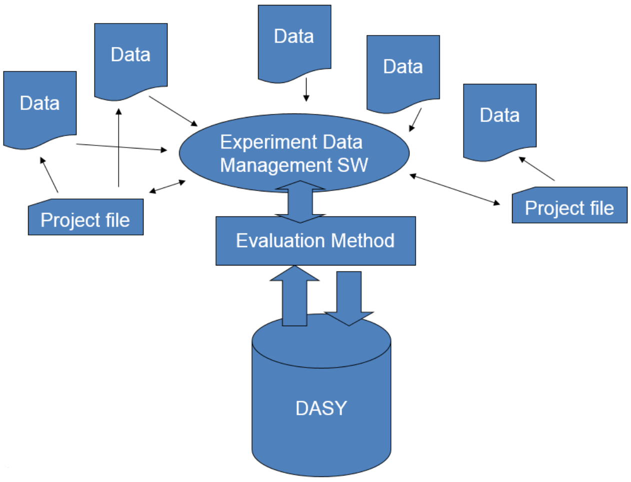


Figure 4 - DASY implementation to external processes [1]

2.2.2 Example of DASY use

The following example shows an IC engine crank train DASY model as explained in [6].

The model in this example is used for the calculation of the load of crank train parts. Calculations to determine the crankcase and bearing load are performed. With this model, the calculation of mechanical efficiency and loading conditions for FEM analysis can be performed.

The components in this model are rigid bodies of engine crank, piston, and the connecting rod. The friction is not considered. Component's input parameters are geometric dimensions, CoG, mass, and inertia moments. These parameters are loaded into DASY from 3D models. As the parts are represented in the form of program blocks, the parameters can be easily changed – setting the parameters thus changing the part's dimensions. The parameters used are run through conversion block recalculating the numerical values to appropriate units. From this block, they are relayed into the Input/Output block, where they are used as input parameters for GT-SUITE solver. As the changes in parameters in the DASY blocks are carried both ways along the connections of blocks, with the results from the GT-SUITE solver, the design of the parts can be easily changed by closing the loop of the design process with connections to their input parameters. [6, p.3-4]

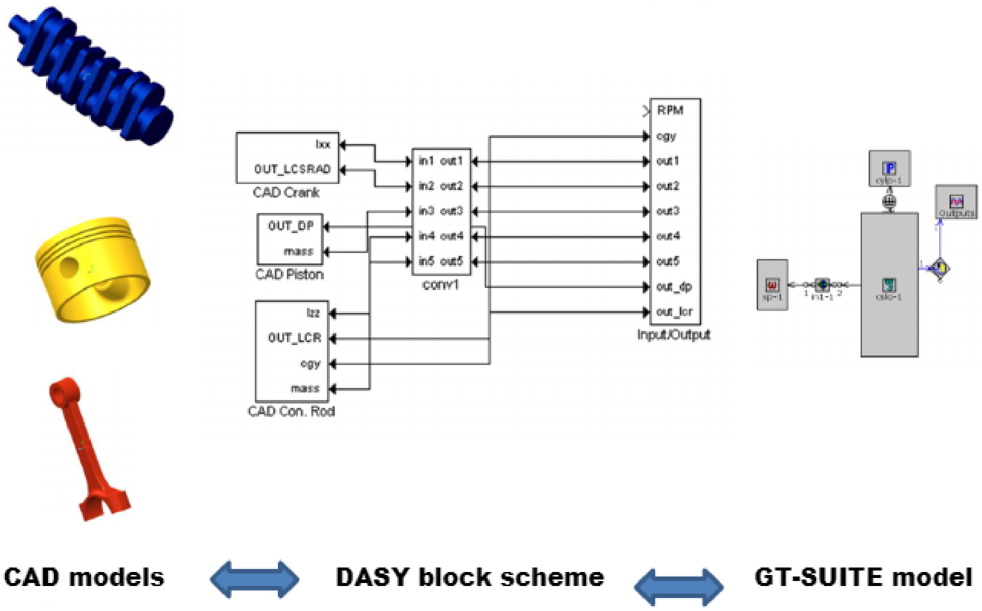


Figure 5 - DASY use in a GT-SUITE calculation [6]

In the conceptual design phase of a new engine, detailed CAD models are not necessary. Therefore, by using simplified, parameterized models that were created, changing the parameters of similar engines accelerates the acquisition of input data for further calculations. As the parameters obtained from these calculations are important for the design process of other engine parts, these can be used in DASY as the input parameters for calculation and design of those other parts (for example the engine block dimensions). [6, p.3-4]

2.3 Vehicle suspension, suspension geometry

There are numerous variations on the vehicle suspension design in the industry. There are great differences in the suspension design and requirements based on the type and use of the vehicle – passenger vehicles have different load and use requirements to heavy commercial vehicles. As this thesis focuses on passenger cars, only those will be discussed here.

Still, even in passenger vehicles exists a great variation in the type of suspension design. Over the years, there has been a great number of different designs used for essentially the same purpose. The main function of suspension is a distribution of forces from the vehicle's frame to the wheels and on the ground in accordance with the design specification in every designed load condition. At the same time, it determines the vehicle trim under static and quasi-static loads, while also allowing the wheels to follow an uneven road profile without transferring excessive loads and accelerations to the vehicle's body and its occupants. In other words, the suspension's function is to ensure the contact between the tyre and the road surface, providing stability and cornering ability to the vehicle, while also providing comfort to the passengers. Suspension determines the distinctive characteristics of a vehicle and its behaviour on the road. [3, p.325; 5, p.133-135; 9, p.185-188]

Different suspension systems have their positives and negatives for different applications. The manufacturer has to select suitable systems based on the performance, function, packaging and cost requirements. Individual systems allow for various levels of variable parameters for suspension geometry and wheel alignment.

Suspension systems can be divided into independent, dependent, and semi-dependent suspensions. With independent suspension, there is no mechanical linkage between the two hubs of the same axle - a force acting on one wheel does not affect the other; steering linkages, anti-roll bars or auxiliary frames are not considered in this description. Ideally, independent suspension systems are designed to constrain degrees of freedom from the general six degrees of freedom of the wheel carrier (rigid body) to leave only one unconstrained – the vertical translational degree of freedom (the direction perpendicular to the road) in addition to the wheel rotation and steering motion of a hub on steerable axle. Dependent wheel suspensions (rigid axles) make a rigid linkage between two wheels on the same axle. In this case, each motion of a wheel caused by road irregularities affects the coupled wheel as well – the force acting on one wheel affects the coupled wheel. Semi-rigid suspension systems have intermediate characteristics between the other two categories – these suspensions wheel hubs cannot be considered independent as the structure's mechanical characteristics ensure that flexibility cannot be neglected – this category includes so-called twist axles (i.e. twist beam axle). [3, p.325-326; 4, p.235,238; 5, p.134-135]

Furthermore, suspension systems can be classified by the damping and elastic systems as passive, that is only reacting to the displacement and acceleration of the suspension, or active systems, which use other energy sources to improve damping effects to limit body movements to minimum. [5, p.135]

2.3.1 Suspension components

Suspension systems are composed of different components, which have different tasks to ensure the correct function of the system. Linkages are parts that connect (link) the wheel hub to the body of the vehicle and guarantee the degrees of freedom of the wheel and its correct position with reference to the ground plane. At the same time, they determine the relative motion of the wheel hub with reference to the vehicle's coordinate system. The linkages transfer part of the load from the wheel to the body of the vehicle. The primary elastic members include springs (coil, bar and leaf springs) and anti-roll bars. The elastic members connect the wheel to the body elastically and store energy from displacement due to uneven road profile. They determine the vehicle's body position in relation to the load and its position in the vehicle. Secondary elastic members include the elastic bushings on linkage joints and elasticity of the links themselves. They are part of the elasto-kinematic behaviour of suspension and are used mainly for comfort of the occupants of the vehicle as they reduce felt vibrations. Damping members are shock absorbers, they waste energy stored by the elastic members and reduce the oscillations and vibrations of the vehicle body. [5, p.135-136; 8, p.226-321]

2.3.2 Suspension systems

2.3.2.1 McPherson suspension

This type of suspension is most widely used in passenger vehicles as the front suspension. Most of smaller, or lower-class vehicles are equipped with this type of suspension as it provides a cost-effective solution that also provides a great space-saving solution allowing transversally mounted engine in a front wheel drive drivetrain. The strut of the shock absorber is mounted directly to the steering/suspension knuckle, the lower control arm restricts the longitudinal and lateral movements, while a steering link allows for toe adjustment. The two wheels are connected with an anti-roll bar. There are cases where a combination McPherson suspension is used, adding upper “arm” comprised of single link. This type of suspension can be also used as a rear suspension solution, with the tie rod acting as a separate link, or replaced by the use of different lower control arm joint type. [4, p.238-240; 5, p.141-148; 8, p.407-410, 412-414]

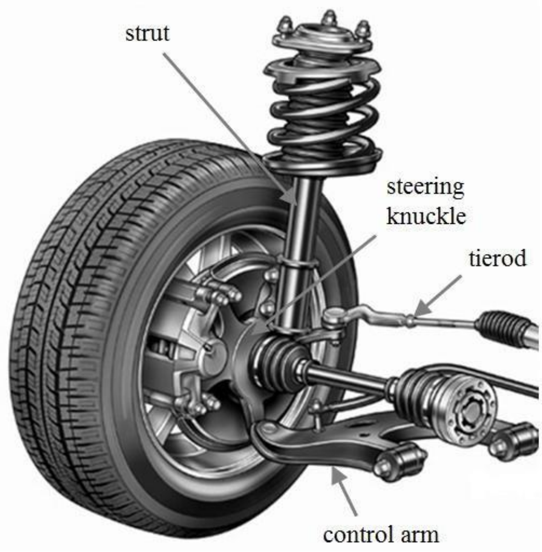


Figure 6 - McPherson suspension [33]

2.3.2.2 Double wishbone suspension

In the passenger vehicles, this type of suspension can be used both at the front or rear axle, however it is usually a costly and more complex solution. Therefore, it is usually found on more expensive, primarily performance-oriented vehicles (luxury sedans, sports cars). This independent suspension system allows for a design of elasto-kinematic parameters that provides great compromise between handling and comfort. The suspension is comprised of a suspension knuckle, lower and upper control arms, shock absorber with spring and an anti-roll bar connecting the two wheels on the axle. [5, p.171-174; 8, p.400-402, 413]

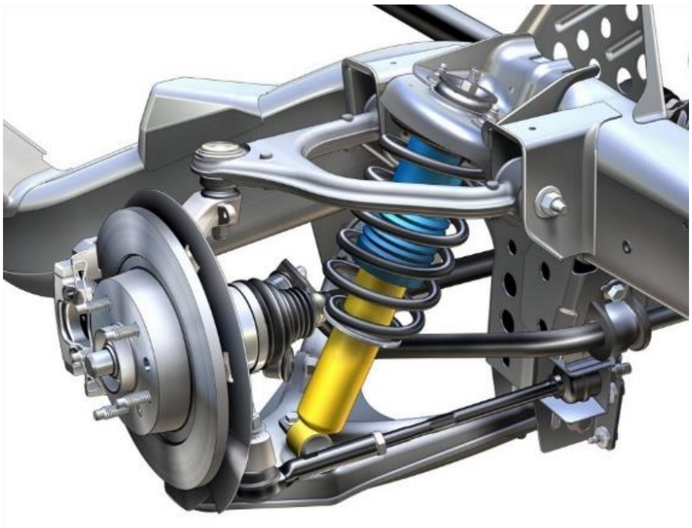


Figure 7 - Double wishbone suspension [34]

2.3.2.3 Multilink

This type of suspension is usually found on the rear axle of passenger vehicles. It is an independent suspension, comprised of five links connecting the suspension knuckle to the vehicle's body, constraining all five DoF. It has its similarities with double wishbone suspension, as four of the links create a pair of control arms and their virtual steering points, while the fifth restricts the wheel steering motion, or the toe of the wheel. In certain applications, some of the links can even be replaced by a control arm and the suspension can still be considered multilink. The multiple links are combined with damper and coil spring and an anti-roll bar connecting the two wheels. [4, p.235-237, p.242-245; 5, p.188-190; 8, p.402-407]

Figure 8 - Multilink suspension [35]

2.3.2.4 Torsion beam suspension

This type of suspension is used on smaller, lower-class vehicles as the rear, non-driven axle. It is a semi-independent type of suspension comprised of two trailing arms connected by an axle beam with dampers and coil springs mounted on each side of the axle. It is usually used as a cost-effective solution and, for higher-end vehicles, it is replaced with independent suspension. However, when designed and set-up correctly, it can still provide satisfactory performance for its intended use. [5, p.190-194; 8, p.390-392]

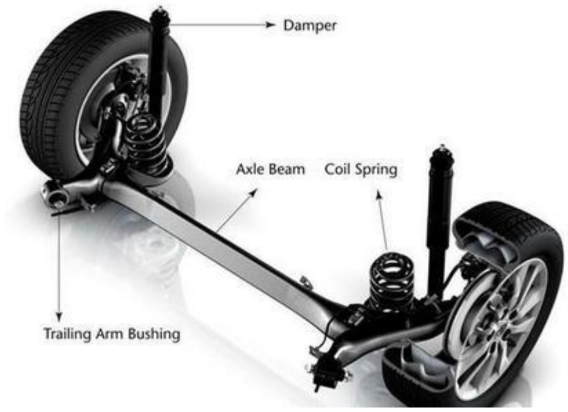


Figure 9 - Torsion beam suspension [36]

2.3.3 Suspension design process and parameters

Suspension design process is a complex one, involving selection of a suspension system with regard to the desired vehicle performance, handling and comfort capabilities, while also considering the available space for the suspension and its costs. During said process, materials, shape, size, and manufacturing procedure of components are considered, while the components interaction, kinematics, elasto-kinematics, as well as connections and fasteners also need to be evaluated. Vehicle's suspension needs to be designed as one interacting system of separate components conforming to the design requirements.

The suspension design process is in a greater detail discussed in the book *The Automotive Chassis Vol. 1: Components Design* [5, p.148-169], where the design details and forces acting on separate components are discussed on an example of a McPherson suspension, and in the book *Chassis Handbook: Fundamentals, Driving Dynamics, Components, Mechatronics, Perspectives* [8, p.449-491], where the development process of a high-volume manufacturing process of a suspension system is discussed, including economic considerations.

With suspension design, the static parameters, kinematics, and elasto-kinematics are considered, as well as the dynamic loads that the suspension system and its parts are exposed to. The suspension kinematics describe the movement caused in the wheels during steering and compression of the suspension. Elasto-kinematics describe the alterations in the position of the wheels and suspension parts caused by forces and torque between the tyres and the road as a result of the elasticity of suspension parts, mainly in the rubber suspension bushings. [4, p.235-237]

The suspension design process follows the pattern used with many other technical products – from the start of the project with planning and definition, concept studies, through design and simulations to prototype construction, testing and validation, optimalisation towards the finished series production part. [8, p.449]

As a part of the design process, the suspension parameters need to be determined. This includes the kinematics, elasticity of components and more. To do so, geometrical parameters of the selected suspension system need to be evaluated, this means combining CAD models of the vehicle's suspension parts and with the help of the CAD software, a multi-body simulation (MBS) of the rigid and flexible associative models can be conducted. From these simulations, the linkage kinematic and elasto-kinematic parameters of the suspension are calculated. As an example, evaluation of kinematic toe-in (Chapter 2.4.1.2) change of a double wishbone suspension as a result of suspension displacement is show in Figure 10. [8, p. 457-461; 5, p.136-139]

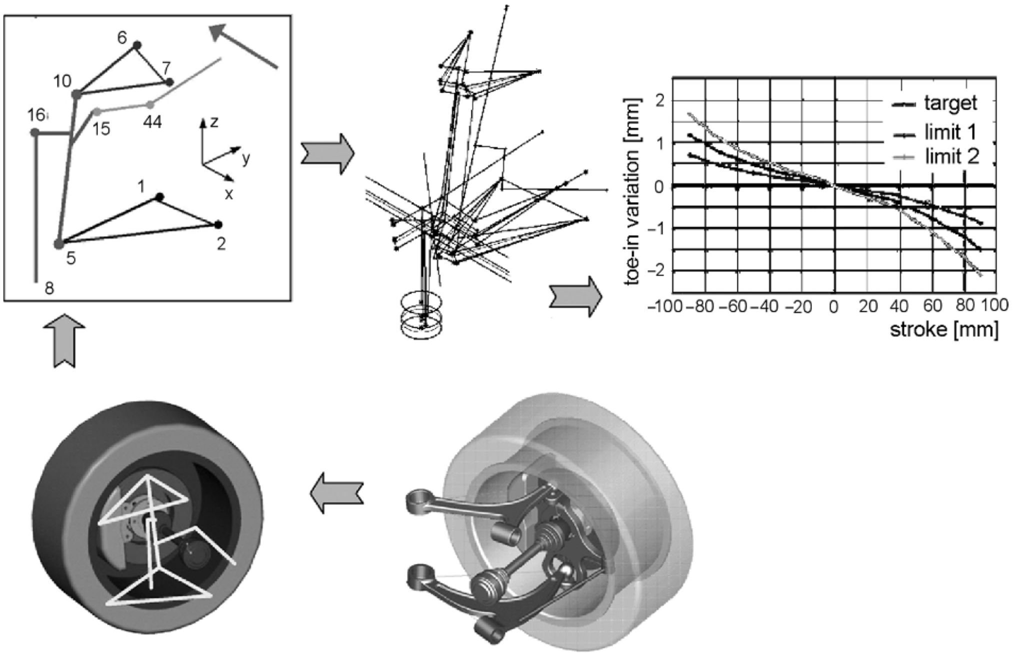


Figure 10 - Suspension design kinematics simulation process [5, p.139]

As the suspension design simulation process continues, the manufacturing tolerances and their effects on the kinematic parameters of the suspension can be evaluated. At the same time, the components size variation influence can be determined and most suitable variation can be selected. [8, p.461]

From the predetermined load requirements, torque and force distribution into the components, a finite element method (FEM) can be conducted to analyse the suspension component's strenght, stiffness, frequency and durability (Figure 11). At the same time, changes to the CAD models can be made accordingly to adhere to the design and safety requirements, including crash simulations. [8, p.462-466]

Afterwards, the designed part is used in whole-vehicle simulations to determine its interaction in the whole system, which includes MBS of kinematics, elastokinematics, dynamic loads and vehicle handling simulations. Finally, a series production evaluation can be done to finalise the manufacturing process of the production part. [8, p.466-490]

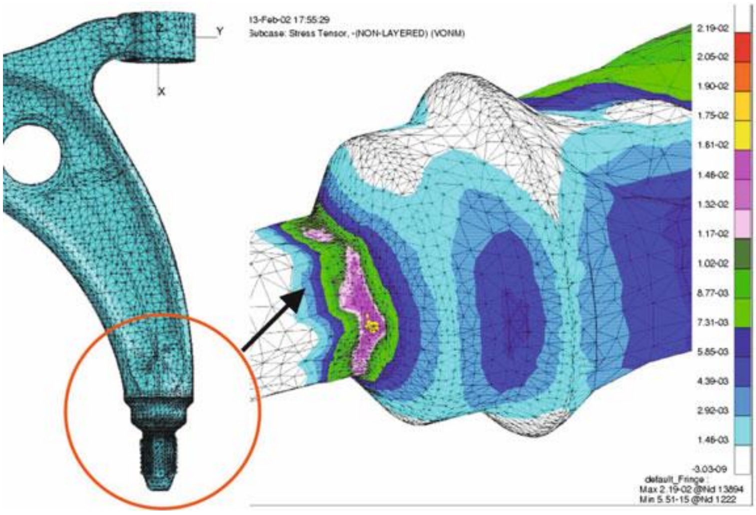


Figure 11 - Control arm stress calculation using FEM [8, p.463]

2.4 Vehicle wheel alignment

Vehicle wheel alignment has a crucial role in determining what the behaviour and performance of a vehicle is going to be on the road. Vehicles with incorrect alignment are likely to be less stable, more unpredictable on the road, but there is also the opposite extreme, where overly stable vehicle will not corner properly, or is going to have a delayed reaction on the steering input from the driver, which could potentially be dangerous.

