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Holistic Testing Strategies for Electrified Vehicle Powertrains in Product Development Process

Filiz Akkaya [1,*], Wolfgang Klos [1], Timm Schwämmle [1], Gregor Haffke [1] and Hans-Christian Reuss [2]

1 Porsche AG, Porschestraße 911, 71287 Weissach, Germany; wolfgang.klos@porsche.de (W.K.); timm.schwaemmle@porsche.de (T.S.); gregor.haffke@porsche.de (G.H.)

2 Research Institute of Automotive Engineering and Vehicle Engines Stuttgart (FKFS), Pfaffenwaldring 12, 70569 Stuttgart, Germany; hans-christian.reuss@fkfs.de

* Correspondence: filiz.akkaya@porsche.de; Tel.: +711-911-81179

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Abstract: In the field of powertrain engineering, longstanding knowledge was gained for testing conventional vehicle powertrains. The hitherto used test strategies here were more focused on the subsystems of the powertrain than on the powertrain as an integrated system. Through the electrification of the powertrain, the topology and the range of functions have changed. This leads to new challenges for the validation and requires not only adjustments of the test strategies for electric vehicle powertrains but establish and develop integrative tests for the powertrain as an integrated system in order to meet the increased complexity. This paper presents a method to develop a holistic test strategy for a hybrid and electrical vehicle powertrain. In order to avoid misunderstandings of the used terms, it is necessary to create a standard understanding of them. Therefore, a nomenclature is defined and described. Furthermore, a definition of a holistic test strategy is provided. The focus of this present study is on the powertrain and not on its single subsystems. Subsequently, the four steps of the method are introduced and the current results are presented. Finally, a new developed test element within the holistic test strategy is introduced. The findings of this study support the integrative testing for powertrains.

Keywords: powertrain; testing processes; standardization; strategy

1. Introduction

The validation branch of the v-model is of great importance as it significantly influences the time, cost and quality during the product development process. In the field of powertrain engineering, longstanding empirical knowledge has been gained for testing conventional vehicle powertrains. Through the electrification of the powertrain, the topology, the range of functions and even the usage behavior have changed. Furthermore, the complexity of the powertrain system has increased, which must still be validated and tested regarding its functionality and durability. This has created new challenges for the validation, with adjustments required in the test strategies for the vehicle powertrains that have been used so far [1].

2. Nomenclature

A standard understanding of the frequently used terms in the field of powertrain engineering forms the basis for developing and describing a holistic testing strategy. As this field encompasses a big area of studies, it has resulted in the same terms having different meanings, which depends on the viewing angle of the professional focus as described by previous studies [2–4]. There is a gap in the research literature here [5]. Therefore, the nomenclature is defined and described. Some of the full nomenclature is illustrated in Figure 1 and listed below.

