V2X AUTOMOTIVE ON-BOARD UNIT COST ANALYSIS

Contents

1 Introduction

The ability for OEMs and other automotive industry players to develop, manufacture and deploy components, products, services and foremost vehicles within attractive cost ranges is still one of the highest priorities of conducting business. New technologies and features within emerging areas as telematics and autonomous driving have high research and development costs for vehicle manufacturers. It is therefore crucial for an OEM to investigate all technical options to implement new products and functions in an economically attractive way if functionality or performance either required by internal requirements or mandate-driven minimum standards can be achieved.

Within the automotive telematics domain, the Vehicle-2-Everything (V2x) communication topic is one of the most investigated areas as a wide spread introduction of this technology can potentially reduce the amount of traffic accidents, fatalities and injuries significantly. V2x consequently receives attention not only from the automotive industry but also from legislators worldwide. In the USA, the National Highway Traffic Safety Administration (NHTSA) actively developed legal framework and technology proposals aiming in the long-term for the widespread availability of V2x products within future vehicles.

As for many products, features or legislative requirements a range of technology options exist that industry players can select from to meet those requirements. In the case of V2x two base technologies are able to provide the fundamental communication to enable certain use cases aiming at accident avoidance and efficient transportation of future mobility services:

- DSRC (Dedicated Short Range Communications)
- C-V2x (Cellular Vehicle-To-Everything)

Major players within automotive and telecommunication industries are developing products around these technologies to be integrated into vehicles to eventually provide periodic broadcasting and reception of various standardized messages related to traffic safety and management. Even though they enable the same use cases (realized through software stacks) the communication base components of both systems are dissimilar as they rely on different base technologies (802.11p versus cellular LTE).

This difference also has an impact on automotive products as each system incorporates unique opportunities and restrictions. Ultimately these differences have an impact on costs for component selection, integration & development efforts. It is therefore advised to execute a transparent cost analysis of potential product scenarios to serve as an objective baseline for future decision making, especially with such high impact on consumers and other markets.

1.1 Scope

An investigation of cost factors attached to various product scenarios of V2x and on-board Telematics Control Units (TCU) to be used within an automotive environment is explored. A detailed comparison of cost factors between DSRC and C-V2x based product configurations that represent viable deployment options executed by either Tier1 supplier or OEM is presented.

1.2 Definitions and Acronyms

AEC-Q100	Automotive Electronics Council Standard for Stress Test Qualification for Integrated Circuits
AP	Application Processor
BCM	Body Control Module
BOM	Bill of Material
BSM	Basic Safety Message
CAN	Controller Area Network
C-V2x	Cellular Vehicle to Everything
DSRC	Dedicated Short-Range Communications
EMI	Electromagnetic interference
GNSS	Global Navigation Satellite System
HMI	Human Machine Interface
HSM	Hardware Security Module
IMU	Inertial Measurement Unit
LTE	Long-Term Evolution
MCU	Micro Controller Unit
MIMO	Multiple-Input and Multiple-Output
OBU	On-Board Unit
OEM	Original Equipment Manufacturer
OTA	Over the Air
PCB	Printed Circuit Board
PHY	Physical Transceiver Chip
PMIC	Power Management Integrated Circuits
R&D	Research & Development
RFFE	Radio Frequency Front-End
RTOS	Real Time Operating System
SG&A	Selling, General and Administrative Expenses
SoC	System on a Chip
T&V	Testing & Validation
TCU	Telematics Control Unit

2 V2X OBU Cost Analysis

This study has been developed with the premise of analyzing technology related product & component costs only. Actual product or component prices have not been investigated and will not be discussed as such topic and related discussions are situated in the relationships between product buyer and its suppliers. All subsequent & derived information of this study should therefore only be considered in the domain of costs (further details of cost factors taken into account see chapter 2.3). Furthermore, this study does not investigate technical performance differences and viability of evaluated scenarios.