2.4.1 Wheel alignment parameters

Wheel alignment is measured on a static vehicle in a drive-ready state. The parameters are dependent on the geometry of the suspension. Depending on the type of suspension system of a vehicle, and its design, these parameters might be adjustable, or set by the design of the suspension, as such this also needs to be considered during the design process. Also, given the kinematics and dynamic motions behind moving vehicle, these parameters are most certainly not the same as the dynamic parameters. The parameters change in reaction to displacement of the vehicle's body as reaction to dynamic forces, or the displacement of the suspension in reaction to road imperfections, are determined in CAD programs and simulations from suspension models. In this chapter, only the static parameters are considered in this project.
The discussed parameters are defined according to the international standard ISO 8855:2011 [7].

2.4.1.1 Camber

The camber angle (ε_V), as shown in Figure 12, is the angle between the Z_V axis and the wheel plane (plane normal to the wheel-spin axis (axis of wheel rotation – coincident to Y_W axis), which is located halfway between the rim flanges), about the X_V axis. Camber angle is positive when the wheel leans outward at the top (the wheel is inclined towards the outside of the vehicle), relative to the vehicle body, and negative if it leans inward (inclined to its inside). [7]
Camber angle affects the vehicle's behaviour during cornering. Positive camber angle is unusual for road vehicles, but in the past was used due to a lack of paved roads and can still be found on heavy vehicles used in off-road conditions. [4, p.229-232]

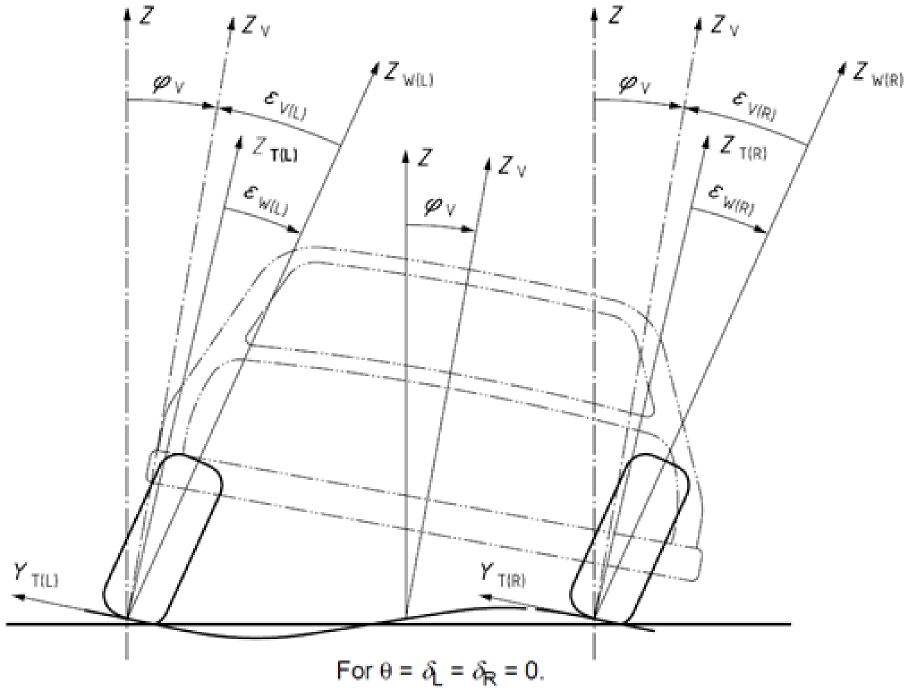


Figure 12 - Camber, inclination, and vehicle roll angles [7]

2.4.1.2 Toe angle (Toe-in / Toe-out)

The static toe angle is the angle between the X_V axis and the wheel plane, about the Z_V axis, with the vehicle at rest with the steering in straight-ahead position. Toe-in is being referred for wheels turned inwards - if the forward portion of the wheel is closer to the vehicle centreline than the wheel centre (point at which the wheel-spin axis intersects the wheel plane) and toe-out if it is farther away - turned outward as indicated in Figure 13 below. [7]

As per convention, toe-in is considered a positive angle, and toe-out a negative angle. During driving, toe angle is introducing side slip to the wheel – parasitical force to the rolling resistance with stabilising effects. [4, p.229-230]

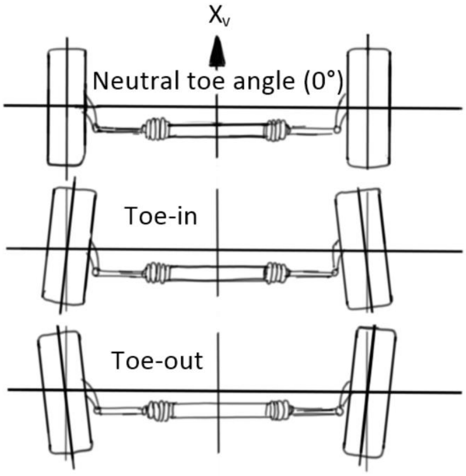


Figure 13 - Toe-in/out angle

2.4.1.3 Caster angle

The caster, or castor angle (τ) (Figure 14), is the angle between the Z_V axis and the normal projection of the steering axis (axis about which the wheel and hub assembly rotates relative to the vehicle structure when steered - upright or steering knuckle rotational points) onto the X_V-Z_V plane. The angle is referred to as positive when the top of the steering axis is inclined to the rear. [7]

The caster angle affects the camber angle while a steering input is given (changing the behaviour while cornering). The camber angle for the outer wheel is decreased for a vehicle with a positive caster angle and increased when the caster angle is negative. The opposite applies to the inner wheel. The caster angle results in a caster offset. The castor offset at ground is referred to as the castor trail, or the kinematic trail (n_k). It is the distance in the X_T direction from the Y_T-Z_T plane to the point where the steering axis intersects the X_T-Y_T plane. The castor offset at wheel centre is referred to as the spindle trail (n_τ). [7]

2.4.1.4 Kingpin inclination

The steering-axis inclination angle, also known as the kingpin inclination angle (σ), is the angle between the Z_V axis and the normal projection of the steering axis (axis about which the wheel and hub assembly rotates relative to the vehicle structure when steered – upright or steering knuckle rotational points) on to the $Y_V - Z_V$ plane (Figure 14). The angle is positive when the top of the steering axis is inclined inward. [7]

2.4.1.5 Kingpin offset

The kingpin offset at ground, also called the steering axis offset (r_k), is the distance or offset in the Y_T direction between the wheel plane (plane normal to the wheel-spin axis, located halfway between the rim flanges) and the point where the steering axis intersects the X_T-Y_T plane (Figure 14). This distance is positive if the steering axis intersection point is inboard of the wheel plane and negative if the point is outside of the wheel plane. Kingpin offset has great importance, as the torque resulting from different road surfaces can have a stabilising effect. [7]

2.4.1.6 Scrub radius

The scrub radius (r) is defined as the distance from the contact centre to the point where the steering axis intersects the X_T-Y_T plane (as shown in Figure 14). [7]

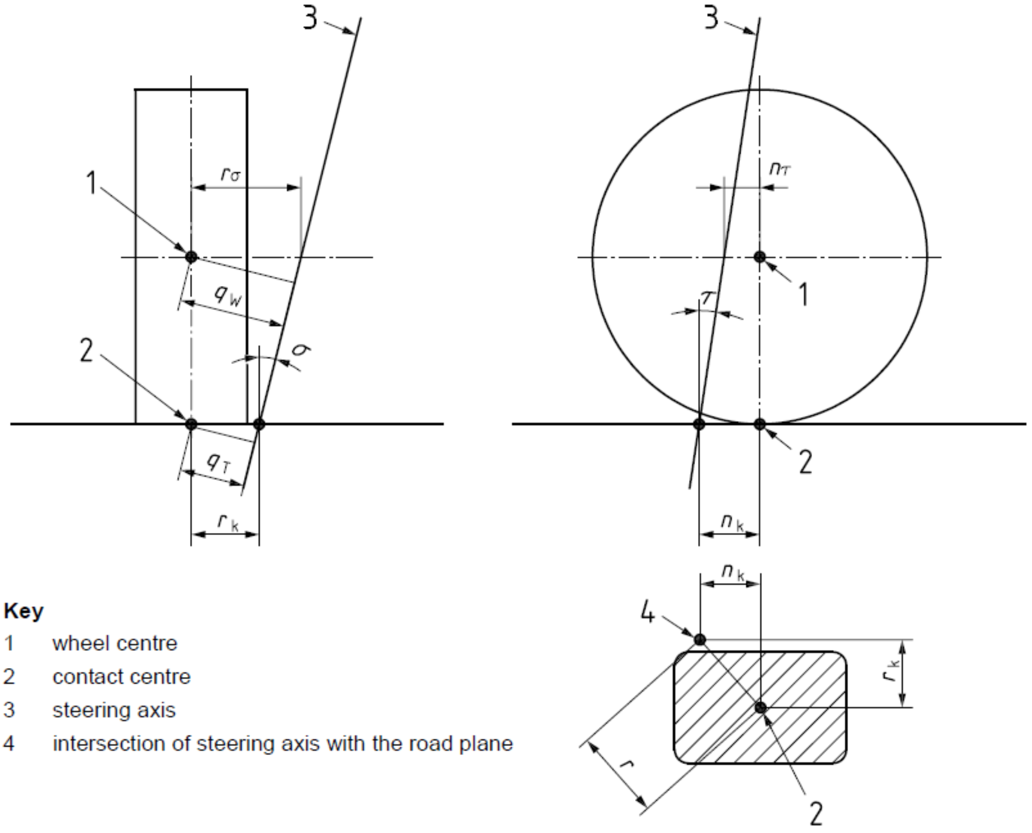


Figure 14 – Wheel alignment parameters [7]

2.4.2 Measuring devices used to determine wheel alignment

To determine the wheel alignment of a vehicle, a measuring device is used. Wheel alignment can be measured with or without special alignment systems. While the former is of a higher precision and much easier and quicker to perform, there are certain ways it can be measured without them, using basic measuring devices. The existing commercial alignment systems are based on optical, mechanical, or laser technology. The wheel alignment systems might also differ by their intended use, as there will be different requirements on measuring systems intended to be used during motorsport events and those used for road, or commercial vehicles.

2.4.2.1 Simple measuring methods

One of the most basic methods to perform wheel alignment is shown in the Figure 15 below. This method relies on simple measuring devices and geometry calculations from the obtained values. With vehicle parked at a flat, level ground and stings stretched alongside of the vehicle at equal distance from the vehicle centreline, at the height of the wheel hub centre, the toe-in characteristics can be measured by measuring the distance at the front and rear of the wheel and the toe characteristics can be calculated. The camber angle can be then measured with a use of a plummet in a similar fashion. Some companies sell commercial products that use this method, connecting the strings to the vehicle with a special bracket system (for example Watkins SmartStrings™ [37]). Such system can be improved by use of electronical measuring devices, like inclinometers, laser measuring devices or other means like specialised rulers – toe/camber board (MK technologies, or SmartCamber™) – that allows for faster, more precise measurements (Figure 15), as this method is usually very time-consuming. [25; 26; 30]

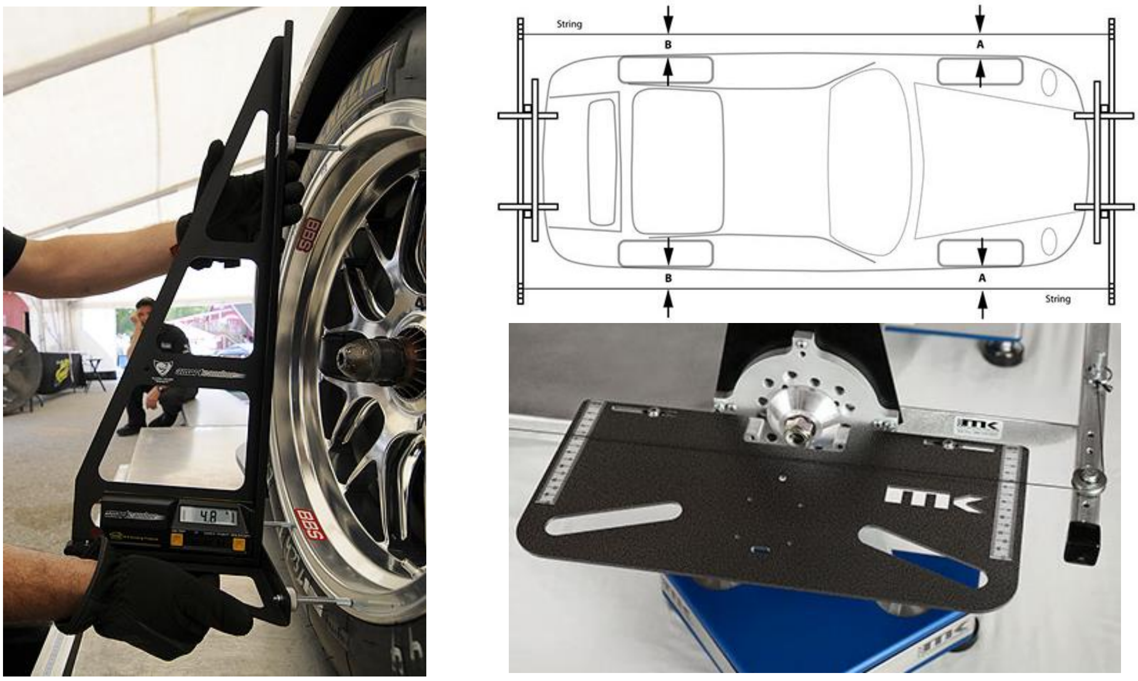


Figure 15 – Left-SmartCamber camber board; Right bottom-MK technologies toe board; Top right-Smartstrings string measuring system [25; 26; 37]

2.4.2.2 Advanced mechanical, optical and electronic racing systems

For racing purposes, special wheel alignment systems are usually used. These systems can work on either mechanical or opto-electronic systems. One such system is Manthey Racing wheel alignment system (Figure 16); this system uses wheel alignment platforms that are placed under a special ‘alignment wheel’ – a rigid metal bracket that connect to the wheel hub instead of a wheel and acts as a wheel replacement for the purpose of eliminating any inconsistences of wheel and tyre. The alignment wheels roller ball feet ensure minimal friction at their contact points, which allows the chassis to move freely and unrestricted by counterforces. This equipment also allows for easier access to the suspension components and alignment threads in comparison with a wheel assembly present. The alignment platforms fulfil two functions – absolute level reference surface and weight measuring of individual wheel load. To the alignment wheels, the measuring equipment can be mounted, with a possibility to specify offset of the wheels. For the toe measurements, laser projection units, projecting on a physical scale, are used. The camber is measured with a digital camber inclinometer. [29]

Figure 16 - Manthey Racing wheel alignment system [29]

2.4.2.3 Common wheel alignment commercial systems

As the previously mentioned systems usually require quite extensive preparation for their use, these methods are not really suitable for standard workshops, which work on road vehicles. Instead, more user-friendly systems, which can be operated by one person and can reduce the overall time necessary for wheel alignment procedure on each vehicle, are being used.