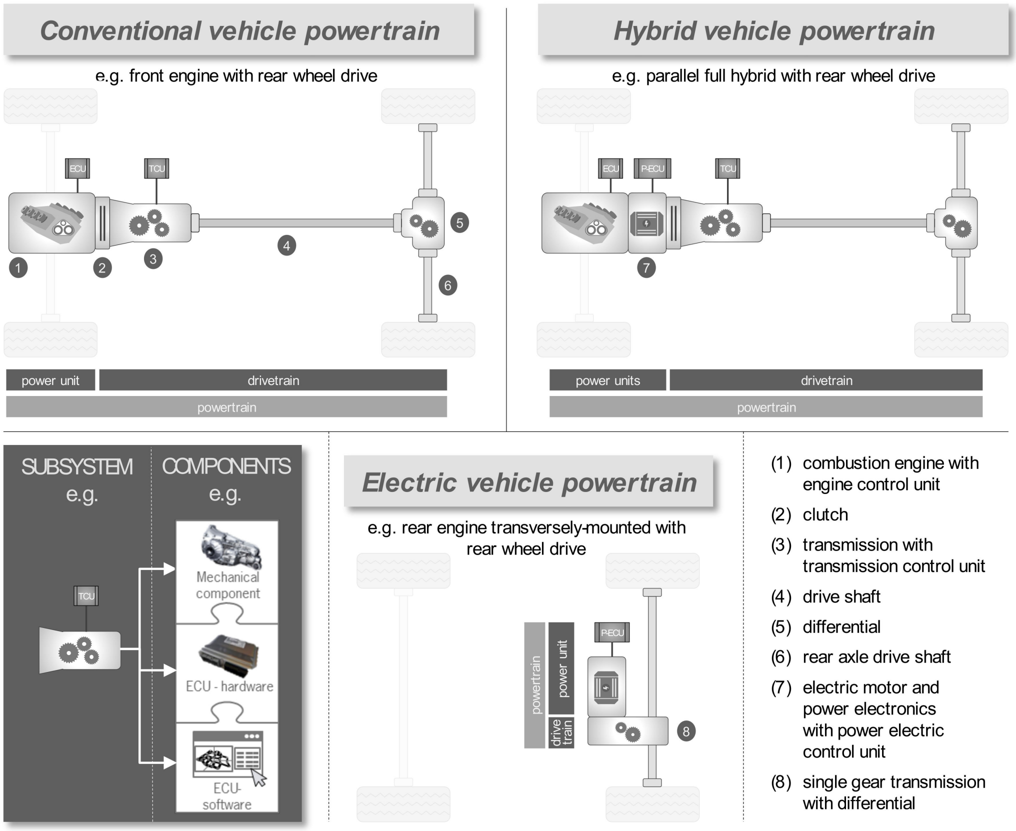

Figure 1. Illustration of the nomenclature.

- **powertrain**: combination of subsystems, which deliver the drive from the power unit up to the wheel flange. The following applies: powertrain = power unit(s) + drivetrain; Therefore, the powertrain and drivetrain are not synonyms.
- **power unit(s):** subsystem(s) of the vehicle powertrain, which generate and provide torque and rotational speed. For example, this can be a combustion engine, including its engine control unit (ECU hardware and software), or an electric motor, including its power electric control unit (P-ECU hardware and software).
- **drivetrain:** combination of subsystems, which transmit and/or convert torque and rotational speed up to the wheel flange.
- **subsystem**: is a functioning intrinsic system, which consists of single components.
- **component**: is a mechanical or mechatronic element. They contribute to the complete functionality of the subsystem. The components of a hybrid vehicle powertrain include the P-ECU (hardware), P-ECU (software) and the power electronics (as the mechatronic component).
- **system levels:** For describing the test system level of a test object in a holistic test strategy, four different system levels are established and combined with the v-model:
    - 1. level: vehicle level
    - 2. level: powertrain level
    - 3. level: subsystem level
    - 4. level: component level

3. Method to Develop a Holistic Test Strategy

A holistic test strategy for vehicle powertrains is a guideline that is used to validate the vehicle powertrain regarding its functionality and durability throughout the product development process. It is displayed in the form of a testing road map. Thus, a test strategy is a holistic one when it is focusing the powertrain instead of each subsystem. This is a top-down instead of a bottom-up approach. Furthermore, all five core questions, which are shown in Figure 2, need to be answered coherently. The research literature provides a selection of test strategies for the subsystems [5]. A few studies [6,7] have provided an approach to describe a holistic test strategy for the powertrain, but do not meet the aforementioned criteria.