2.1 Objectives of V2x Cost Analysis

At the begin of this study the following objectives have been set to provide readers a tangible framework within the complex topic of V2x and its many discussion areas:

- **Scope Definition:** Development of potential V2x product scenarios into viable product configurations for an automotive grade installation that includes the actual HW components, required SW stacks and efforts for the actual product realization process, e.g. R&D, SG&A, etc.)
- **Identification of Cost Realities:** Determination of tangible & realistic cost factors for aforementioned elements to ensure a practical display of overall cost levels
- **Transparent Comparison:** Development of cost model in such way that all scenarios share the same cost structure and elements so that analysis results can be compared directly with each other
- **Identify Incremental Costs for V2x Functionality:** On the cost basis of a Telematics Control Unit (TCU) determine the incremental V2x functionality cost value for each product scenario

A similar cost analysis has been published by the National Highway Traffic Safety Administration in 2016 as part of a Notice of Proposed Rulemaking [1]. Two different DSRC product configurations have been analyzed regarding cost impact based on their bill of material and overhead related costs (research and development, selling and administrative costs, as well as OEM profits, transportation costs, and dealer costs and profits).

This V2x OBU cost analysis study follows the approach of creating viable DSRC/C-V2x based product configurations in order to analyze & display their cost impact in a structured way.

2.2 V2x OBU Product Scenarios Investigated

Although this cost study has been initiated to investigate V2x related cost factors for automotive it was necessary to evaluate the cost structure of a conventional Telematics Control Unit (TCU, e.g. for LTE broadband connectivity between vehicle and OEM backend infrastructure) as well within the same framework to obtain a baseline for joint technology scenarios (e.g. V2x and LTE-broadband function realized within one product). This TCU baseline will be used especially for the determination of the V2x-related monetary impact from today's telematics solution for an OEM and subsequently for the consumer.

The scenarios that have been investigated were defined to represent multiple options on how future V2x functionality can be integrate into a standard vehicle. These options enable different views on physical and logical integration of V2x features with existing on-board TCUs. To maintain a certain level of comparability and to enable differentiation between product scenarios it was decided to separate the scenarios logically as follows:

- **Scenario 1: Distinct Products Within Vehicle.** Two different control units enabling LTE broadband connectivity and V2x communication (either DSRC or C-V2x) with complete logical and physical separation.

- **Scenario 2: One Product/ Two Systems.** Two communication systems situated in the same physical enclosure where the V2x related part (e.g. PCB) is mounted on the main TCU module, both are physically connected, but logically (processing & external communication environment) separated.
- **Scenario 3: Highly Integrated System.** One single control unit using distinct modems for each communication systems (V2x, LTE), though both modems are controlled by the same main application processor and other elements as the Hardware Security Module (HSM). The application processor offers logical separation for both communication stacks and other SW through a hypervisor.
- **Scenario 4 A&B: Fully Integrated System.** Similar to scenario 3 only with the difference that V2x-functionality (here only C-V2x) is integrated into the same semiconductor modem packaging as the LTE modem, logical separation of processing environments also realized through hypervisor. The concept A & B are differentiated by the level of integration of the GNSS function into the main modem package.

Figure 1 and 2 hereby provide a visual representation of all four scenarios outlining the main components used and each topological structure of the corresponding product configuration.