Most common wheel alignment systems used on regular road vehicles are those based on computer vision. These are systems composed of HD cameras, LED sources of light, and special wheel target plates that with their reflective surface provide exact position of each wheel calculated by a computer. Such system is described in the US patents “*Method and apparatus for determining the alignment of motor vehicle wheels*” (US6148528A) and “*Machine vision vehicle wheel alignment image processing methods*” (US7583372B2). This system is used for example in the ML35 Beissbarth wheel alignment machine, or in Hunter Standard Alignment machines. Its operational diagram is shown in the Figure 17. As the whole process of the measurements is computer operated and requires only for the target plates to be mounted correctly, it is easy to use and offers rapid measurements. [27; 28; 31; 32; 39]

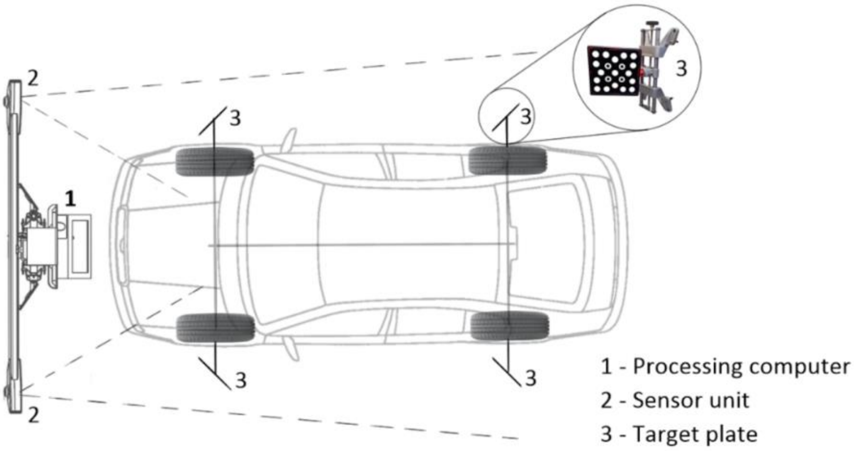


Figure 17 – Computer vision measuring system

Similar to the technology mentioned above are systems based on CCD (charge-coupled device) measuring technology. This alignment system uses a light source and a CCD to measure the angle. Instead of having target plates, the sensor units are placed on each individual wheel and the internal system calculates the angles and geometry (Figure 18). Such system is used at CVUM, where a Launch X-631 system with four probe rods is being used. The provided computer system can be connected to a vehicle database from which the manufacturer specifications of the parameters can be loaded, and the measured parameters can be compared to them. Lastly, contactless wheel alignment commercial systems are also available. These systems rely on computer vision sensors to scan the existing geometric features of the vehicle's wheel and calculate the wheel alignment from them. [28; 29; 31; 40; 41]

Figure 18 - CCD measuring system [38]

2.5 Vehicle dynamic testing

The dynamic behaviour of a vehicle is a very important aspect of the active vehicle safety. For any vehicle, together with its driver and the environment in which it is being operated, constitutes a unique closed-loop system. Vehicle dynamic testing is used to determine and describe the behaviour of a vehicle on the road. In other words, these tests are used to assess the vehicle and driver–vehicle performance. The evaluation of the dynamic behaviour is a very difficult task since the significant interactions of the driver–vehicle and environmental effects are each separately complex issues. An accurate, complete description of the behaviour of a vehicle must therefore involve information obtained from a number of different tests. [2, p.123-124; 10, p.V]

2.5.1 Testing and evaluation methodologies

A number of different methodologies for vehicle's performance evaluation can be distinguished. One criterion in classifying test methods is by the input characteristics definition as open-loop and closed-loop test. [2, p.125]

The closed loop testing is done with a driver using the vehicle to follow a specific task (following predetermined route that the vehicle is to follow), while responding to the vehicle's behaviour - adjusting the input commands accordingly. This testing method focuses on the vehicle-driver-environment aspects. On the other hand, an open-loop test is done in a way where the input is predetermined and is not corrected during the test – the driver acts as a robot, only following the predetermined input commands, not correcting it in any manner; or alternatively, a steering robot can be used. This test is used to eliminate the driver's reactions from the testing procedure; therefore, it focuses on the vehicle-environment effects only. The testing methods can also be divided into subjective and objective methodology strategies, as described below. [2, p.125; 7, p. 31; 8, p.123-124]

Subjective methodology strategies rely solely on the subjective determination of vehicle's behaviour by the testing driver(s). Part of these strategies are performance tests for a specific task, for example determining a maximum speed that allows for a controllable lane change. Rating scale of the performance of such test can be recorded in a form of a questionnaire on a predetermined scale system (10-point, 100-point scale), followed by data reduction. For additional data, open questions are a great way to find the subjective evaluation of the vehicles. [2, p.125; 8, p.123]

Objective methodology strategies rely on measurable instances, such as reference manoeuvres with instrumented vehicles (sensors, data logging, time measured checkpoints on a predetermined test track). [2, p.125-126; 8, p.123]

For subjective testing methods, there is only a limited standardisation of the tests and evaluation, meaning the comparison of tests performed by different organisations is difficult. The main purpose of normalised test procedure, such as ones defined by the International Standard Organisation (ISO), is to provide a repeatable test procedure that gives comparable results. As there is very little standardisation in the subjective handling assessment, mostly objective reference tests are being used in the development phase of suspension design. However, subjective methodology has a great importance in determining a good handling vehicle. For the user, the "feel" of the vehicle is not only a determining factor in a purchasing decision, but also determines the confidence the driver experiences operating the vehicle. As such, use of both methods and their combinations is necessary. [2, p.125-126; 8, p.123,127-136]

Objective testing methodology, where a vehicle is fitted with instruments, sensors and logging devices and given a defined and recorded input, for which vehicle behaviour is characterized by using the recorded measured instances (i.e. accelerations, reaction times, lag of certain variables in relation to the steering input, etc.). This not only means that the tests are repeatable, but it also provides possibility to simulate the objective reference tests with computational programs, where used simulations can vary in complexity that can be appropriately selected according to their usage (precision of a tyre model, necessity of the number of the DoF etc.). Simulations can be used to gain a great amount of usable data, if implemented onto the development process correctly. [2, p.125-126; 8, p.123,137-145]

Single tests cannot be used to evaluate a vehicle's handling. Only with a combination of different tests, testing procedures and exposal to different driving conditions can a sufficient amount of data be obtained to describe the overall dynamic behaviour of a vehicle. [10, p.V]

To introduce some normalised reference tests, several ISO test will be briefly introduced in this chapter.

2.5.1.1 ISO 4138:2012 Passenger cars — Steady-state circular driving behaviour — Open-loop test methods [10]

This test is not representative of a real-life driving condition. It is, however, useful to describe the steady state driving behaviour of a vehicle. This norm includes three test methods: method 1-the constant radius, method 2 – the constant steering-wheel angle, and method 3 – the constant speed. Each test has different requirements on the testing space, driver skills and instrumentation used.

For example, for the testing method 1, the constant condition is the radius of the test circle, with a varied speed and measured steering-wheel angle, longitudinal velocity, and lateral acceleration (other variables can also be measured). The steady-state behaviour is usually represented by a handling curve composed of steering-wheel angle as a function of lateral acceleration, describing the yaw stability properties of a vehicle. Other variables, such as vehicle roll angle, or steering-wheel torque, can be also measured and used to describe different behaviour elements of the steady-state conditions. The minimum recommended value of the radius of the test path is 30m. The steady state for each measurement has to last at least 3s, for which the limitations of path radius, steer angle, speed, rate of increase of lateral acceleration and the throttle position specified are being observed.

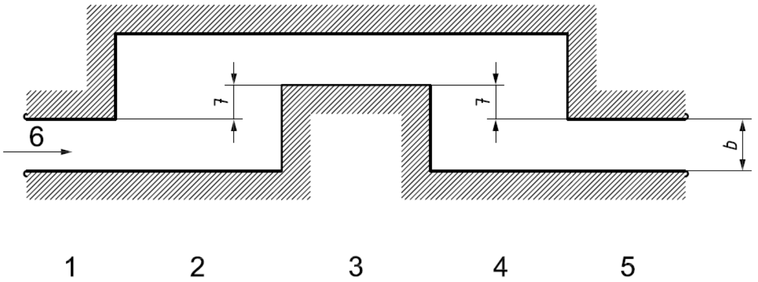
This test is in theory quite a simple one, but with differing road conditions, environmental conditions and considering modern vehicles with variable steering ratio, tyre overheating issues and failure to maintain steady-state can affect the test results.

2.5.1.2 ISO 3888-1:2011 and ISO 3888-2:2016 Test track for a severe lane change manoeuvre – double lane change and obstacle avoidance [11; 12]

Both norms define the dimensions of the test track for a closed-loop, severe lane-change manoeuvre test for determining the performance of a vehicle during those manoeuvres, as one specific part of vehicle dynamics handling behaviour and road-holding abilities. These tests are used to evaluate the lateral and longitudinal transient response of a vehicle and can be used to simulate common and extreme real-life situations. The evaluation of the test results can be both subjective and objective. The test manoeuvre involves driving a vehicle by a test driver from initial lane to another lane parallel to the first, and returning to the initial lane, without exceeding the predetermined lane boundaries indicated with cones (successful pass is one without any of the cones being displaced). The norm provides the test track layout and the cone placement layout for both tests respectively (Figures 19 and 20). The severe lane change test is also known as a moose test, made famous by independent tests conducted by Swedish motor magazine, resulting in redesign of the suspension system in Mercedes A-class vehicles [53]. More recently with the standardised ISO test Spanish company 77km.com ([14]) publishes videos of these test on their YouTube channel and the test results on their website.

Key

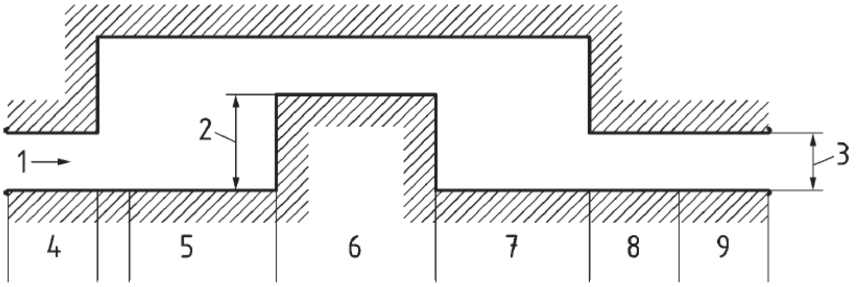
1	section 1
2	section 2
3	section 3
4	section 4
5	section 5
6	driving direction
7	lane offset



Section	Length	Lane offset	Width *b*
1	12	—	1,1 × vehicle width + 0,25
2	13,5	—	—
3	11	1	vehicle width + 1
4[a]	12,5	—	—
5	12	—	1,3 × vehicle width + 0,25, but not less than 3 m

[a] To ensure high lateral accelerations at the end of the track, section 4 is 1 m shorter than section 2.

Figure 19 - Obstacle avoidance test track with section designation [12]



Key

1	Driving direction	4	Section 4	7	Section 7
2	Lane offset	5	Section 5	8	Section 8
3	Width	6	Section 6	9	Section 9

Section	Length	Lane offset	Width
1	15	—	1,1 ´ vehicle width + 0,25
2	30	—	—
3	25	3,5	1,2 ´ vehicle width + 0,25
4	25	—	—
5	15	—	1,3 ´ vehicle width + 0,25
6	15	—	1,3 ´ vehicle width + 0,25

Figure 20 - Double lane change with section designation [11]

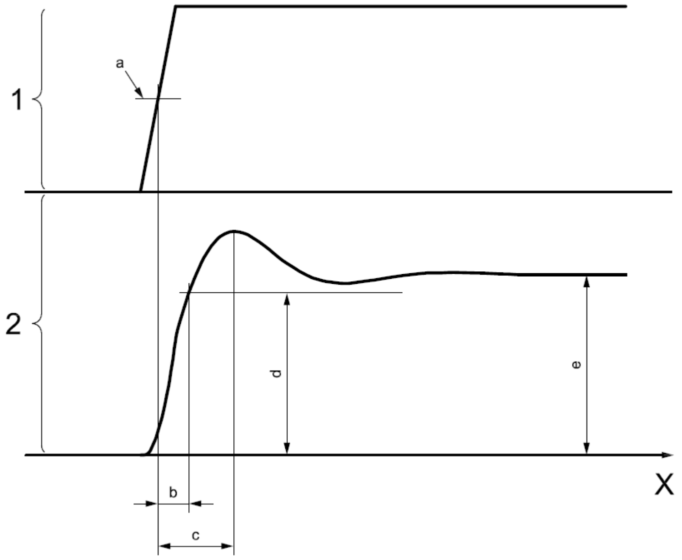
2.5.1.3 ISO 7401:2011 – Lateral transient response test methods – open-loop test methods [16]

This open-loop test is used to determine the transient response behaviour of road vehicles. Open-loop manoeuvres do not represent real driving conditions but provide measurements of vehicle under a specific test condition. The primary object of these tests is to characterise vehicle's time and frequency domain response characteristics.

Time domain characteristics are the time lags between steering-wheel angle, lateral acceleration and yaw velocity; response times of lateral acceleration and yaw velocity; lateral acceleration gain; yaw velocity gain; and overshoot values. These characteristics show correlation with subjective evaluation during road driving. Important characteristics in the frequency domain consists of the frequency responses (amplitudes and phases) of lateral acceleration related to steering wheel angle; and the yaw velocity related to steering wheel angle.

There are several test methods used to determine the different characteristics. For the time domain characteristics, step input and one period sinusoidal steering input tests are used. For frequency domain characteristics, a random input, pulse input, or a continuous sinusoidal input tests are used. The test methods are optional, but at least one test of each domain should be performed. It is important to also mention that it is possible that the characteristic values of the lateral acceleration gain, and yaw velocity gain obtained by the different test methods might not be comparable due to the different conditions of the tests, such as linear versus nonlinear vehicle behaviour, periodic versus non-periodic steady state condition and steady state versus dynamic vehicle behaviour that can occur during these tests.

The norm not only gives detailed explanation of the different test methods, but it also provides data analysis procedure and test report form alongside data results presentation template.



Key

1	steering-wheel input	a	50 % level.	d	90 % steady state.
2	vehicle response time	b	Response time; T.	e	Steady state.
X	time	c	Peak response time; Tmax.		

Figure 21 - Example of data analysis for response time and peak response time of ramp steer input [16]

2.5.1.4 Other testing methods

There are many other normalised and non-normalised testing methods utilised for vehicle dynamics testing that may be considered. Different test methods are useful to determine the behaviour of vehicle in different conditions. For example, when studying the on-centre handling abilities of a vehicle, an open-loop weave test ISO 13674-1:2010 ([13]) can be used. This is a frequency-varying steering input test, where steering oscillations are introduced to the vehicle. A similar closed-loop test is a slalom course, such as the one performed by km77.com ([14]), where driver follows a set route by avoiding hitting cones placed in line. In this test, the frequency changes with the distance between cones and velocity. Other tests can study the vehicle behaviour under breaking, or acceleration, in differing conditions, such as in a turn, on surface with split, or low coefficient of friction. Furthermore, more complex studies of vehicle behaviour are done by subjective, closed loop testing methods on test tracks, where professional test drivers hone the vehicle suspension components and assistance systems to the desired ‘feeling’ and performance. One such track is the Nürburgring Nordschleife, where during the Industrie-Pool manufacturers test their vehicles on a demanding test track [52].

3 METHODS

3.1 DASY expansion – vehicle dynamics database

Based on the literature review conducted, a DASY database expansion regarding vehicle dynamics is discussed in this chapter. To create suitable database extension to the current DASY database system as described in Chapter 2.2, the requirements of the database, based on the previous knowledge of vehicle systems and literature survey outlined above, need to first be evaluated before a suitable database system can be selected and a database model created.

3.1.1 Database requirements

The database is required to store data on individual vehicles, their parameters, vehicle kinematic and dynamic test data and parameters of the tests conducted with these vehicles. The database also needs to store the related CAD models and technical drawings of suspension parts and their parameters. In the foreseeable future, an expansion of the database to also cover vehicle dynamics simulation models and results from simulations processed outside of the database system is to be expected. The database should be flexible enough to allow for the vehicle data, the suspension data, and the test data to be connected in order for them to be easily retrievable, while also allowing the parameters to be used as input parameters for future simulations. In the Figure 22, the preliminary draft layout of the database requirements is shown.

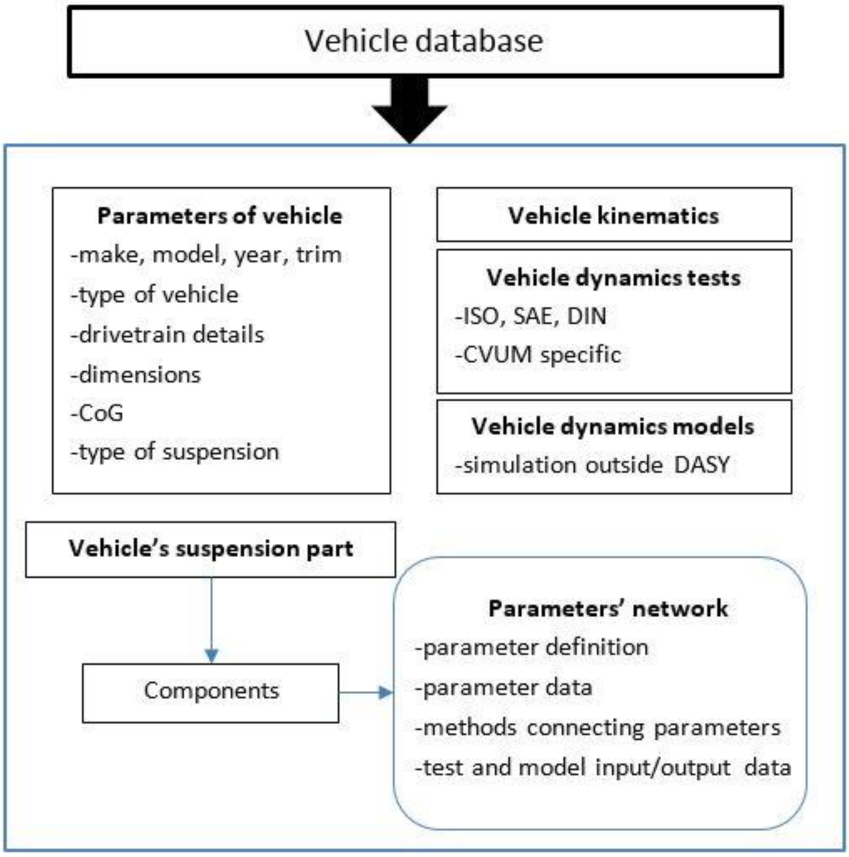


Figure 22 - Database requirements – draft layout

3.1.2 High-level, conceptual database model

From the requirements evaluation, the proposed database system is a relational database solution that is created individually and made a part of DASY system by implementing a data pump (integration module that connects two database systems and allows for data transfer between them, for example as shown in [20]) in the current DASY system that allows to access the new vehicle dynamics sub-database through a vehicle list that would be accessible both in the current DASY and separately in the new database. The proposed database is a relational, snowflake database design, which means all of the tables are given relationships – for example for a specific ID of a vehicle, its parameters are listed in a separate table, similarly a list of parts models available in the database is recorded in a separate table for the specific vehicle's ID. For a specific part of this list, a table of its parameters is catalogued. When considering the vehicle dynamic and kinematic testing, these tests can be connected to individual vehicle ID, the test parameters, and their results.

The relational database model was selected due to the type of the current DASY database, as it is possible to connect it to the current system. The relational database was selected with this integration in mind, but it was also selected for its benefits compared to other database types. Mainly as this type of database allows for a meaningful information representation in the structure from the stored data, SQL includes the ability to perform mathematical calculations and logical transformations of the stored data. This allows for a high flexibility of the database, and redundancy reduction, as with the relations between entities, the repeating data can be linked to the original instance. Shown in the Figure 23 below, the proposed high-level model is shown. This database model allows for future expansion, for example by adding a separate branch of mathematical models of the vehicles and simulation results from these models that can be compared and validated with the test results from real-life tests.