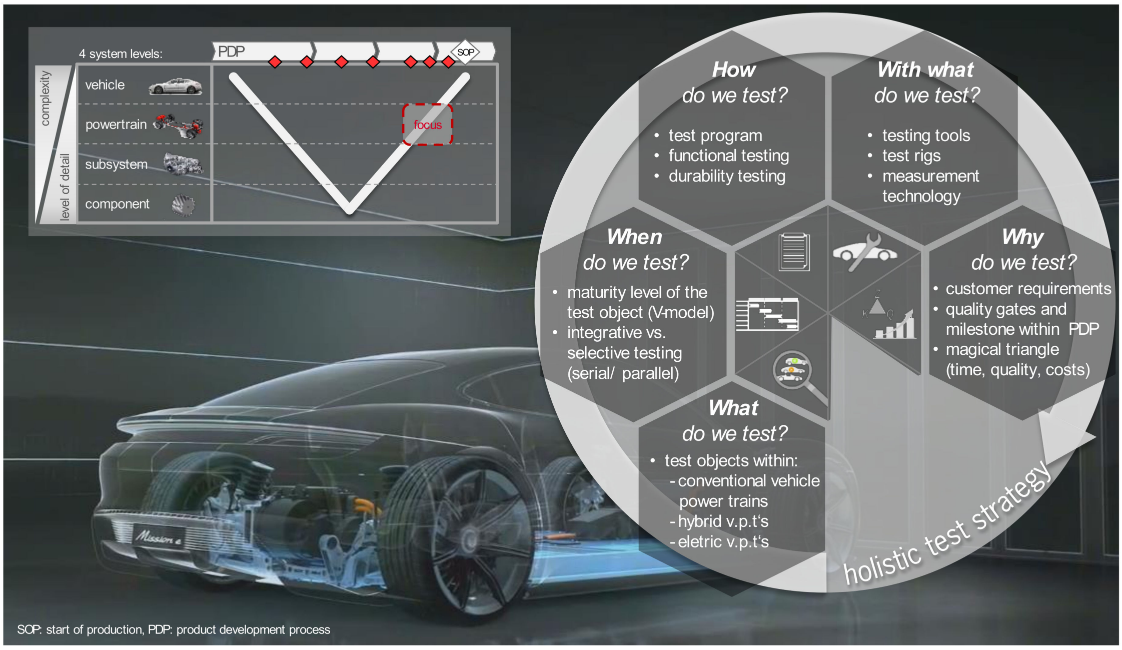

Figure 2. Holistic test strategy.

By applying the following method, including four steps, a holistic test strategy can be developed:

- **Step 1:** Analyze the test strategy of a conventional vehicle powertrain by answering the five core questions (Figure 2).
- **Step 2:** Perform a requirement determination by function analysis for either a hybrid or electrical vehicle powertrain topology.
- **Step 3:** Overlay the test strategies to identify emerged vacancies and dependencies.
- **Step 4:** Complete the test strategy by filling up the vacancies with testing methods and display it in form of a testing road map.

The previous results for Step 1 show a current volume of over 2000 tests.

The strategies that are currently being worked on by using the four aforementioned steps are also being used within the framework of knowledge management. The holistic test strategy displayed in the form of the testing road map can be used by developers as a procedural model/manual in the product development process. By successively integrating the experiences of the developers, it protects the test knowledge and also recirculates it into the development. This is particularly important because there are different knowledge levels in the development for electrified powertrains compared to conventional powertrains [8]. In the field of electrified vehicle powertrains, a diverse range of competencies exist in the individual disciplines on the subsystem and component level. It is important to build up and network the connected knowledge on the powertrain level.

3.1. Five Core Questions

In this broad thematic area, the scope must be clear in order to develop the holistic strategy. This is defined as an entrance requirement. In order to derive the application of the core questions, these are explained below:

- **What** do we test?
  Within this core question, it is necessary to clarify the extent of consideration of the powertrain with regard to its subsystems and where required, to its components. In the current analysis, the powertrain topologies from Figure 1 are considered. The HV battery, the charging technology and stations are similar to the tires and brake units, which are not covered by the extent of consideration.
- **When** do we test?
  This core question analyzes the maturity levels of the test objects at different times in the product development process. It is important to identify interdependent tests as a qualitative indication so they can be categorized regarding an integrative or selective testing strategy. Therefore, it is linked to the core question "How do we test?".
- **How** do we test?
  Within this core question, the test programs need to be gathered and categorized regarding their testing focus. For example, this includes durability testing, functional testing, misuse testing or testing acoustics or thermodynamics.
- **With what** do we test?
  A large toolbox of testing tools is available for realizing and implementing the test requirements. These include simulation models, test rigs and measurement technologies. As test resources have to follow the trend to be more flexible and not just cover one test application [9], the description of several configurations is quite permissible. For this core question, both analysis and categorization of the toolbox is to be carried out to connect the contents to the other core questions. An example categorization of the test rigs is shown in Figure 3.
- **Why** do we test?
  This core question examines the customer requirements, quality gates and milestones within the product development process referring to the magical triangle of time, quality and cost factors. This question is superordinate.