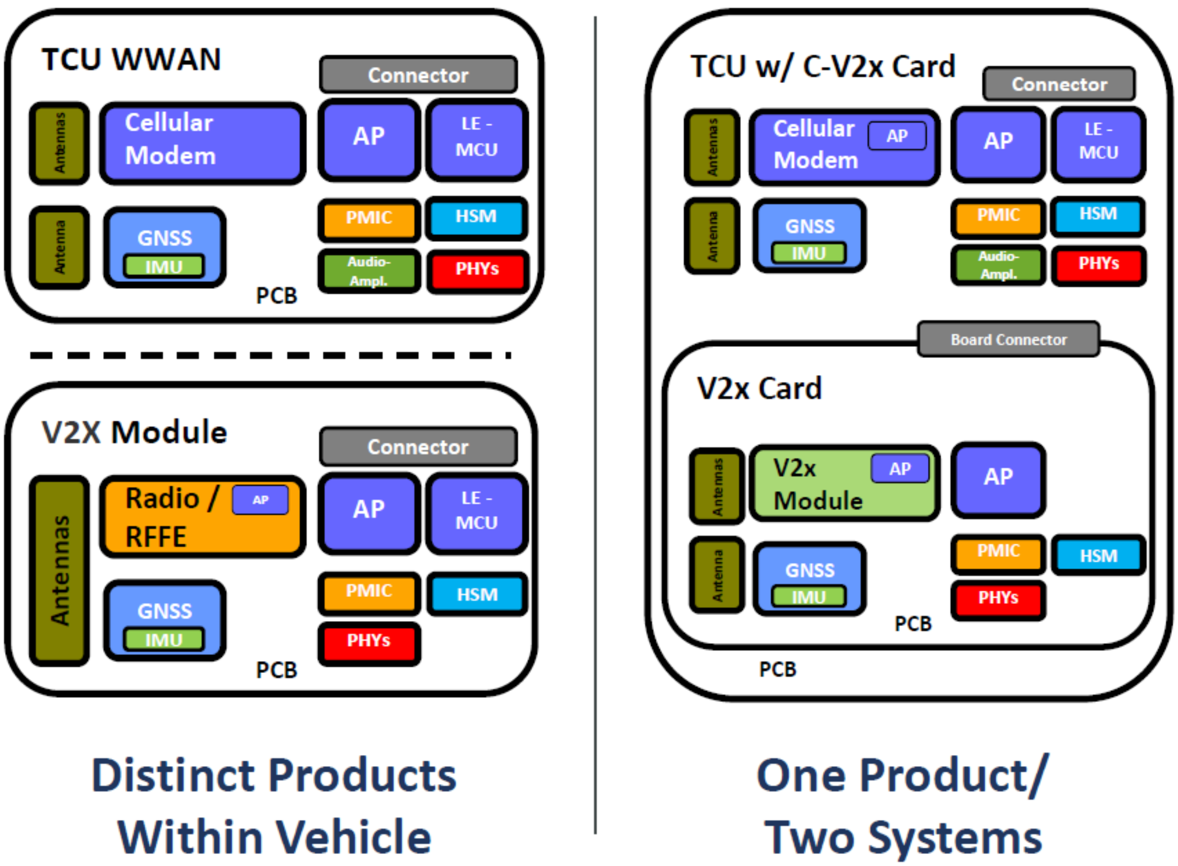


Figure 1: Product Configurations Scenario 1 (left) & Scenario 2 (right)