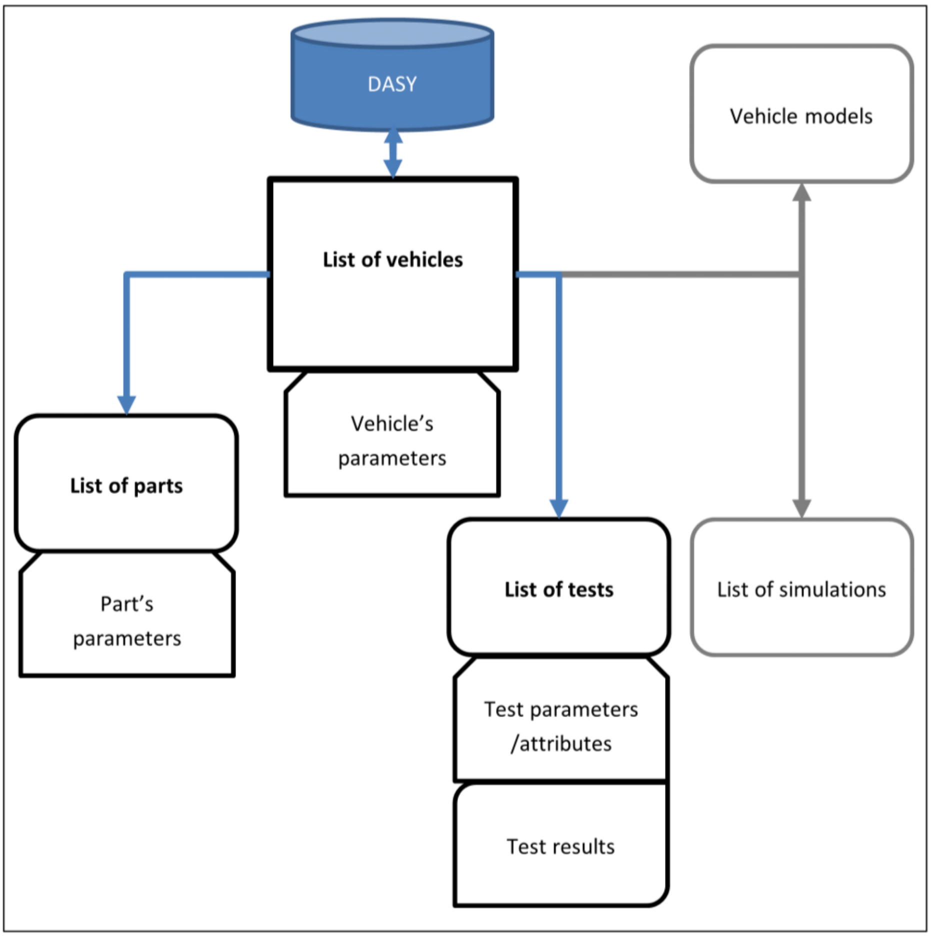


Figure 23 - Database high-level conceptual model

3.1.3 Logical, conceptual database model

To give the conceptual high-level model of the database a logical base that can be used as a road map for physical implementation of a new database, a logical database model has to be created. As already discussed in the literature study, this type of model is based on entities, which are the logical groupings of data filled with attributes. The model is not focused on the entities themselves, as they can be formed by multiple tables, but rather on the relation types between the entities, as can be seen in the Figure 24 below.

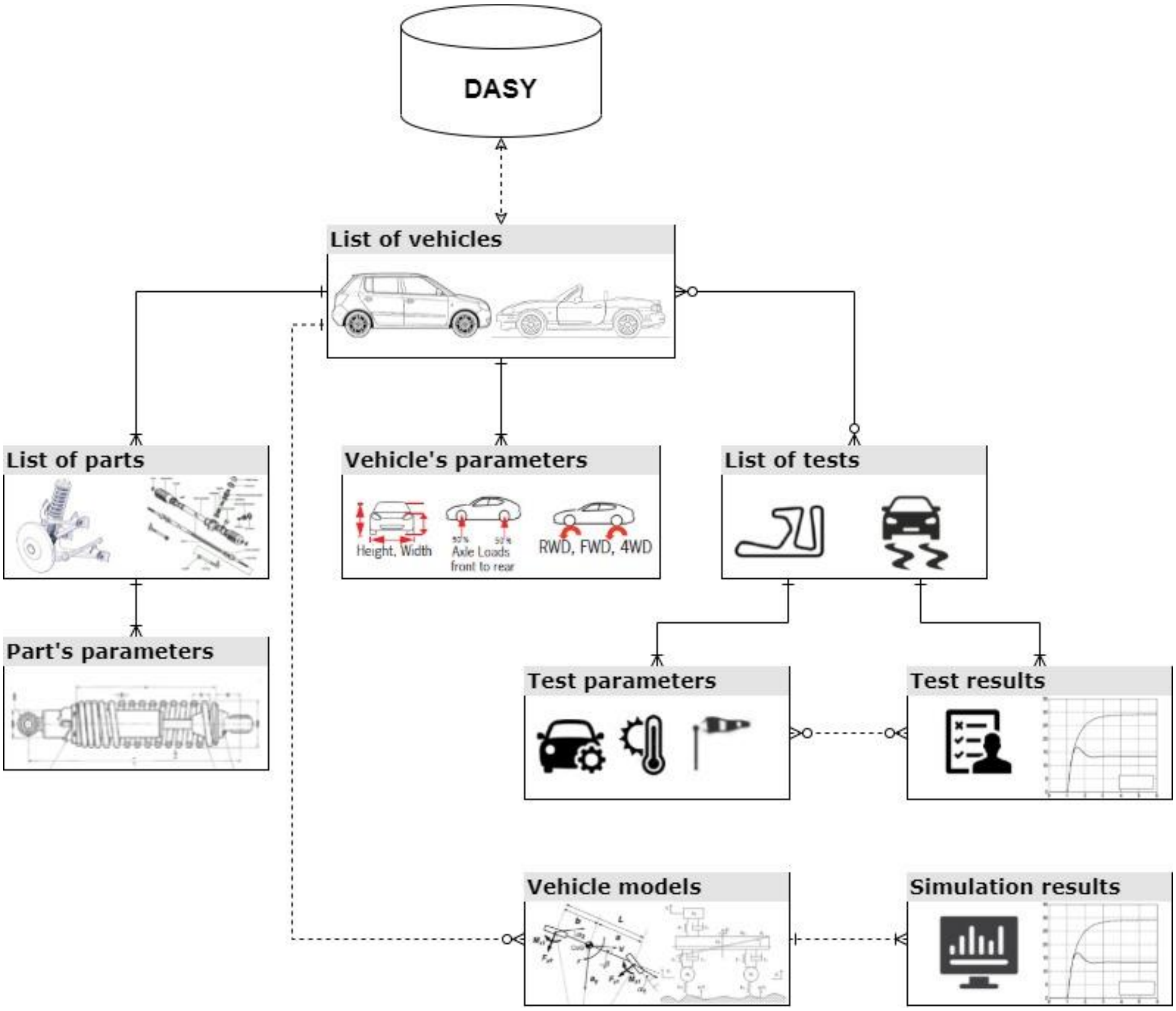


Figure 24 - Logical database model

In this case, the logical database model is based around the main entity that is the list of stored vehicles in the database (*list of vehicles* in the diagram). This entity can be directly interacting with the current DASY system, as a two-way communication can be established by a data pump. The included vehicles in the *list of vehicles* entity can be either real, already produced vehicles, or vehicle concepts that are being developed.

For each vehicle on this list, a number of v*ehicle’s parameters* attributes will be connected by the vehicle’s ID and their stored data. Such parameters can for example include vehicle’s dimensions, weight, the type of driveline system, powertrain, the layout of the vehicle and the measured and calculated CoG parameters (ISO 10392:2011 [15]).

To store the corresponding parts to a vehicle, an entity *list of parts* will contain the studied parts and reference to their CAD models (Creo, CATIA based). A separate entity of the *part’s parameters* is used – in this entity, the physical dimensions, material information and other parameters related to the individual parts can be stored, related to each part by its ID. These parameters could also be used as input parameters for the stored CAD and associative models, which would be useful for example when an FEM method is used during development process of new parts, or when kinematic characteristics are being studied, as this would allow for a quick application of changes to the design, possibly even automating the process.

The *list of tests* entity is connected to the individual ID of a vehicle, but when comparing multiple vehicles on a test course, connecting one test with multiple vehicles would be possible as well. If a test is only proposed, but unrealised, it can be stored separately. Each of the tests has its own *test parameters*, that should include the test vehicle parameters, such as the vehicle set-up (wheel alignment parameters from Chapter 2.4.1), tyre information (their dimensions, make and model, thread measurements and pressure), the vehicle load and its distribution, but also the measuring parameters, such as the used measuring and logging devices, as well as the test course layout, the road and weather conditions during the test procedure. The entity of the *test results* may include not only the separate raw and processed measured data, but also the test driver information and any necessary comments. As this can be connected with the *test parameters* by the individual test ID, more information to sort and evaluate the test results by can be stored and divided according to the vehicle setup and other test parameters.

As in the foreseeable future it can be expected for kinematic and vehicle dynamics models to also be a part of this database, each of the models can be connected to the vehicle ID from the *list of vehicles*. With this, the models could be created and validated by comparing the simulation results gained from the vehicle models to the results from real word tests.

3.1.4 Component implementation

To show possible function of the proposed database system extension to DASY, an implementation of a suspension component into the proposed database is shown in this chapter. As this is not done by physical implementation, the logical procedure is followed and shown. The selected vehicle from which the component was selected is a Toyota Corolla E12 hatchback, which is a compact passenger car. The manufacturer equipped this vehicle with a McPherson front suspension mounted on a crossbar subframe to the frame of the body in combination with rear torsion beam suspension, both axles equipped with coil springs and non-adjustable dampers. This vehicle was selected as it is a good representation of the lower-class small compact and subcompact vehicle market, for which this type of suspension system is mostly used.

The vehicle itself would need to be added into the database system in the *list of vehicles* under its individual ID, for example the vehicle identification number (VIN – as defined in ISO 3779:2009 [46]), or its section could be used as its identifier. To this ID – PK, the parts, their information, and corresponding files of this vehicle can be assorted in the part list entity. This entity can be further separated into multiple tables of logical groupings of parts (for example all parts of the front suspension can be stored in one table, while the rear axle parts can be stored in another and so on).

This can be demonstrated on the lower control arm of the front McPherson suspension of this vehicle. This part is a structural part of the front suspension. At one end, it connects the suspension to the vehicle’s body via a subframe with bolts through two rubber bushings; on the other, a ball joint assembly is bolted to the control arm and connects it to the steering knuckle. The lower control arm is actually an assembly of parts, which consists of the main metal structure of the arm, the two bushings and another part assembly that is the spherical boll joint. This can be seen in the Figure 25 below, where the expanded drawing of the front suspension parts assembly is shown. The lower control arm with the two bushings is shown as one part, the lower ball joint assembly is shown also as one assembly, with the fasteners as separate parts.

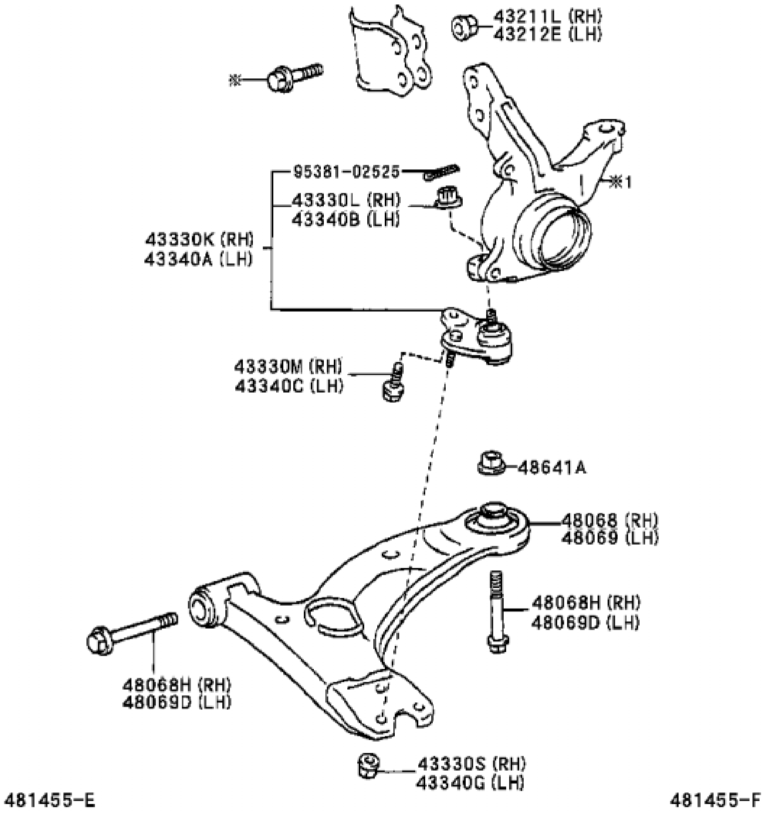


Figure 25 - Corolla E12 front suspension [45]

When adding parts to the database, it is necessary to realise what purpose each entry will serve. When considering the lower control arm, several parts together are acting as one part. In the Table 1, that is a part of the *List of parts* entity, the components implementation is shown. To clarify, the shown table is not complete, as it does not include all the front suspension parts.

Table 1 - List of parts table (front suspension)

Part ID = PK	VIN = FK	Part name
48069AS	SB1KY28	Lower control arm assembly (LF)
48069	SB1KY28	Lower control arm
30-146100003	SB1KY28	Front bushing
30-146100004	SB1KY28	Rear bushing
43340A	SB1KY28	Ball joint assembly

Individual parts in this table have their own individual, unique part number, which acts as the primary key for each entry. The table is connected to the *list of vehicles* entity by a foreign key, which in this case is the VIN number of the vehicle the parts belong to. On this example, the part 48069AS is actually not a separate part, it represents the assembly of several parts (48069, 30-146100003, 30-146100004, and assembly 43340A). The part 48069AS is included in the table only for faster computing during associative model simulations – as the parameters of this part are available in the individual part entries, however, having said assembly separately pre-empts the necessity to calculate the basic parameters during each simulation, instead it is calculated in advance, resulting in lower computational workload.

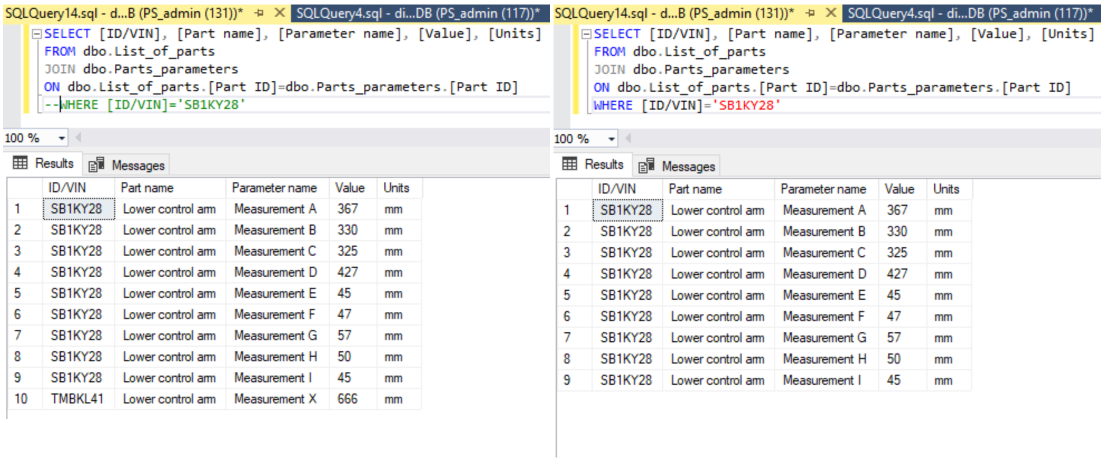
For each of the part entry in the front suspension table of the part list entity, a related *part's parameters* entity table exists. In this entity, several tables might appear. For example, in the Table 2 an example of geometrical parameters of the part 48069 is displayed. In this table, the primary key is the ID of the parameter as it appears in the CAD/associative model, or in the technical drawing of the part. The parameters can represent both physical reference measurements, as well as the manufacturing tolerances for each of the reference measurements. As the *part's parameters* entity can include multiple tables, separate tables for the material designation and properties can be created, or the parameters can be stored in one table, divided by a column with the type of parameter information.

Table 2 - Part's parameters – geometrical parameters

Parameter ID = PK	FK	Parameter name	Value	Units
A48069	48069	Measurement A	367	mm
B48069	48069	Measurement B	330	mm
C48069	48069	Measurement C	325	mm
D48069	48069	Measurement D	427	mm

3.1.5 Database verification

From the proposed logical conceptual database model, a physical model in sqlDBM ([42]) was designed, as this tool allows to design the physical model in a graphic form (Appendix A) and afterwards generates the necessary code, from which a database was created in the Microsoft Azure (SQL server) ([43]). The Microsoft SQL Server Management Studio (SSMS) ([44]) was used to deploy the database and to upload test data into it. In the Figure 26 below, the request for measurements of a part for a specific vehicle is shown. The proposed database is working as intended and its expansion would be possible by adding separate tables, columns and even relations by adding FK references to the existing tables.



```sql
SELECT [ID/VIN], [Part name], [Parameter name], [Value], [Units]
FROM dbo.List_of_parts
JOIN dbo.Parts_parameters
ON dbo.List_of_parts.[Part ID]=dbo.Parts_parameters.[Part ID]
--WHERE [ID/VIN]='SB1KY28'
```

	ID/VIN	Part name	Parameter name	Value	Units
1	SB1KY28	Lower control arm	Measurement A	367	mm
2	SB1KY28	Lower control arm	Measurement B	330	mm
3	SB1KY28	Lower control arm	Measurement C	325	mm
4	SB1KY28	Lower control arm	Measurement D	427	mm
5	SB1KY28	Lower control arm	Measurement E	45	mm
6	SB1KY28	Lower control arm	Measurement F	47	mm
7	SB1KY28	Lower control arm	Measurement G	57	mm
8	SB1KY28	Lower control arm	Measurement H	50	mm
9	SB1KY28	Lower control arm	Measurement I	45	mm
10	TMBKL41	Lower control arm	Measurement X	666	mm

```sql
SELECT [ID/VIN], [Part name], [Parameter name], [Value], [Units]
FROM dbo.List_of_parts
JOIN dbo.Parts_parameters
ON dbo.List_of_parts.[Part ID]=dbo.Parts_parameters.[Part ID]
WHERE [ID/VIN]='SB1KY28'
```

	ID/VIN	Part name	Parameter name	Value	Units
1	SB1KY28	Lower control arm	Measurement A	367	mm
2	SB1KY28	Lower control arm	Measurement B	330	mm
3	SB1KY28	Lower control arm	Measurement C	325	mm
4	SB1KY28	Lower control arm	Measurement D	427	mm
5	SB1KY28	Lower control arm	Measurement E	45	mm
6	SB1KY28	Lower control arm	Measurement F	47	mm
7	SB1KY28	Lower control arm	Measurement G	57	mm
8	SB1KY28	Lower control arm	Measurement H	50	mm
9	SB1KY28	Lower control arm	Measurement I	45	mm

Figure 26 - Select command to list measurments of a part for a specific vehicle

3.2 Vehicle dynamics testing (database data acquisition)

The final task of this project was to determine a viable test procedure to measure real-life data on road vehicles which could be used as entries into the database.