The answers to the core questions combined with continuous consideration during the product development process result in a holistic test strategy for a vehicle powertrain topology. For this purpose, the v-model is used as a procedural model, which is explained in the following Section 3.2.

3.2. System Levels in the v-Model

The v-model has proved to be a procedural model for the approach in addition to others, such as the VDI 2221 guideline or the Munich product concretization model (MKM), to the development of complex mechatronic systems in the vehicle development process [10,11]. Therefore, it is used as a basis for a holistic view of the validation and testing. However, it is extended by the system levels and the core questions, which have been explained above. The fifth core question "Why do we test" in this connection is superordinate. Figure 4 shows that the holistic test strategy is therefore multi-dimensional, making it a very complex matter in the v-model.

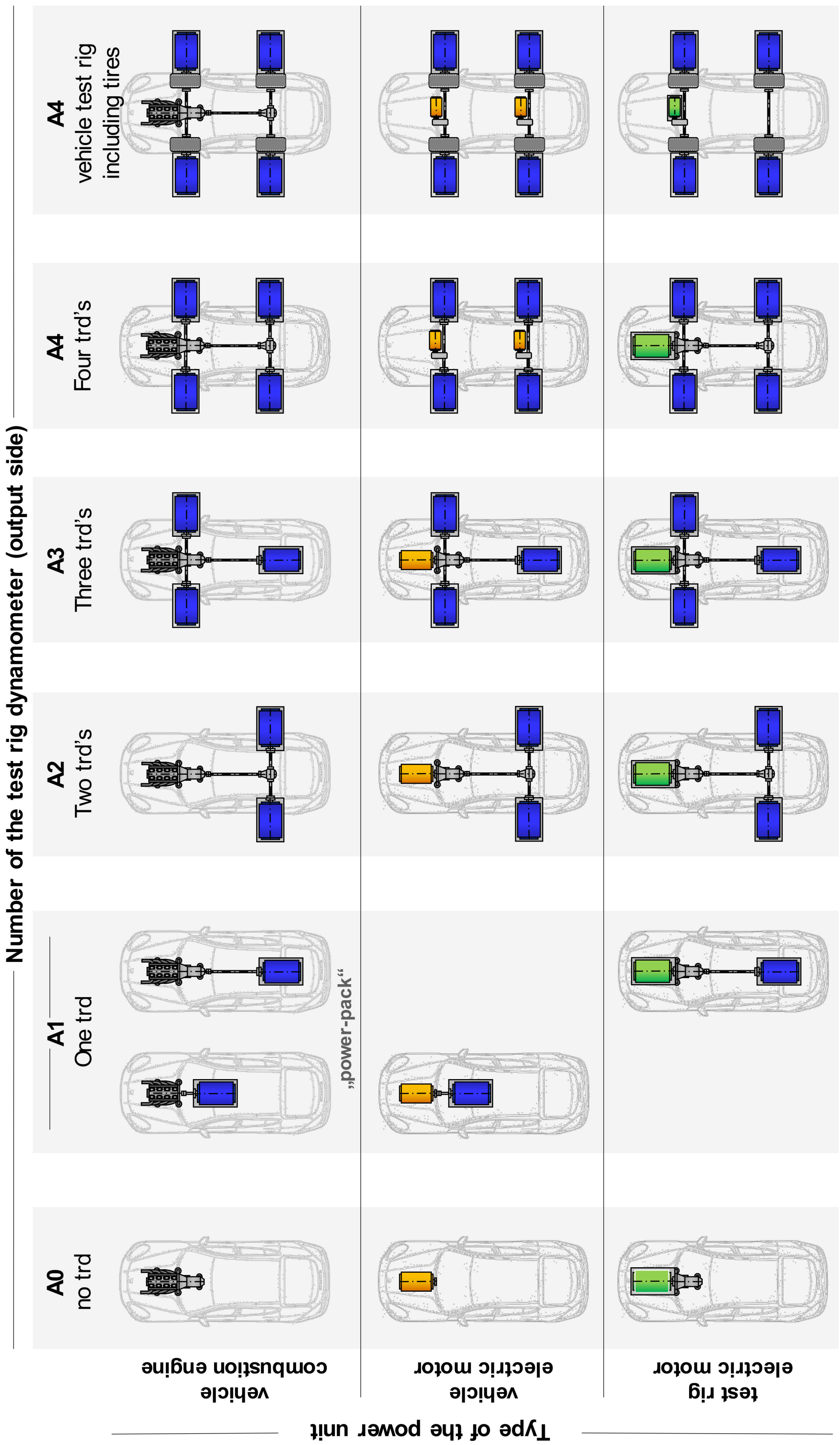

Figure 3. Exemplary categorization of test rigs "With what to test?".

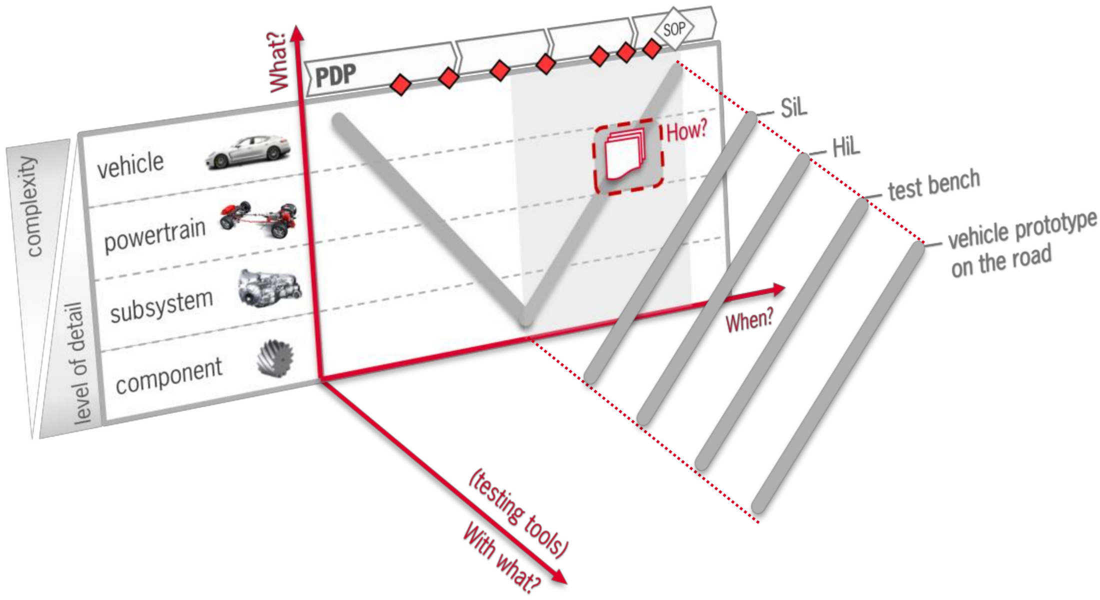

Figure 4. Multidimensional v-model.

3.3. Maturity Level of the Powertrain

Quality management methods are used to identify and assess the maturity level of the powertrain. In terms of the holistic test strategy, the milestones are defined on the powertrain level as the so-called "powertrain milestones". They also serve for maturity monitoring. The defined milestone-conversations criteria are assessed with experts regarding their degree of fulfillment. Thus, a constant degree of maturity monitoring and the maturity level of the powertrain with regard to its development is ensured. The newly developed test element, which is namely PST (Powertrain System Test), within the holistic test strategy is also a milestone criterion.

4. Concept of the Powertrain System Test (PST)

The PST is a new developed test element within the holistic test strategy for hybrid vehicle powertrains. Its aim is to test the interaction of all subsystems in the powertrain of one vehicle-charge before entering the vehicle-level to increase the overall quality and maturity of the powertrain, which is shown in Figure 5. The test is performed in the low load range either on a powertrain test rig or on a parts-carrier vehicle. Regarding the product development process, it will be implemented at any moment, with reservation of the substantial hardware and software updates (vehicle-charge). Both mechanical components, ecu-hardware and ecu-software of all subsystems of the powertrain are deployed (Figure 6). Therefore, the powertrain system test supports the integrative testing of powertrains.