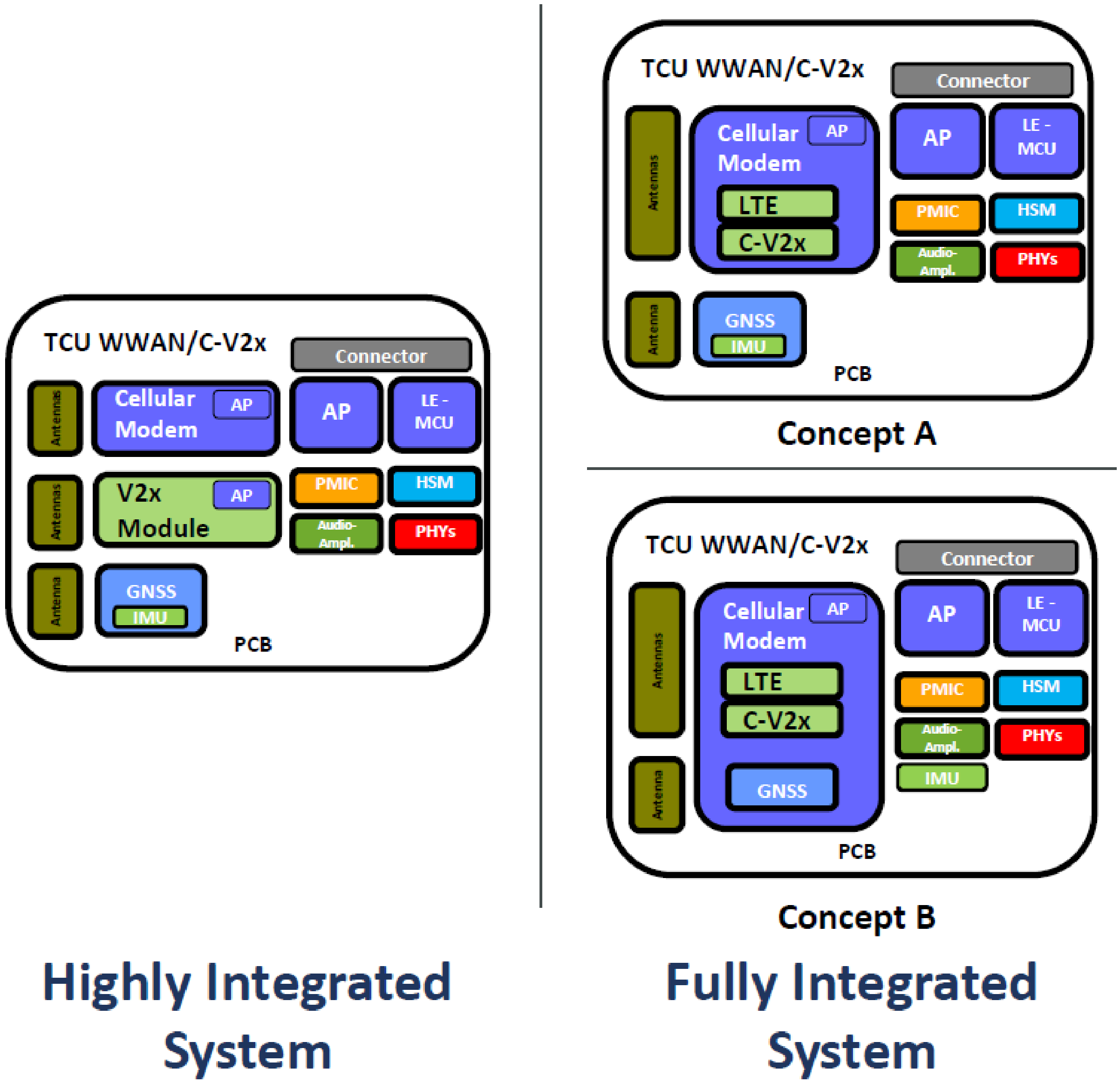


Figure 2: Product Configurations Scenario 3 (left) & Scenario 4A (right, top), 4B (right, bottom)

It is important to highlight the fact that scenarios 1 to 3 are able to integrate V2x independent from the actual communication technology (either DSRC or C-V2x), whereas scenario 4 A&B are only realizable with C-V2x as the integration of systems is happening on the semiconductor level which has not been commercially demonstrated yet with DSRC.

Starting from those product scenarios it was crucial to assign further components that enable a viable product for an automotive environment. This includes component types showing necessary automotive qualifications (e.g. AEC-Q100 and other automotive electronic quasi-standards) as CAN/Ethernet PHYs, Power Management Integrated Circuit or GNSS sensor chips. Full list of component categories used as follows:

- **Processing:** System-On-Chip (SoC)/Application Processor (AP), Low Energy MCU, Hardware Security Module (HSM)
- **Connectivity:** Modem, Radio Frontend
- **Memory:** RAM, ROM/Flash
- **Power Management:** PMIC, Standby Battery
- **Sensors:** GNSS, IMU
- **Packaging:** PCB, Connectors, Casing, Passive Elements
- **Interfaces:** CAN, Ethernet
- **Antenna:** Connectors, Wiring, Antenna body

Final (or real-world) product configurations, especially within automotive industry, depend on many factors including the type of EE-architecture in use, type of processing environment (centralized/distributed), preferred selection of suppliers, amount of integrated features, forward-looking capacity reserves for future feature additions (e.g. OTA updates), etc. will have significant impact on overall costs of the final product.

This study however wants to provide an overview of overall costs levels and drivers for the aforementioned product scenarios by balancing the goal of a realistic automotive product serving OEM requirements and the comparability of base technologies in an automotive environment.

2.3 Cost Model Premises and Scope

The utilized cost model is based on the experiences of P3 in the field of cost management within the automotive industry. It provides substantial information even in cases where the concrete product configuration is yet unknown and only a certain detail level of product scenario (as outlined above) is available.

Main part of this cost model is the setup of a Bill-of-Material (BOM) baseline with transparent and mutually exclusive component categories (as outlined above). This BOM contains all components and elements as formulated by the product scenario option. To assess cost factors of specific line items, e.g. the System-On-Chip application processor, comparable supply information from existing models will be utilized that provides similar or matching performance & functionality. The comparable baseline is assessed for each individual scenario where the proposed product configuration has an impact on performance levels or features set of the selected component, e.g. hypervisor functionality for scenario 3 & 4 require higher-performance processor with HW capability & accelerator for virtualization.