The original goal of this project's test phase was to propose a custom test layout for the available location, which would allow for quick data acquisition for the proposed database, and to verify the proposed measuring procedure of vehicle parameters for a test focused on determining the effects of wheel alignment on vehicle's handling on this test track (Appendix C).

However, this goal was not possible to adhere to as the wheel alignment measuring device, which was supposed to be used during this test, was not operational. Moreover, due to time limitation of the test location availability, an alternative test was devised. This test, focusing mainly on the custom track layout, the measuring procedure, and the data acquisition, is described in the following chapter.

3.2.1 Test location and test layout

As the test locations are currently limited, the Aerodrome Panenský Týnec (LKPC) was selected due to its availability, specifically its' farther taxiway and airport apron (tarmac area used for aircraft parking and manipulation) next to LKPC-27 touchdown area as depicted below (Figure 27).

Figure 27 - Test location

The test layout was dependent on the conditions of the surface of the apron and taxiways available on the aerodrome, avoiding some of the biggest potholes, cracks of the tarmac and loose debris that were present at some parts. This caused the actual test track to be slightly different to the proposed one (Appendix D). The test track was marked using traffic cones, their placement was measured using a tape measure and marked using marking spray paint. The track layout can be seen in Figure 28.

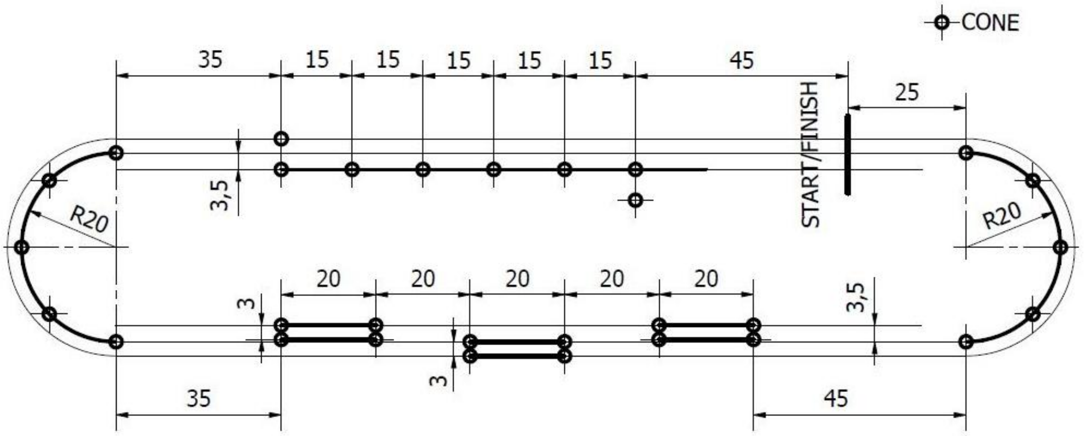


Figure 28 - Test track layout (distance in meters)

This test layout was selected to maximise the data acquisition for a given timeframe, efficiently and safely using the available space, while adding different manoeuvres to test different aspects of vehicle's handling behaviour and maintaining simplistic layout to minimise driver errors. The different elements of the layout were selected according to the literature research, combining some of the currently used normalised test elements. Those elements were then modified to the needs of the available space, test vehicles and test drivers. From the proposed test layouts, a final test track layout was selected with the aim to be dynamic even for low to moderate vehicle's velocity, while still allowing less experienced test drivers to complete the course without issues.

The track consists of two turns at opposite ends with a radius of twenty meters, an obstacle avoidance element with twenty meters sections, with the middle section offset by three and a half meters. On the opposite straight part of the track, slalom course with fifteen meters between the cones was incorporated, beyond which the starting/finish line was placed.

The radius of the turns at each end was unfortunately restricted by the available space. Instead of the minimum recommended value of 30 m, a 20 m radius was selected, with the reasoning, that even if the test drivers were not able to reach a steady state for the minimum of the required 3 s for the steady state behaviour evaluation, the non-steady state cornering behaviour could be studied. At the same time, the corners provide a quick, defined turning point connecting the two central sections. This helps with consistency of the measured results, as the drivers have the same approach route into the individual sections.

The evasion manoeuvre was designed with a lower velocity in mind, providing sufficient lateral acceleration peak values, while not being highly demanding on the test drivers.

The slalom section was designed as a way to measure and evaluate the on-centre handling behaviour of a vehicle for an extreme steering input, with a possibility to easily change the frequency and difficulty level of the test by changing the distance between the cones.

Originally, the layout was designed to be symmetrical so that it would be possible to drive the track in both directions, but the condition of the apron tarmac did not allow for this.

3.2.2 Tested vehicles

The test was performed on two vehicles. As preliminary testing showed that one of the measuring systems was not correctly working with vehicles of different manufacturers, two Volkswagen Group vehicles were selected (Figure 29, 30, 31). First tested vehicle was a first-generation (2001) Skoda Octavia 1.8T (PQ34 platform) with a 4wd Haldex system, equipped with a front McPherson and rear multilink suspension. The second tested vehicle was a third-generation (2009) VW Scirocco 2.0 TSI (PQ35/A5 platform), equipped with front McPherson and rear four-link trailing independent suspension along with magnetorheological adaptable dampers and steering DCC system. Both vehicles were graciously provided by V. Císař, as other VW group vehicles were not available from CVUM at the time. These vehicles were selected for their availability, representing two different suspension systems, drivetrain systems and two platform generations of Volkswagen group vehicles. The vehicles and their suspension were inspected for damage and wear. No damage, or extensive wear, was noted on the suspension components.

Figure 29 - Tested vehicles

Figure 30 - VW Scirocco equiped with measuing devices

3.2.3 Measuring equipment

The tested vehicles were equipped for the test with an assortment of measuring devices. The Racelogic DriftBox telemetry datalogger ([22; 23]) was placed in the middle of the front windshield (Figure 32) with its external GPS antenna mounted on top of the vehicle's roof on the passenger side of the vehicle. This device can measure the position and velocity of the vehicle with the GPS data, lateral and longitudinal accelerations by its accelerometers and the yaw rate of the vehicle. The vehicle was connected to a computer with a VCDS diagnostics/logging software via OBD2 interface ([47]). This software was logging, from the internal steering wheel sensor, the steering angle and angular speed of the steering wheel, together with the acceleration from the internal accelerometer sensor of the vehicle in the lateral direction. Originally, the vehicle's velocity from the ABS sensors was supposed to be also measured, however the CAN Bus system communication capability of the VCDS software limited the possible data logging frequency with multiple sensor banks, therefore it was decided to only use one bank with a higher log frequency. Additionally, a Corrsys logging system ([48]) with a Datron MicroStar sensor ([49]) mounted to the passenger door was used (Figure 31). This device measures the velocity and acceleration in the sensor's axis, from which the relative position can be calculated. Originally, a two-sensor, two-axis setup with one sensor for longitudinal and one for lateral direction was supposed to be used, however, as one of the sensors was not operational, only the lateral sensor was used.

Figure 31 - Skoda Octavia with measuring devices

Figure 32 - RaceLogic DriftBox placement

3.2.4 Test procedure

After the preparation of the test track layout, the general environmental conditions on the test grounds were measured and noted (the air and tarmac temperatures, wind direction and speed).

All the test drivers were given practise session to familiarize themselves with the track and the vehicles prior to the actual test.

The test itself was performed with the instrumented vehicles from a standing start (as marked in the diagram in Figure 28). For each vehicle, the test drivers were to complete three full laps of the marked test track, finishing at the starting line, meaning for each measurement there is one lap with acceleration towards the first turn, one uninterrupted lap, and one lap with deceleration after the slalom course to a stop, where the measurements from that run were saved. For each saved file, the vehicle-driver combination was noted.

In the first vehicle, the VW Scirocco, each of the drivers drove one set with the suspension and steering set to a ‘comfort’ setting and one set to a ‘sport’ setting. Once all drivers finished with the first vehicle, the drivers drove with the second tested car, the Skoda Octavia, two sets of three lap measurements. Ideally, each driver would complete multiple measuring runs with each vehicle varying the velocity, however, due to time limitations on the track, this was not possible to achieve during this test, so instead the emphasis was on the repeatability of the test with different test drivers.

The test drivers were instructed to drive at a steady, smooth pace at which they felt comfortable and able to follow the designated test track without touching the cones, with extra emphasis on keeping steady speed on separate elements of the track (for example in the turns or during the slalom course). If a driver hit a cone, or made another mistake, the test run was to be repeated.

After the test was finished, the drivers were asked questions for their opinions with regards to the test track layout, perceived difficulty level, and workload during the test.

4 RESULTS

In this chapter, only the results obtained during measurements from the performed test procedure discussed in Chapter 3.2 are introduced. The verification of the database expansion function is shown in the Chapter 3.1.5 of the Methods chapter.

4.1 Data synchronisation, section designation

As the different measuring devices were operating individually, their run time, measuring start point, as well as their logging frequency differ from one another. Therefore, a synchronisation of the data was necessary, which was done from the lateral acceleration sensors (Appendix B, Figure B2).

The measured GPS location data from the RaceLogic DriftBox were plotted to Google maps. In the Figure 33, this plot shows the results for all the test runs with the VW Scirocco. This data was later used to distinguish the start and end of each lap, and to determine individual sections in each lap.

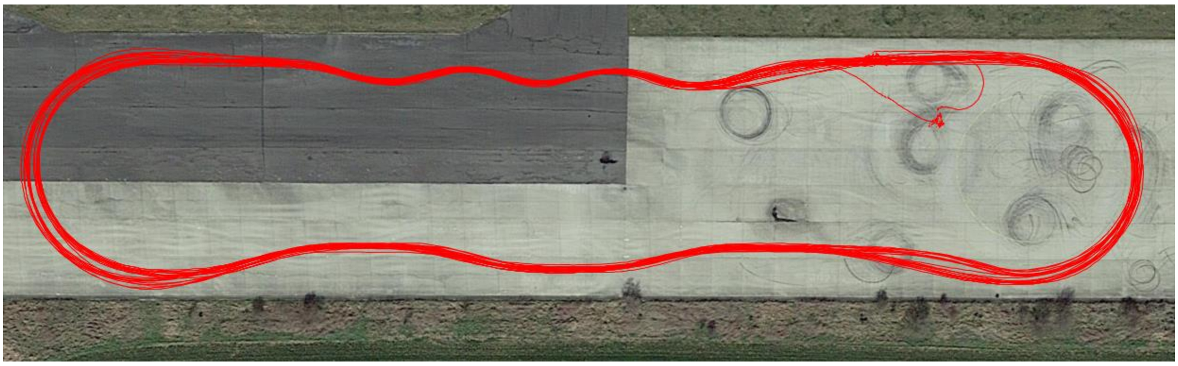


Figure 33 - Plotted GPS data into Google Earth map

In the Figure 34 below, a measurement obtained from the second driver with the VW Scirocco with ‘comfort’ suspension settings is shown. Plotted data from the other drivers can be found in the Appendix B. The green vertical dashed line marks each instance when the vehicle crossed the start/finish line, showing the start and beginning of the three completed laps.

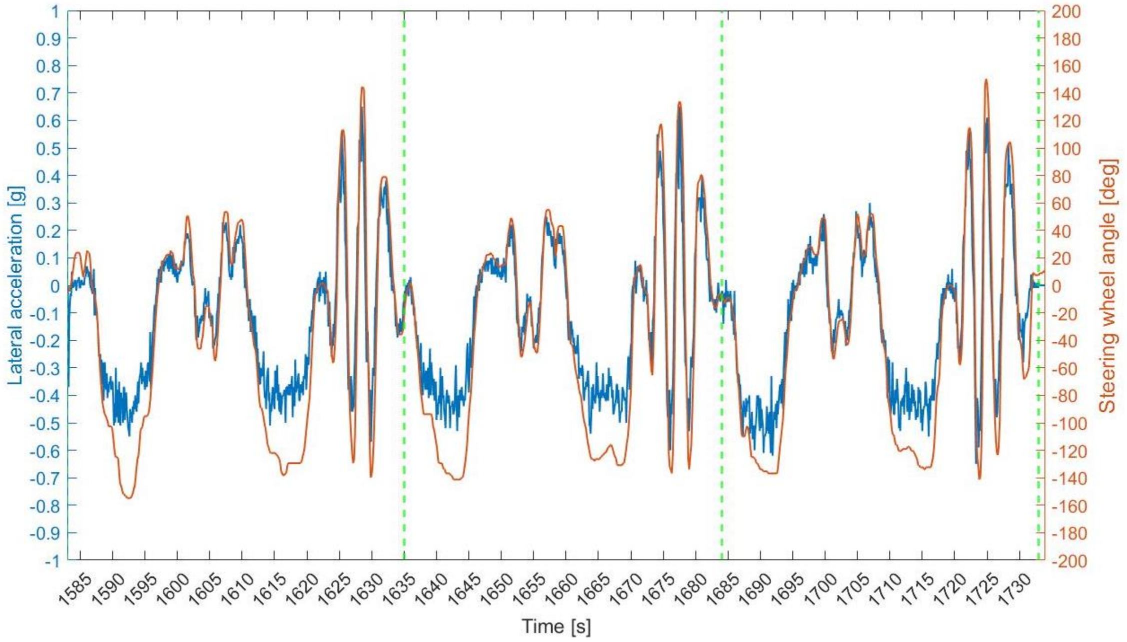


Figure 34 – Lap designation - Lateral acceleration, Steering wheel angle (Driver 2, VW comfort)

From this diver’s run, each of the displayed laps can then be divided into separate sections according to the performed test manoeuvre. As an example, the second (continuous) lap from the same test run is displayed in the Figure 35 and divided into separate sections. To ease the data evaluation process, a designation was given to each section. The first right hand turn was designated as section 1, the evasion manoeuvre section 2, second turn section 3 and the slalom course as section 4, while the connecting sectors between those were given designation a through e.

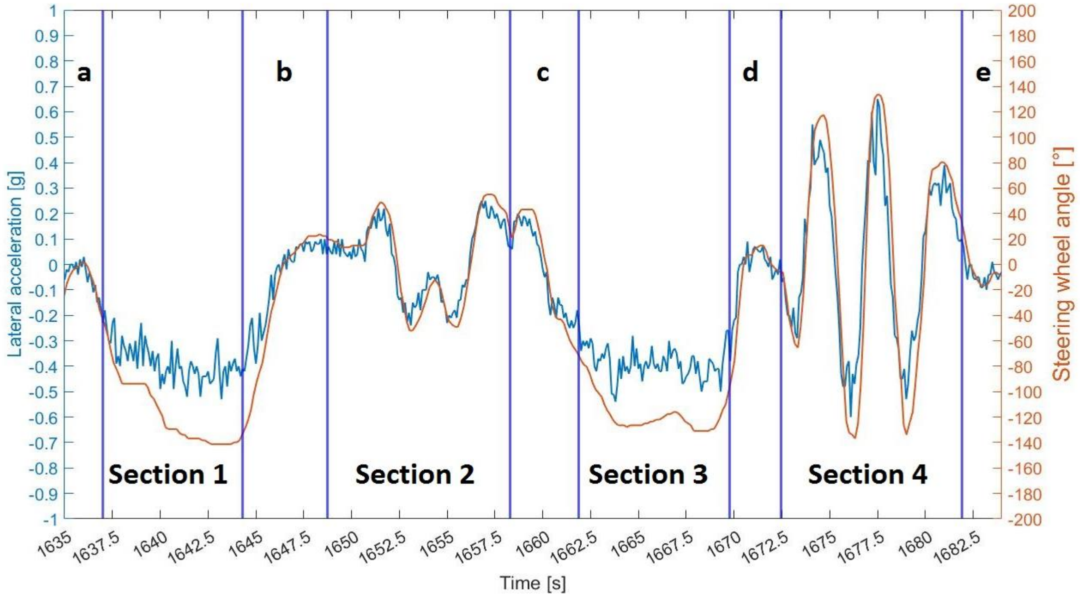


Figure 35 -Section designation (2nd lap, Driver 2, VW comfort)

4.2 Data examination

With the synchronised, assorted data, an evaluation of the measured values can be done.

Each of the sections can be studied individually, evaluating the measured output values of lateral acceleration and yaw rate to the velocity of the vehicle and the steering wheel input angle (Figure 36). Similarly, longer sections can be studied, including the entry and exit sections, which allows to compare the driver behaviour in these sections. For a comparison of the consistency of the drivers during each run, the whole measured three laps section can be compared.