The focus of the PST is to validate the functionality of the powertrain as a whole system of subsystems. Therefore, the developed test catalog is not a continuous program but a sum of different function, interface and network tests. Testing the mechanical durability is not the focus of this test element.

An important point regarding the implementation of the PST is that the latest hardware and software is obtainable. For example, this means that the vehicle charge 1 is fully available on a powertrain test rig or on a parts-carrier vehicle. It is tested there before the vehicle of charge 1 is even accessible for testing. This makes frontloading possible. In this case, the vehicles of charge 1 receives a powertrain with a higher total maturity level compared to a powertrain received after testing in the vehicle level directly at the subsystem level. This results in an expectation for good project and part management in order to fulfill this important framework condition.

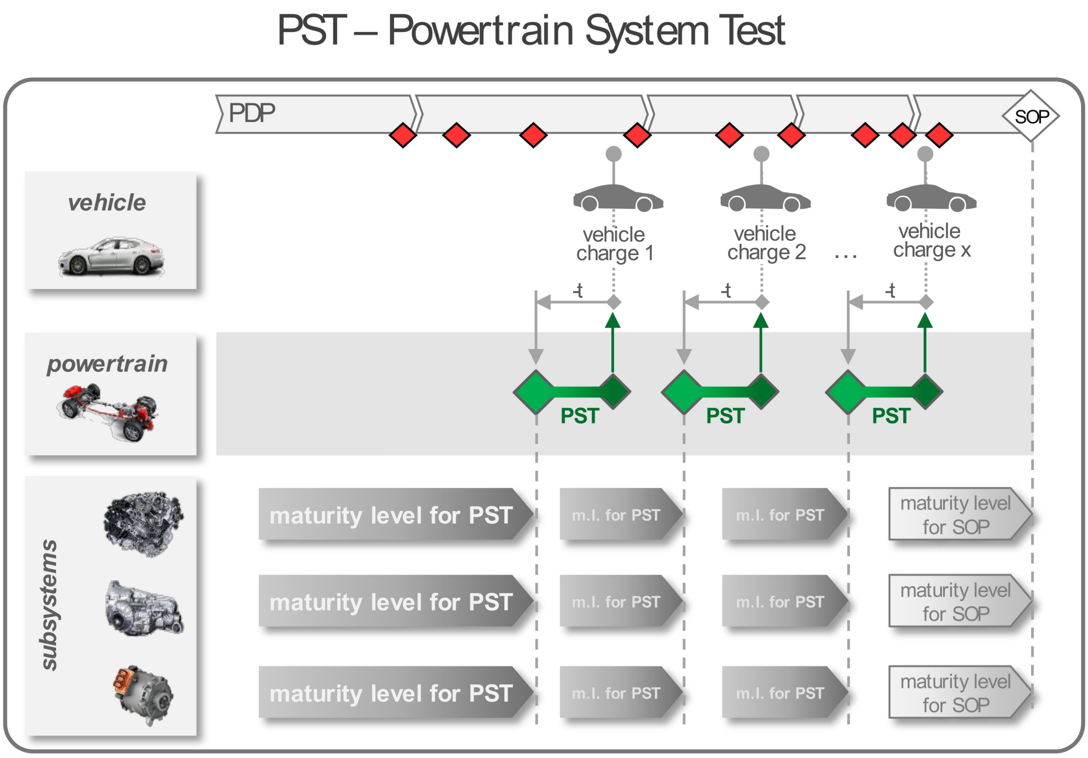

Figure 5. Concept of the powertrain system test (PST).

Figure 6 shows the classification of the PST as a test element in the ascending branch of the v-model. The use of the test tools is not necessarily chronological but partly parallel or overlapping. The PST will be used systematically for all vehicle powertrain topologies to expand the integrative testing at the Porsche AG and is currently in the roll-out phase for the topologies shown in Figure 1:

- **conventional vehicle powertrain:** rear wheel drive (two wheel drive) with a front engine, clutch, automatic transmission, drive shaft, differential and rear axle drive shafts
- **hybrid vehicle powertrain:** rear wheel drive (two wheel drive) with a front engine, clutch, automatic transmission, drive shaft, differential and rear axle drive shafts and an electric motor with power electronics
- **electric vehicle powertrain:** rear wheel drive (two wheel drive) with a rear engine transversely-mounted with an electric motor (including power electronics) and a single gear transmission with a differential

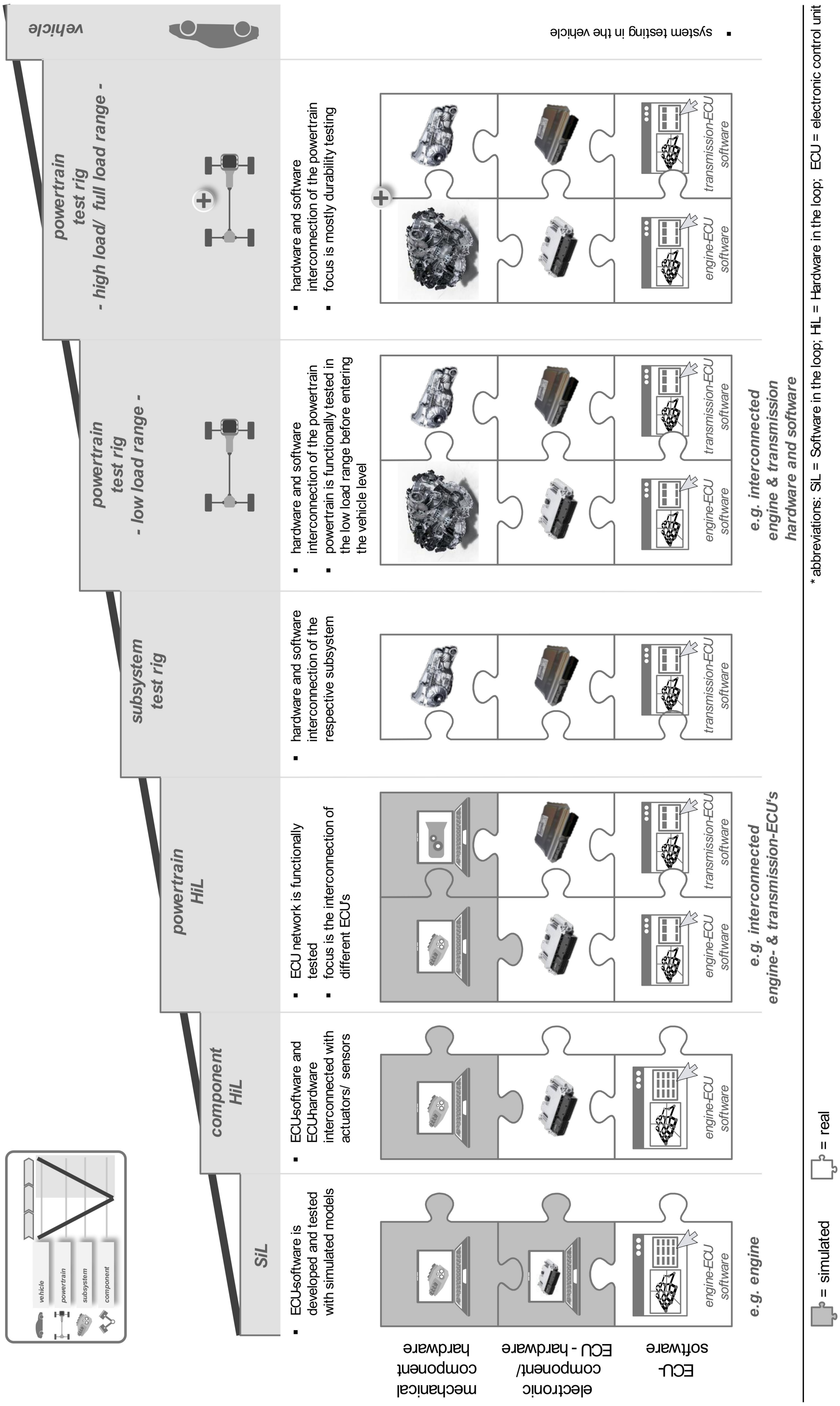

Figure 6. Classification of the PST in the ascending branch of the v-model.