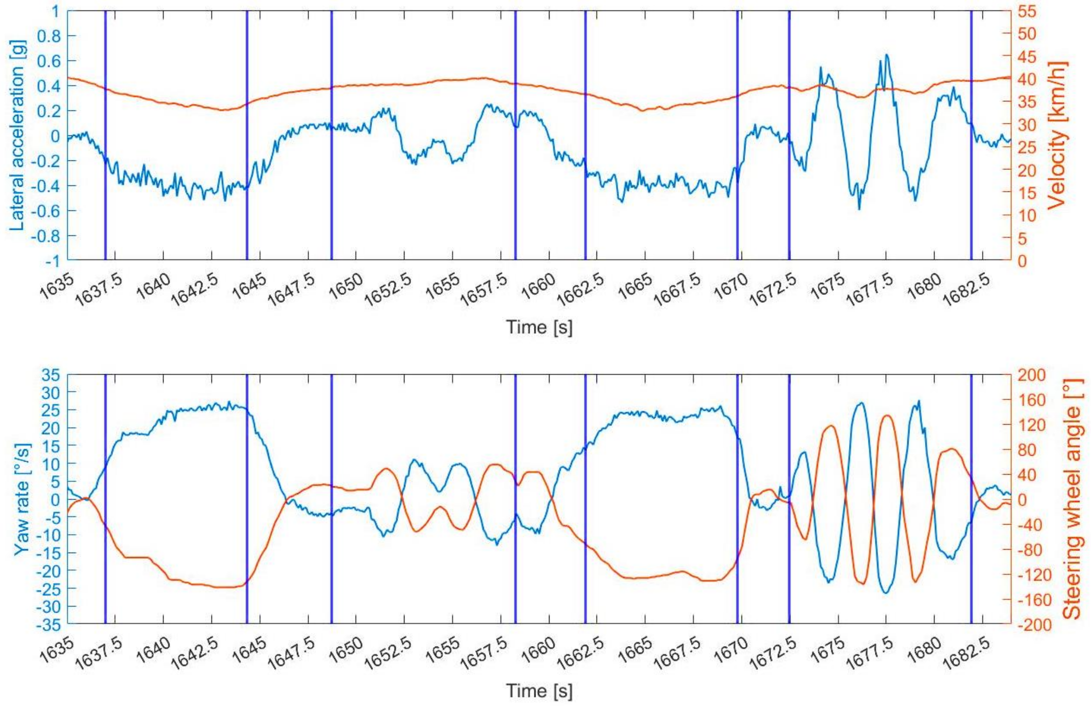


Figure 36 -Above-velocity, lateral acceleration; Below- Yaw rate, Steering wheel angle (Driver 2, VW comfort)

In the Figure 37 below, the comparison between the ‘comfort’ and ‘sport’ setting on VW Scirocco with the second driver behind the wheel is shown. As this driver was the most consistent during the measurements, it can be used as a good example of what good, repeatable results from this test can look like.

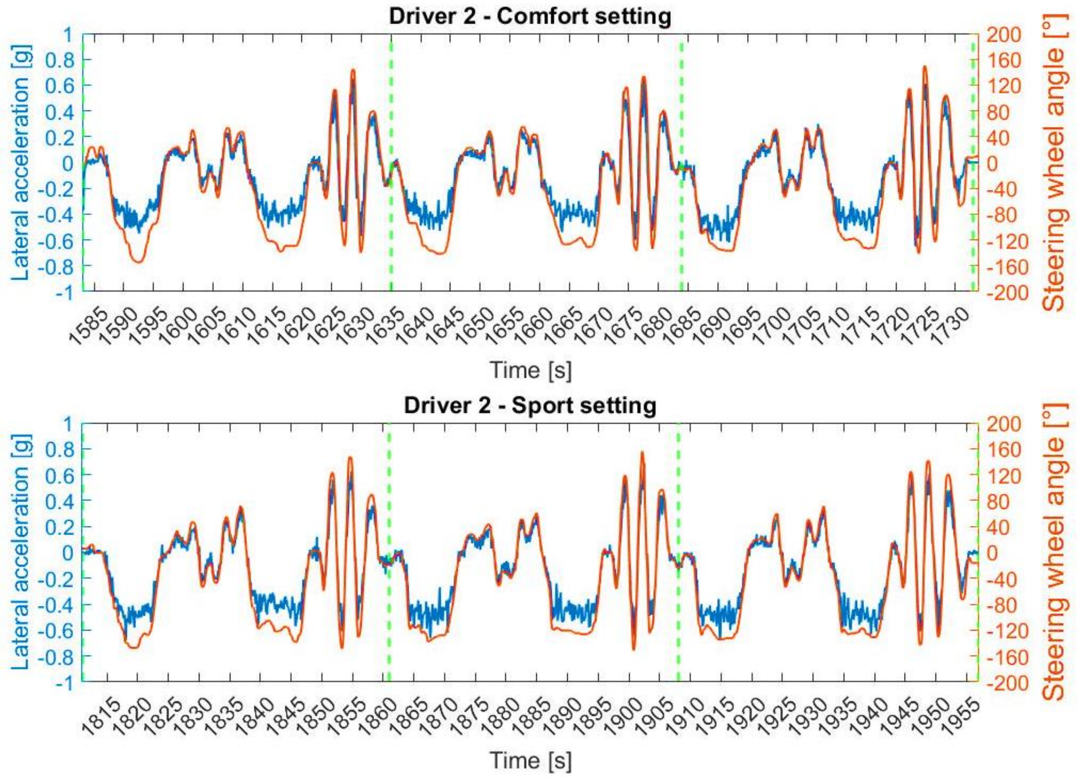


Figure 37 - Driver 2 comparison VW (sport, comfort setting)

From the same driver-vehicle combination, a comparison table (Table 3) is shown below. This table comprises of averaged values from all three laps in sections 2 and 4, comparing ‘sport’ and ‘comfort’ DCC settings. The average values (a_y average, a_x av., yaw rate av.) are from the absolute values.

Table 3 - Driver 2 average values comparison table (average values from three laps measurements)

Section	**Section 2 - Evasion (Driver 2)**		**Section 4 - Slalom (Driver 2)**		
DCC selection	***comfort***	***sport***	***comfort***	***sport***	
Velocity max	39,883	40,413	40,030	40,250	km/h
Velocity min	37,757	37,633	35,620	34,953	km/h
Velocity av.	38,652	38,941	37,631	37,722	km/h
a_y max	0,250	0,270	0,637	0,643	g
a_y min	-0,240	-0,247	-0,607	-0,620	g
a_y av.	0,120	0,122	0,289	0,296	g
a_x max	0,067	0,080	0,140	0,110	g
a_x min	-0,087	-0,087	-0,113	-0,133	g
a_x av.	0,026	0,025	0,045	0,042	g
yaw rate max	10,790	10,883	27,903	29,753	°/s
yaw rate min	-11,723	-11,723	-28,610	-29,620	°/s
yaw rate av.	6,252	6,260	15,054	15,551	°/s

5 DISCUSSION

5.1 DASY database expansion

The main task of this project was to determine how a vehicle dynamics database can be added to DASY. In the Methods Chapter 3.1, the proposed DASY expansion process was introduced. The proposed database model shown in the Chapter 3.1.3 was created as a self-contained relational database, which can later be connected to the current DASY system via data pump. This was done as a way to allow for the database to be created and run separately from the main system on a separate server, validating the proposed model functions and enabling to hone the physical model's structure to the needs and preferences of CVUM in the near future without interfering with the operation of the current system. However, once the need arises for the databases to be connected, the whole database structure can be integrated to DASY, which would allow for the currently stored components to be connected to the vehicle dynamics database. The database model was designed with future expansions in mind, therefore adding relationships with the driveline and powertrain entities would be possible once the merge is complete.

The components implementation into the database introduced in the Chapter 3.1.4 can be further evaluated in the manner of categorization of the components, as the only category shown in the example there is based on the suspension component's placement (left front wheel). However, with more suspension and other components added, more categories to sort the parts by may be included. This can be done with a component identification column, where more detailed categories could be added, by which the components can be sorted and searched in the database, for example the suspension components could be sorted by their main functions as described in Chapter 2.3.1, or by the related subassemblies, which can be done by connecting the assembly ID as a foreign key to the individual parts listings.

The component implementation and the database functions were verified, as shown in the Chapter 3.1.5, by creating a vehicle listing and adding measured values to a specific part from a parts list. A second vehicle and its part parameter were added to demonstrate the functionality.

For the database to reach its full potential, a graphic user interface (GUI) should be added to simplify the use of the database for users. Furthermore, an Extract Transform Load (ETL) function ([51]) should be added to the database for loading Excel or csv files to the database automatically, as without this function, the database input would be limited to manual operation, negating other advantages of the database operation.

5.2 Data acquisition

As a database without any data in it doesn't serve any purpose, a data acquisition process for the database in vehicle dynamics testing was introduced in Chapter 3.2, as a secondary task of this project. The main criterion for CVUM was to be able to obtain a high amount of usable data in a short time, so instead of normalised test procedures, a custom test track for the given test location was proposed and is shown in Chapter 3.2.1. Originally, the planned test procedure was supposed to validate this test track layout by performing measurements on a single vehicle with varying wheel alignment geometry parameters. However, due to numerous issues with the wheel alignment measuring device and the scheduling due to the pandemic situation, a different test was proposed and performed instead. This test focused mainly on the custom track layout, the measuring procedure, and the data acquisition. It was performed with two Volkswagen Group vehicles (Chapter 3.2.2), equipped with measuring devices (Chapter 3.2.3).

The custom test track was designed as a closed loop testing process, which gives a good initial view as to the handling behaviour of a vehicle with the driver's influence. Main criteria of the layout were to be able to obtain more data in a shorter amount of time, compared to individual tests.

Observing the obtained results (Chapter 4), it can be summarised, that this test procedure achieves this goal, with some caveats.

Individual elements of the track layout could replace certain separate test procedures. For example, the section 2 is an evasion manoeuvre, that is a purely dynamic obstacle that can serve to evaluate an excessive input handling performance. The performance of vehicles in this section can be evaluated subjectively by the test drivers, or the peak values and lag in response to the steering input for the yaw rate, body slip angle and lateral acceleration can be studied (in respect to different tyres, velocities, suspension, and wheel alignment settings). From the data samples in the previous chapter (Figure 40, Table 3), the comparison between two suspension settings with a single driver can be observed. In this instance, both the averaged peak values for the acceleration were around 0,25 g, and yaw rate of 10,8 °/s for a velocity of approximately 40 km/h, which is sufficient for such relatively low velocity. Similarly, with the section 4 (slalom), this test shows an extreme steering input vehicle behaviour, with the change of the distance between the cones, a frequency of the test can be changed, but as it was designed, it could be used for on-centre handling evaluation of a vehicle, as the three sinusoidal periods course at 40 km/h amplitude of the lateral acceleration exceeds 6 m/s^2. By a variation of velocity, or the distance between the cones, the frequency can be changed.

Naturally, this test cannot completely replace other closed loops tests. In instances where a higher velocity is required, or where the evaluation focuses on one individual performance requirement, a full ISO, or other test can be performed, similarly to how open loop testing would still be required to be performed to gain the values of responses of vehicles without the driver's influence.

When looking at the data between the designed individual sections (1-4), the time in the transient sections (a-e) to achieve steady state of a vehicle is only fractional, therefore there is not enough time for the vehicle to settle before the next section. This can be improved upon by elongating the distances between each section, giving the driver enough time to straighten the vehicle before the following section. From the data, it is also apparent, that in the sections 1 and 3, the drivers were not able to consistently achieve steady-state cornering at this velocity for the required minimum of 3 s, which would be useful as it could potentially replace an open-loop constant radius test. This was expected, as the minimal recommended radius of 30m for the turning circle is not possible to achieve at this given location, however this layout still provides the benefit of a quick, and consistent way to connect sections 2 and 4. Furthermore, if this type of test were to be performed at a location that can provide a bigger area, the whole test track could be scaled up, enabling more possibilities of this track layout.

During the test run with the second vehicle (Skoda Octavia), the RaceLogic measuring device did not record the data, therefore the measurements are limited to only steering wheel angle and lateral acceleration from the internal vehicle sensors, as the CAN bus connection with the VCDS was limiting the logging frequency, the vehicle's wheel velocity was not measured, which would be preferred. Therefore, it is not possible to compare the two vehicles to each other. The data acquisition process is only as good as the tools that are used. For more precise measurements, it would be possible to equip the vehicle with additional sensors, such as an external device logging the steering angle, roll angle sensors, and use the two-axis Datron sensor, which was not operational during this test, to measure the relative position, as well as the vehicle velocity and heading. A custom measuring equipment could be also used. What needs to also be considered is that with additional sensors and equipment, the preparation process becomes more complex and more time consuming.

According to the consultations with the test drivers, the test track was overall well received. While the layout was simple, with increasing velocity the difficulty level rapidly increases, as drivers needed to concentrate on maintaining velocity through the obstacle course, while maintaining their distance from the traffic cones to avoid hitting them. The most difficult task for the drivers was the slalom course (section 2) as the tightest section of the track, where the entry into this section needed to be especially precise. The most difficult connecting section for them was section c, where after the evasion manoeuvre it was necessary to align the vehicle into the turn of constant radius (section 3). Unexpectedly, even with section 2 entrance being the most demanding for driver skill, the connecting section d was not pinpointed as an issue as the exit from the turn allowed for the correct approach angle. As the database is not limited to only store data obtained with objective methods, a questionnaire could be given to the test drivers, noting their subjective inputs and insights to the behaviour of the measured vehicle, even giving a scale to the performance evaluation based on the subjective reasoning.

5.3 Extended database utilization

With the proposed database structure, the obtained data from the performed closed-loop test can be transferred and stored in the database under a specific test ID (date and location based), connected to the corresponding vehicle ID. When dealing with different measuring devices and data loggers, it might be necessary to convert the units and format of the measured values to standardise them, which can be done by implementing an ETL function. Both the raw measured data, and the processed data (where the values were corrected for zero drift, phase shift, smoothing or other reduction of noise was performed) can be stored separately, connected to each other, so that all the performed operations are repeatable. The test results can be connected with the vehicle from the list of vehicles and the test parameters, where all the necessary information can be stored.

Database of the test data allows not only for evaluation of test data from individual vehicles, but due to the easy access to the archived data, also for comparison with other vehicles for the same, or similar, tests. This evaluation data can be also stored in the database. Database approach allows for data from different sources to be gathered, structured, and organised, so that data measured on test benches, component data and testing can be related to vehicle dynamics testing data and compared to previously obtained data. With a further expansion of the database to include vehicle mathematical models in mind, the data can also be used to create and verify those models.

A further advantage of storing large quantities of data in this database is that it may lead to further advances in the development of vehicle suspension systems. To illustrate, there are several research papers studying the relationships between closed-loop test performance and open-loop handling metrics, such as in [21], which it would be possible to build upon. However, currently, for CVUM the main purpose of the database is the potential future reduction of the development time and costs for suspension components design.

6 CONCLUSIONS

The goal of this project was to be a steppingstone towards a greater project at CVUM, researching how a vehicle dynamics database expansion for the existing DASY database can be made and how vehicle components and parameters related to the vehicle dynamics behaviour can be implemented into it. Creation of a working, usable database of data, parameters, and vehicle information that can be used in knowledge-based design of vehicles is a labour intensive and time-consuming process. As such, this is a long-term project, which will require years until a full-scale realisation is possible.

To reach the goal of the current project, literature review on database theory, structure, and the current DASY system was necessary. The relevant suspension and wheel alignment parameters to the vehicle dynamics behaviour were also explored, alongside the means to measure them.

Based on the literature survey, and by exploring its requirements, a model of a database expansion for vehicle dynamics to the existing DASY database was proposed.

The proposed conceptual logical database model was validated by creating a physical database model in sqlDBM software, from which a code was generated, and the database was successfully deployed with the Microsoft SQL Server Management Studio on a Microsoft Azure SQL server. By implementing a set of vehicle parameters, components and their parameters, the function of the database was verified. Additionally, research on the possible vehicle dynamic testing methods and the test manoeuvrers that could be considered for obtaining data to be stored in the proposed database was conducted. Based on this, a vehicle dynamic testing methodology to obtain data for the database from real-word vehicles was proposed, and on a custom track layout a test was performed with two selected vehicles.

As the method of implementing the database expansion consisting of suspension components, parameters and vehicle dynamics related to suspension design into DASY system has been identified, the objective of this project has been reached, thus allowing for the further expansion projects to build on this groundwork. Particularly, the next step would be to perform the full-scale database deployment on CVUM server, adding the necessary graphic interface and ETL function to it, followed by data acquisition and importation.

Using knowledge from the expanded DASY database about the effect of powertrain and suspension design on vehicle dynamics will in the future reduce the time and costs of development activities. For example, when a vehicle is being designed, in the database a similar vehicle, based on its specifications and parameters, could be found. If the testing has been previously performed with this vehicle, evaluation of the similarities and the performance could be done, speeding up the design process considerably.

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APPENDIX A DATABASE EXTENSION

From the logical conceptual, a physical model in SqlDBM was created, as shown below.

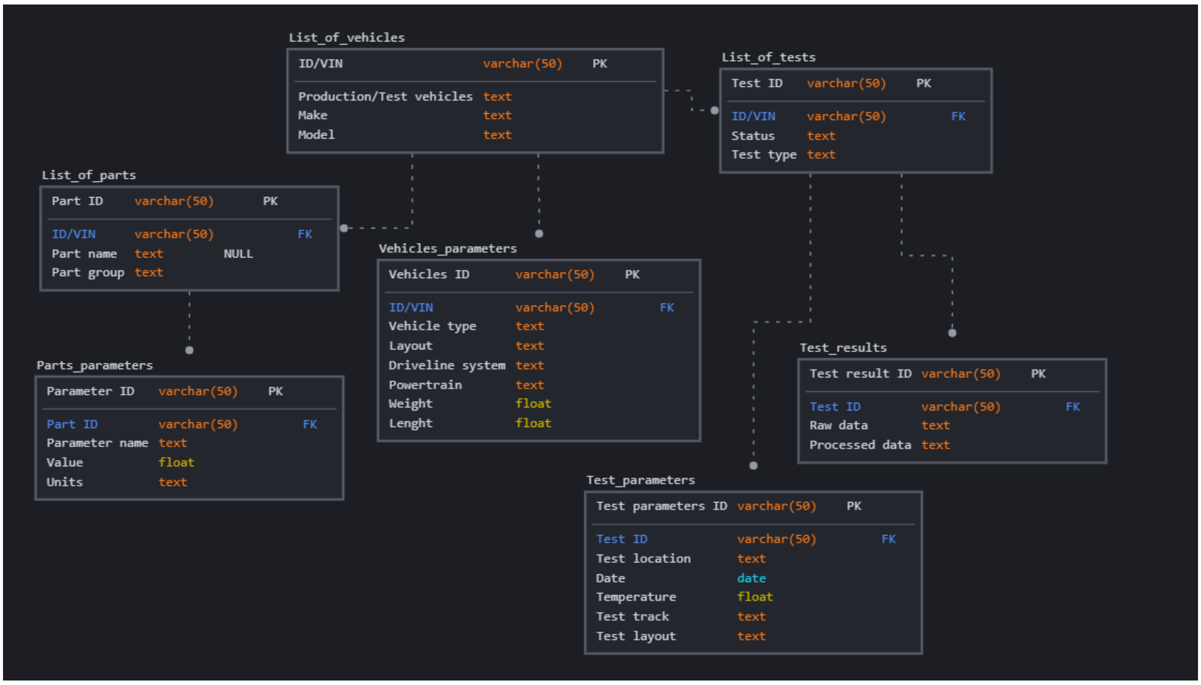

Figure A 1 - Physical model in SqlDBM

From this model, SQL code was generated to deploy the database on a server.

```
-- ***************** SqlDBM: Microsoft SQL Server *****************
-- ****************************************************************


-- ************************************** [List_of_vehicles]
CREATE TABLE [List_of_vehicles]
(
 [ID/VIN]                varchar(50) NOT NULL ,
 [Production/Test vehicles] text NOT NULL ,
 [Make] text NOT NULL,
 [Model] text NOT NULL,


 CONSTRAINT [PK_17] PRIMARY KEY CLUSTERED ([ID/VIN] ASC)
);
GO
-- ***************** SqlDBM: Microsoft SQL Server *****************
-- ****************************************************************


-- ************************************** [List_of_parts]
CREATE TABLE [List_of_parts]
(
 [Part ID]    varchar(50) NOT NULL ,
 [ID/VIN]     varchar(50) NOT NULL ,
 [Part name]  text NULL ,
 [Part group] text NOT NULL ,
```

```
 CONSTRAINT [PK_13] PRIMARY KEY CLUSTERED ([Part ID] ASC),
 CONSTRAINT [FK_List_of_parts_TO_List_of_vehicles] FOREIGN KEY ([ID/VIN])  REFERENCES
[List_of_vehicles]([ID/VIN])
);
GO


CREATE NONCLUSTERED INDEX [FK_23] ON [List_of_parts]
 (
  [ID/VIN] ASC
 )

GO
-- ****************** SqlDBM: Microsoft SQL Server ******************
-- ******************************************************************

-- *************************************** [List_of_tests]
CREATE TABLE [List_of_tests]
(
 [Test ID]   varchar(50) NOT NULL ,
 [ID/VIN]    varchar(50) NOT NULL ,
 [Status]    text NOT NULL ,
 [Test type] text NOT NULL ,


 CONSTRAINT [PK_42] PRIMARY KEY CLUSTERED ([Test ID] ASC),
 CONSTRAINT [FK_List_of_tests_TO_List_of_vehicles] FOREIGN KEY ([ID/VIN])  REFERENCES
[List_of_vehicles]([ID/VIN])
);
GO


CREATE NONCLUSTERED INDEX [FK_38] ON [List_of_tests]
 (
  [ID/VIN] ASC
 )

GO
-- ****************** SqlDBM: Microsoft SQL Server ******************
-- ******************************************************************

-- *************************************** [Vehicles_parameters]
CREATE TABLE [Vehicles_parameters]
(
 [Vehicles ID]      varchar(50) NOT NULL ,
 [ID/VIN]           varchar(50) NOT NULL ,
 [Vehicle type]     text NOT NULL ,
 [Layout]           text NOT NULL ,
 [Driveline system] text NOT NULL ,
 [Powertrain]       text NOT NULL ,
 [Weight]           float NOT NULL ,
```

```
 [Lenght]         float NOT NULL ,


 CONSTRAINT [PK_40] PRIMARY KEY CLUSTERED ([Vehicles ID] ASC),
 CONSTRAINT [FK_Vehicles_parameters_TO_List_of_vehicles] FOREIGN KEY ([ID/VIN])  REFERENCES
[List_of_vehicles]([ID/VIN])
);
GO


CREATE NONCLUSTERED INDEX [FK_35] ON [Vehicles_parameters]
 (
  [ID/VIN] ASC
 )

GO
-- ****************** SqlDBM: Microsoft SQL Server ******************
-- *****************************************************************

-- ************************************** [Parts_parameters]
CREATE TABLE [Parts_parameters]
(
 [Parameter ID]   varchar(50) NOT NULL ,
 [Part ID]        varchar(50) NOT NULL ,
 [Parameter name] text NOT NULL ,
 [Value]          float NOT NULL ,
 [Units]          text NOT NULL ,


 CONSTRAINT [PK_25] PRIMARY KEY CLUSTERED ([Parameter ID] ASC),
 CONSTRAINT [FK_Parts_parameters_TO_List_of_vehicles] FOREIGN KEY ([Part ID])  REFERENCES
[List_of_parts]([Part ID])
);
GO


CREATE NONCLUSTERED INDEX [FK_28] ON [Parts_parameters]
 (
  [Part ID] ASC
 )

GO
-- ****************** SqlDBM: Microsoft SQL Server ******************
-- *****************************************************************

-- ************************************** [Test_parameters]
CREATE TABLE [Test_parameters]
(
 [Test parameters ID] varchar(50) NOT NULL ,
 [Test ID]            varchar(50) NOT NULL ,
 [Test location]      text NOT NULL ,
 [Date]               date NOT NULL ,
```

```
 [Temperature]      float NOT NULL ,
 [Test track]       text NOT NULL ,
 [Test layout]      text NOT NULL ,


 CONSTRAINT [PK_50] PRIMARY KEY CLUSTERED ([Test parameters ID] ASC),
 CONSTRAINT [FK_Test_parameters_TO_List_of_tests] FOREIGN KEY ([Test ID])  REFERENCES
[List_of_tests]([Test ID])
);
GO


CREATE NONCLUSTERED INDEX [FK_45] ON [Test_parameters]
 (
  [Test ID] ASC
 )

GO
-- ****************** SqlDBM: Microsoft SQL Server ******************
-- ******************************************************************

-- ************************************** [Test_results]
CREATE TABLE [Test_results]
(
 [Test result ID] varchar(50) NOT NULL ,
 [Test ID]      varchar(50) NOT NULL ,
 [Raw data]      text NOT NULL ,
 [Processed data] text NOT NULL ,


 CONSTRAINT [PK_52] PRIMARY KEY CLUSTERED ([Test result ID] ASC),
 CONSTRAINT [FK_Test_results_TO_List_of_tests] FOREIGN KEY ([Test ID])  REFERENCES
[List_of_tests]([Test ID])
);
GO


CREATE NONCLUSTERED INDEX [FK_48] ON [Test_results]
 (
  [Test ID] ASC
 )

GO
```

APPENDIX B MEASURED VALUES PLOTS

The measurements shown in this appendix are from the first vehicle (VW Scirocco). Each driver completed two measuring rounds, each having three laps. First driver hit a cone in the last lap, therefore they repeated the run with the same settings, others completed the runs without issues.

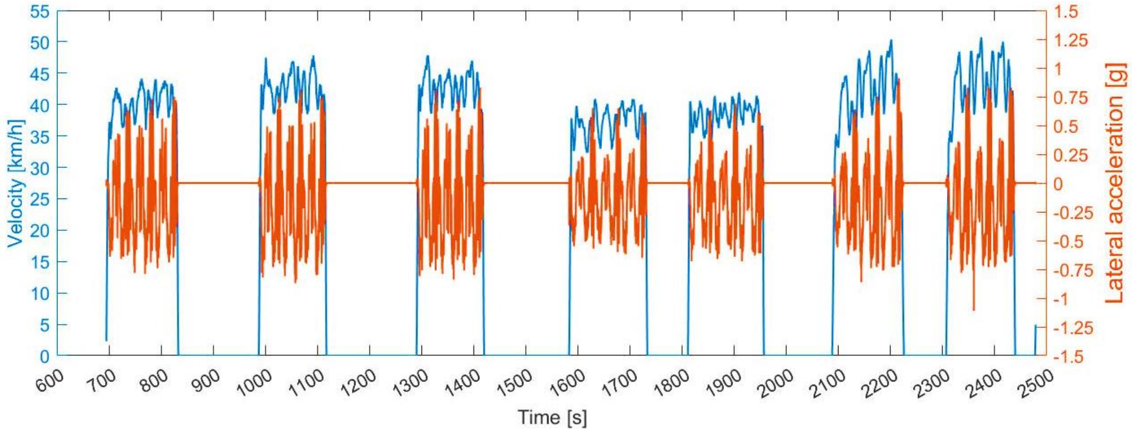

Figure B 1 - Velocity and lateral acceleration, all drivers (VW)

As the data were measured on several different devices, synchronisation needed to be performed.

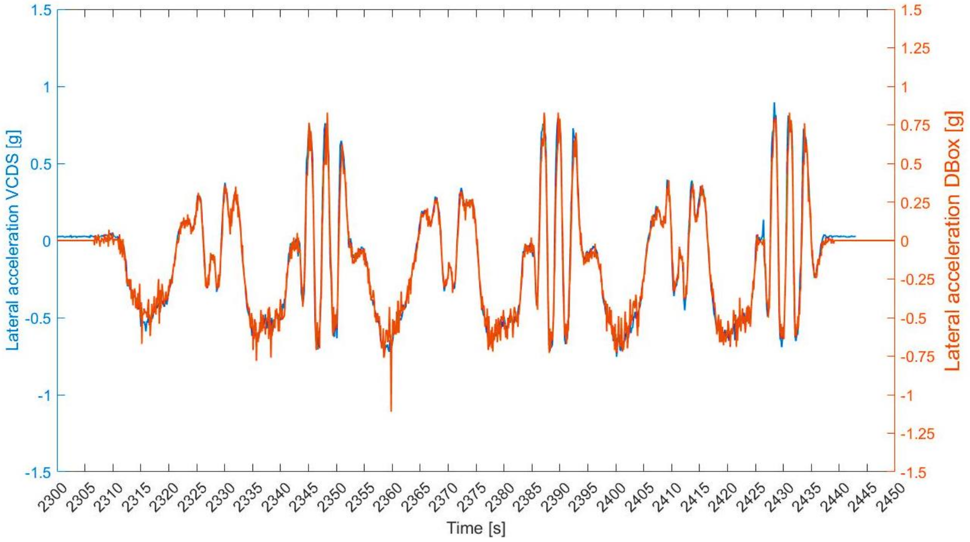

Figure B 2 - Synchronisation of data (lateral acceleration)

An example of the measured, plotted data is shown on the following pages.

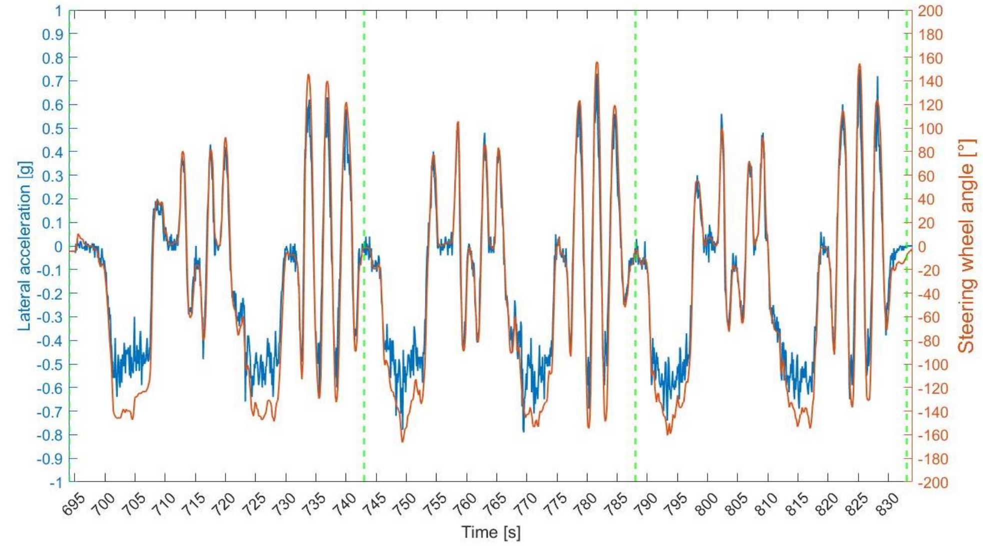

Figure B 3 - Steering wheel angle vs lateral acceleration - Driver 1, comfort setting, run 1

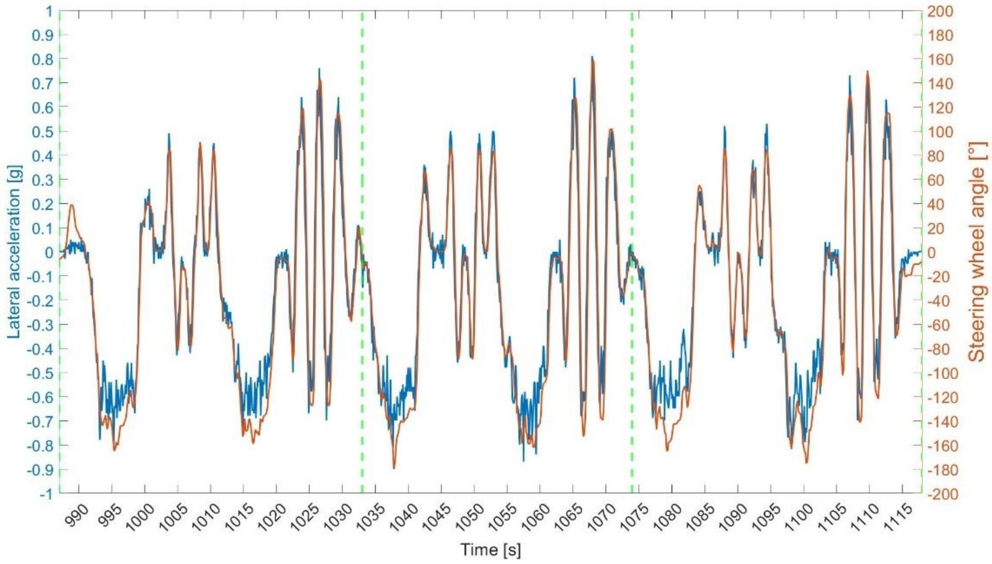

Figure B 4 - Steering wheel angle vs lateral acceleration - Driver 1, comfort setting, run 2

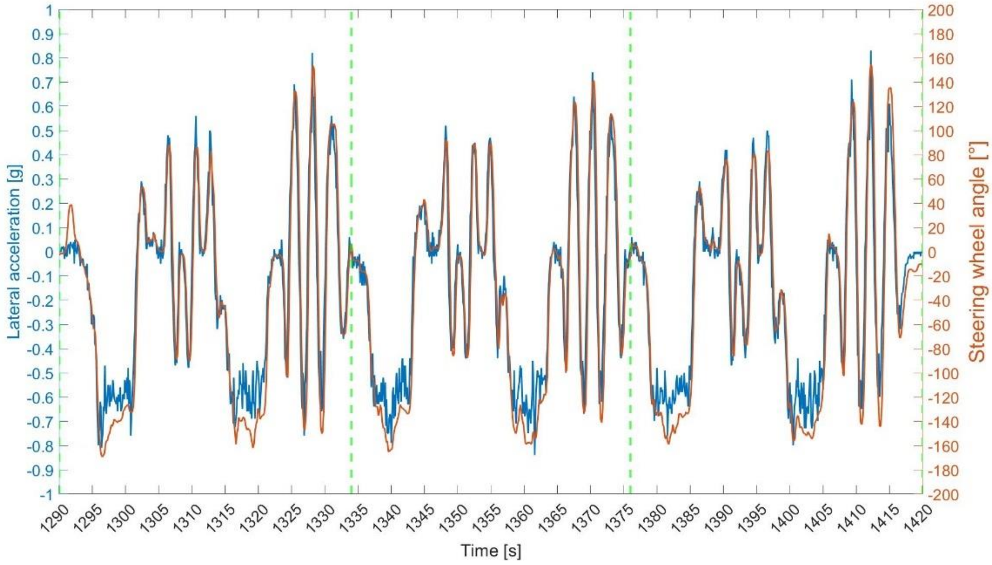

Figure B 5 - Steering wheel angle vs lateral acceleration - Driver 1, sport setting

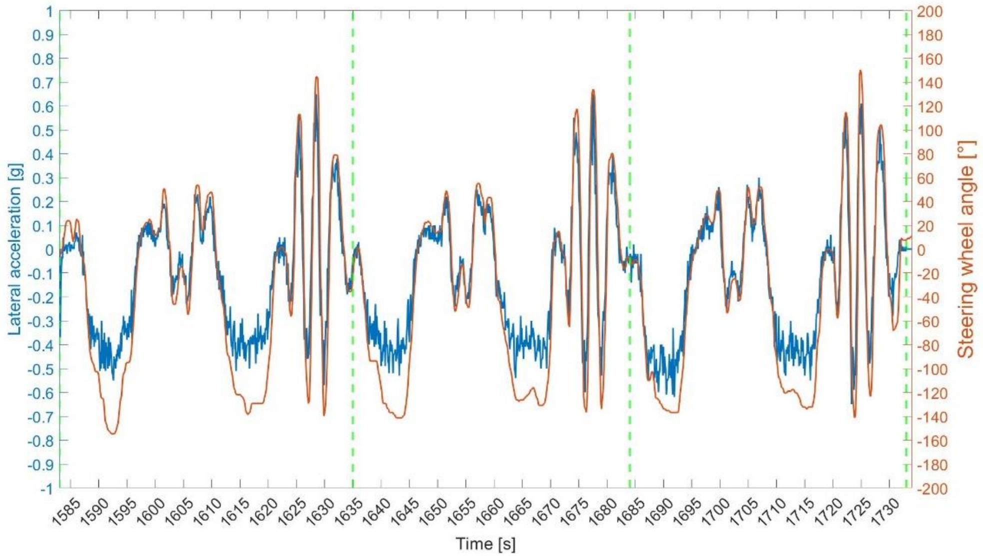

Figure B 6 - Steering wheel angle vs lateral acceleration - Driver 2, comfort setting

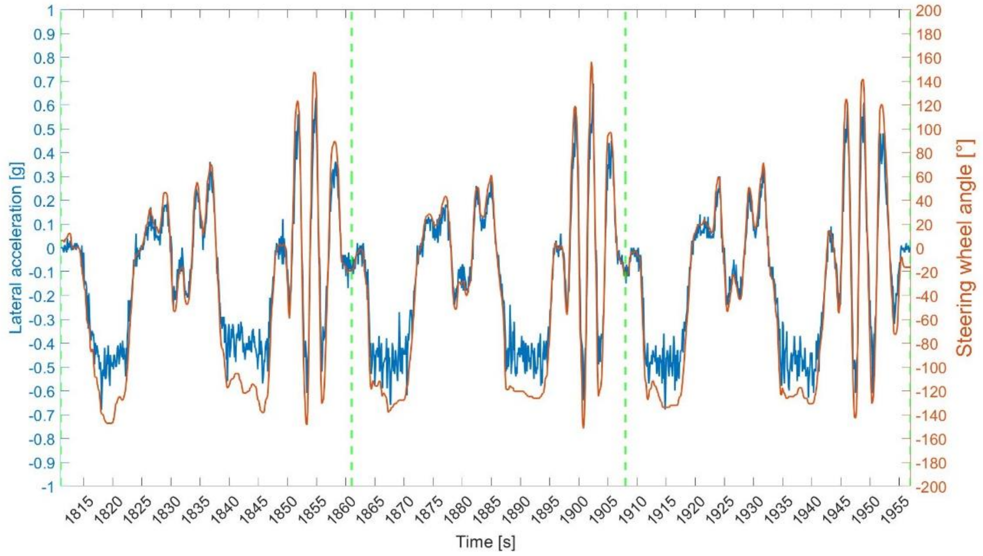

Figure B 7 - Steering wheel angle vs lateral acceleration - Driver 2, sport setting