5. Conclusions and Outlook

In summary, an insight into the nomenclature was provided in the area of the vehicle powertrain development in order to avoid different understandings of the used terms in this field. Based on this, the need for a holistic test strategy for the further advancement of electrified vehicle powertrains was presented. The holistic test strategies are currently in active development and serve as a guideline for developers. As components of this holistic strategy, the powertrain system test, the importance and added value for the expansion and the better integration of the powertrain within the product development process are highlighted as important issues.

The scope of the holistic test strategies includes the open potential of not only presenting a guideline and approach but also an active project control tool for the development of vehicle powertrains. For this purpose, it is necessary to develop a valuation method for the potential risk in the case of non-fulfillment of the strategy content. This could be based on risk priority numbers (RPN), which are from the quality method "failure mode and effects analysis" (FMEA).

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References

1. Burgard, K.; Krohn, C.; Geisler, J. Prüfkonzepte für elektrifizierte Antriebe: Mess- und Prüftechnik Antriebsstrang. *ATZextra* **2014**, *19*, 20–25.
2. Schenk, M.; Klos, W.; Schwämmle, T.; Müller, M.; Bertsche, B. Antriebsstrangerprobung bei der Daimler AG: Moderne Erprobungsmethodik. In Proceedings of the Internationales Symposium für Entwicklungsmethodik, Wiesbaden, Germany, 8–9 November 2011; AVL Deutschland GmbH: Stuttgart, Germany, 2011.
3. Schyr, C. Modellbasierte Methoden für die Validierungsphase im Produktentwicklungsprozess Mechatronischer Systeme am Beispiel der Antriebsstrangentwicklung. Ph.D. Dissertation, Institut für Produktentwicklung (IPEK), Universität Karlsruhe, Karlsruhe, Germany, 2006.
4. Düser, T. *X-In-The-Loop-ein Durchgängiges Validierungsframework für die Fahrzeugentwicklung am Beispiel von Antriebsstrangfunktionen und Fahrerassistenzsystemen*; Institut für Produktentwicklung (IPEK), Universität Karlsruhe: Karlsruhe, Germany, 2010.
5. Bock, M. Literaturrecherche und Bewertung von Erprobungsstrategien für Hybride und rein Elektrische Fahrzeugantriebe auf Prüfständen. Master's Thesis, Institut für Verbrennungsmotoren und Kraftfahrwesen (IVK), Universität Stuttgart, Stuttgart, Germany, 9 December 2016.
6. Ott, M.W.; Bartzsch, M.; Holtkötter, C. Optimierte Entwicklung von alternativen Antriebssystemen. *ATZextra* **2013**, *18*, 48–53.
7. List, H. Zukünftige Antriebsentwicklung: Bewältigung kurzer Entwicklungszeiten und hoher Komplexitäten. In *35th Internationales Wiener Motorensymposium*; Lenz, H.P., Ed.; Fortschritt-Berichte VDI Reihe 12, Verkehrstechnik/Fahrzeugtechnik; VDI: Düsseldor, Germany, 2014.
8. Lindemann, M.; Wolter, T.-M.; Freimann, R.; Fengler, S. Konfiguration von Hybridantriebssträngen mittels Simulation. *ATZ Automob. Z.* **2009**, *111*, 332–338.
9. Guggenmos, J.; Rückert, J.; Thalmair, S.; Stopper, D. Das Prüffeld der Antriebsentwicklung im Wandel. In *VPC–Simulation und Test 2015*; Springer: Wiesbaden, Germany, 2016; pp. 12–17.

10. VDI Wissensforum GmbH (Ed.) *6th Fachtagung AUTOREG 2013: Steuerung und Regelung von Fahrzeugen und Motoren mit Fachausstellung*; VDI Wissensforum GmbH: Düsseldor, Germany, 2013.
11. Lindemann, U. *Methodische Entwicklung Technischer Produkte: Methoden Flexibel und Situationsgerecht Anwenden*; Springer: Berlin, Germany, 2009.