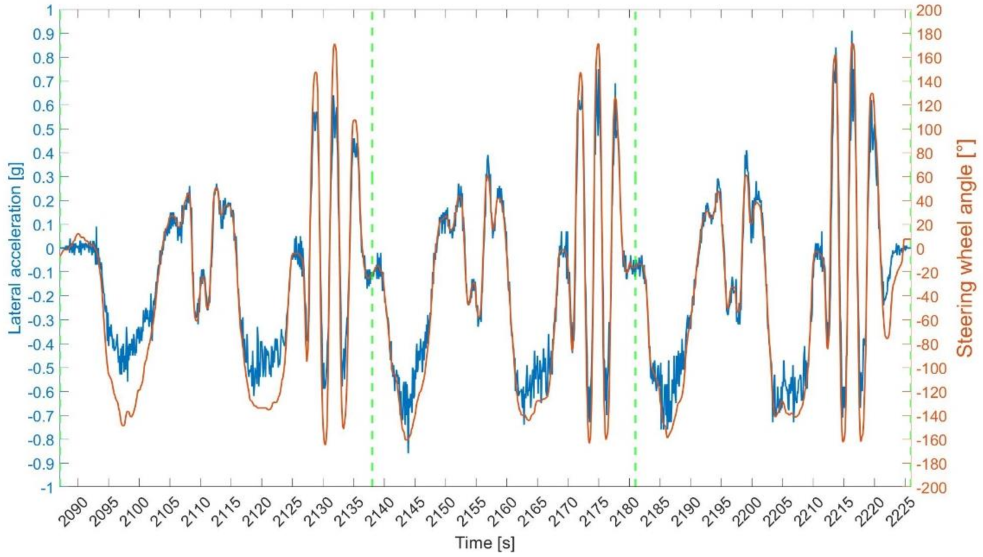

Figure B 8 - Steering wheel angle vs lateral acceleration - Driver 3, comfort setting

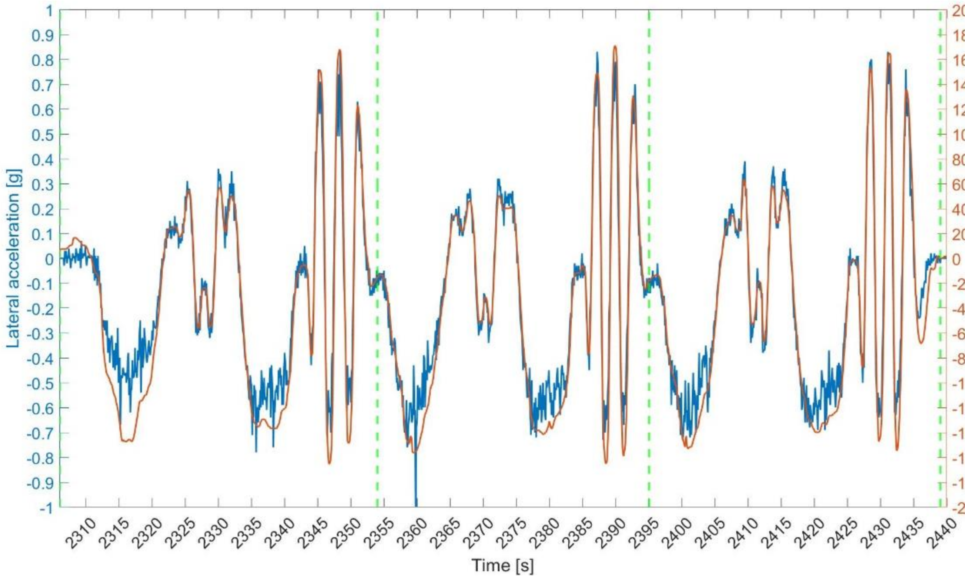

Figure B 9 - Steering wheel angle vs lateral acceleration - Driver 3, sport setting

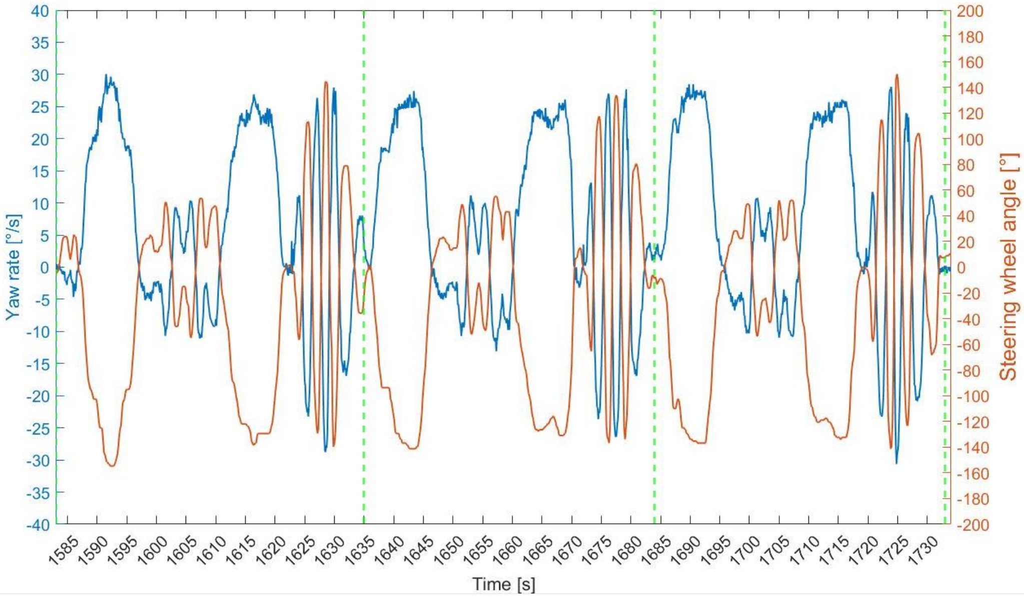

Figure B 10 - Steering wheel angle vs yaw rate - Driver 2, comfort setting

APPENDIX C VEHICLE DYNAMICS DATA ACQUISITION TEST PLAN

This test plan is a part of the thesis Design Assistance System applied to vehicles suspension design, as a part of the major project at HAN University of Applied Sciences for CVUM research institute.
The goal of this test is to obtain test data that could be used in DASY vehicle dynamics database, as well as a way to verify the custom test layout that is being used.

Available Location for Test

As the test locations are currently limited, the safest choice in terms of scheduling and availability is the Aerodrome Panenský Týnec (LKPC), more precisely the farther taxiway and airport apron (tarmac area used as aircraft parking) next to LKPC-27 touchdown area as depicted below (Figure C1). The available space for the test is also depicted on screen grabs from Google Earth (Figure C2).

Figure C 1 - LKPC Panenský Týnec

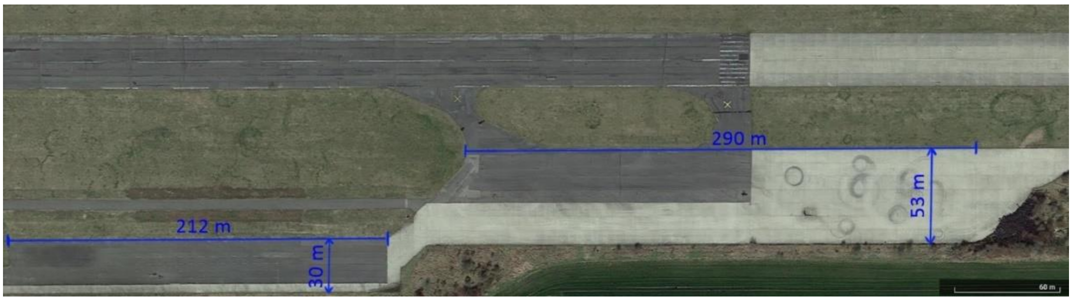

Figure C 2 - LKPC-27 taxiway and apron tarmac area

Necessary Equipment

Cones, washable spray – track layout marking
Measuring tape, laser straight line indicator
Data logger (Racelogic PerformanceBox)
OBD2 data logging device
Anemometer (wind velocity measuring device)
Weather station (wind, temperature, humidity)
Thermometer- Temperature on the surface, temperature of tyres
Tyre pressure gauge
Air pump (compressor)

Measured Values

The necessary input and output measured values should be the vehicle velocity, lateral acceleration, longitudinal acceleration, heading, yaw rate, body slip angle, GPS position data (latitude, longitude), time, steering wheel angle, wheel speeds and throttle position.

Test layout

The real test layout will be dependent on the real-life conditions of the surface of the apron and taxiways available at the aerodrome, as well as any limitations given during the testing date.

The available test area doesn't allow enough space for a conventional steady state circle (ISO4138-2012) method 1 as described in the chapters 4.1 and 8.4 – the constant radius circle (recommended min 30m radius of circle). For the custom test layout, a smaller radius of turns will thus be tested, where at least 3s of steady state conditions is sought to be achieved. These turns will be connecting the track to include an evasion manoeuvre (similar to the one described in ISO3888-1 and ISO3888-2), and a slalom course on the opposite straight section. This test course is shown in Figure C3.

Other tests (like the open loop test of a step steer input) are to be considered, but due to time constrains are not likely to be performed during this test date.

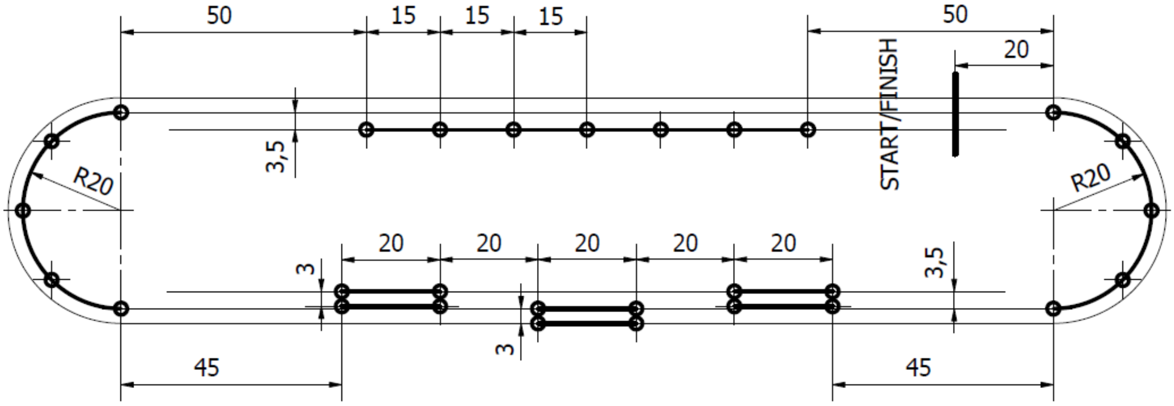

Figure C 3 - Test layout

Vehicle preparation

The tested vehicle(s) are to be inspected at CVUM laboratory's workshop for any suspension issues, damage and overall condition of the suspension parts. The vehicle's suspension geometry is to be measured and noted, and if necessary, adjusted to manufacturer's specifications.

During the test procedure, if possible, the ISO15037-1:2019 – Vehicle dynamics -General conditions for passenger cars is to be used as reference for the vehicle's general conditions.

The vehicle is to be equipped with the data logging devices (PerformanceBox and OBD2 interface).

Test procedure

After the vehicle is prepared, the general conditions on the test grounds are to be measured and noted (the air and tarmac temperatures, air humidity, wind direction and speed).

Meanwhile, the first test driver will warm up the vehicle to operational temperature, the temperature and tyre pressure are to be measured before the test run.

During the first test run, the test driver is to complete the course as stated in the layout chapter at a low to moderate speed. The test driver shall repeat the test course several times, each time increasing velocity. After each run, the data is to be saved with the driver and vehicle marked, the tyre temperature and pressure checked and marked. The test driver repeats this process to either his/hers limit, the vehicle limit to follow the given layout, or a up to a velocity of 70km/h.

Multiple test drivers are to run the test course. Once finished, the vehicle wheel alignment parameters are to be changed and noted and the test shall be repeated with a different vehicle setup. If possible, a second vehicle is to be prepared and test run the same way with this vehicle. After all the combinations of available vehicle and driver combination are exhausted, the test is successfully completed.

APPENDIX D VEHICLE DYNAMICS DATA ACQUISITION TEST PLAN

This test plan is a part of the thesis Design Assistance System applied to vehicles suspension design, as a part of the major project at HAN University of Applied Sciences for CVUM research institute.

The goal of this test is to obtain test data that could be used in DASY vehicle dynamics database, as well as a way to verify the custom test layout that is being used.

Available Location for Test

As the test locations are currently limited, the safest choice in terms of scheduling and availability is the Aerodrome Panenský Týnec (LKPC), more precisely the farther taxiway and airport apron (tarmac area used as aircraft parking) next to LKPC-27 touchdown area as depicted below (Figure D1). The available space for the test is also depicted on screen grabs from Google Earth (Figure D2).

Figure D 4 - LKPC Panenský Týnec

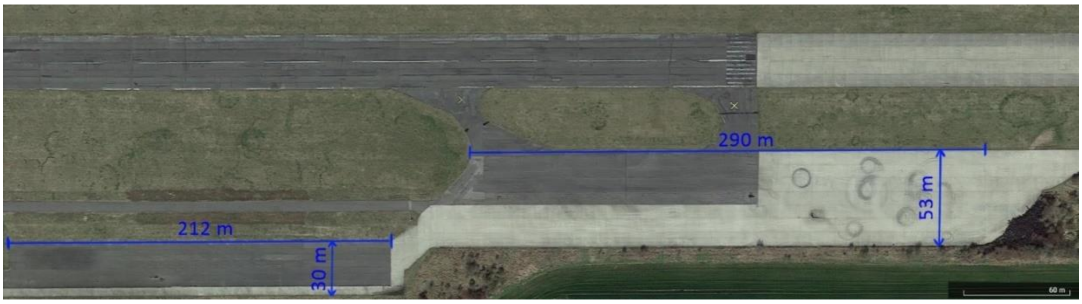

Figure D 5 - LKPC-27 taxiway and apron tarmac area

Necessary Equipment

Cones, washable spray – track layout marking
Measuring tape, laser straight line indicator
Data logger (Racelogic PerformanceBox)
OBD2 data logging device
Anemometer (wind velocity measuring device)
Weather station (wind, temperature, humidity)
Thermometer- Temperature on the surface, temperature of tyres
Tyre pressure gauge
Air pump (compressor)

Measured Values

The necessary input and output measured values should be the vehicle velocity, lateral acceleration, longitudinal acceleration, heading, yaw rate, body slip angle, GPS position data (latitude, longitude), time, steering wheel angle, wheel speeds and throttle position.

Test layout

The real test layout will be dependent on the real-life conditions of the surface of the apron and taxiways available at the aerodrome, as well as any limitations given during the testing date.

The available test area does not allow enough space for a conventional steady state circle (ISO4138-2012) method 1 as described in the chapters 4.1 and 8.4 – the constant radius circle (recommended min 30m radius of circle). For the custom test layout, a smaller radius of turns will thus be tested, where at least 3s of steady state conditions is sought to be achieved. These turns will be connecting the track to include an evasion manoeuvre (similar to the one described in ISO3888-1 and ISO3888-2), and a slalom course on the opposite straight section. This test course is shown in Figure D3.

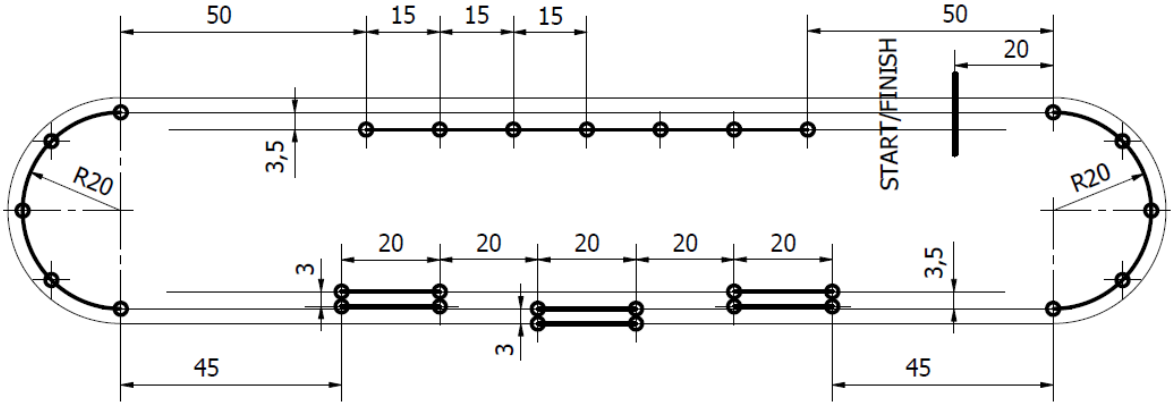

Figure D 6 - Test layout

Vehicle preparation

The tested vehicles (VW Scirocco, Skoda Octavia) are to be inspected at CVUM laboratory's workshop for any suspension issues, damage and overall condition of the suspension parts.

During the test procedure, if possible, the ISO15037-1:2019 – Vehicle dynamics -General conditions for passenger cars is to be used as reference for the vehicle's general conditions.

The vehicle is to be equipped with the data logging devices (PerformanceBox and OBD2 interface).

Test procedure

After the test track and the vehicle are prepared, each driver is given a practise session at the track to familiarise themselves with the layout. Before the measurement runs, the general conditions on the test grounds are to be measured and noted (the air and tarmac temperatures, air humidity, wind direction and speed).

With vehicle at operational temperature, the temperature and tyre pressure are to be measured.

During the test run, the test driver is to complete three laps of the course as stated in the layout chapter at a moderate, consistent speed at which he/she is confident with. The test driver shall repeat the test course with a different DCC settings. After each run, the data is to be saved with the driver and vehicle marked, the tyre temperature and pressure checked and marked. After all test drivers finish their measuring runs, a second vehicle is to be prepared and the test repeated with this vehicle, completing two runs for each driver with the same vehicle setup.