Some components and their cost information can be applied across scenarios as the actual differences are minuscule within real-world scenarios or would be hard to justify without having a detailed BOM with specifications present (e.g. connectors). Costs factors for PCBs or passive components (e.g. resistors, capacitors, quartz, etc.) have been assigned based on comparable information present from our cost management experience.

To provide a more comprehensive picture of all cost factors, cost drivers for software (Real-time Operating System, Application Software & Communication Stacks), overhead (SG&A, R&D, T&V, manufacturing), and HW-component related inputs have been considered.

As overhead related costs are heavily driven by supplier and OEM specific factors it is normal to outline those as percentage of the total bill-of-material sum populated by the various components implemented within the product. P3 hereby utilized common values from internally performed industry benchmarks.

Not included in the cost model were any profit margins by any of the potential developer, manufacturer (e.g. Tier1) or the buyer of such product (e.g. OEM). The same applies for any applicable license fee or royalties that are related to specific intellectual property (e.g. 3rd party patents), assembly-into-vehicle costs or ongoing operations fees to operate (e.g. a backend for operating & provisioning).

To populate the cost input of the BOM line items P3 has leveraged public available information as well as internally available cost information for automotive standard components. Additional subject matter expert intelligence & feedback was provided by a 3rd party to validate cost assumptions for strategic BOM components. For scenarios 4.A and 4.B additional feedback has been received by automotive/telecommunication industry-related manufacturers of relevant OBU components to provide further validation of their cost levels. All selected/investigated components fulfil typical automotive standards, requirements respectively qualifications and are specified to operate in typical automotive conditions and use cases as outlined by the product scenarios.

The author of this study is aware that in a real-world setting product with same specified functionality will be developed in different ways to accommodate OEM & vehicle specific baselines, interfaces and target cost level expectations. This has ultimately an impact on the selection of the actual used components for a product effecting actual costs. To represent such flexibility within this study cost information specific to each product scenario has been broken down as follows:

- **Maximum cost level:** High product requirements/integration of overall features into product
- **Expected cost level:** Balance of costs versus amount of overall product features
- **Minimum cost level:** Large economies of scale/ lower integration degree of overall features into product

In this way, different product strategies of OEMs and their suppliers can be considered in a differentiated manner without losing cost transparency. The “expected cost level” represents here also a common baseline across industry for future offerings and is used as the main cost indicator for each product scenario.

The scheme of Max./Expected/Min. is reflected in the cost factors for BOM line items as well where it is feasible e.g.

- **Application Processor:** Low Performance, no advanced features towards high performance multi-core with accelerators for hypervisor
- **LTE modem:** different UE speed categories, type of MIMO for antenna configurations

It has been discovered within this study based on reverse cost analysis and industry expert feedback that the actual sourcing cost differences between DSRC and C-V2x modems (including RF packages) are not significant (less than 10% or $2-3, across Max./Expected/Min. cost scenarios). For this reason, the cost information across scenario 1,2 and 3 displayed in the cost chart (see Figure 3) can be referenced for both V2x communication technologies. (not applicable for scenario 4 as it is a C-V2x only product configuration)

To maintain an appropriate level of complexity and scope, Human Machine Interface (HMI) components or backend operations for Security Credentials Management System (SCMS) were not investigated within this cost study. Instead, the investigated scenarios are representing a minimum viable product configuration:

- **TCU:** Establish a broadband connectivity towards OEM backend through a mobile network. Providing internal/external interfaces management tools for security purposes (e.g. firewall) and data forwarding (to head unit of infotainment system or vehicle gateway)
- **V2x:** Transmitting and receiving Basic Safety Messages (BSM) generated out of vehicle and other sensor information including certificate related processing (as outlined in commonly known standards drafts). Relay of BSM messages to vehicle Body Control Module (BCM) or infotainment head-unit.

2.4 Scenario Cost Comparison

The rapid increase of vehicles equipped with telematics systems within the European and North American market will lead to a quasi-standard of cellular broadband connectivity realized similar to the TCU as outlined in scenario 1. In this respect it was decided to outline the V2x related costs by each scenario as an incremental factor on top of typical TCU cost levels.

Based on the aforementioned cost model details and inputs it is now possible to compare easily the scenario specific incremental costs. (see chart Figure 3).

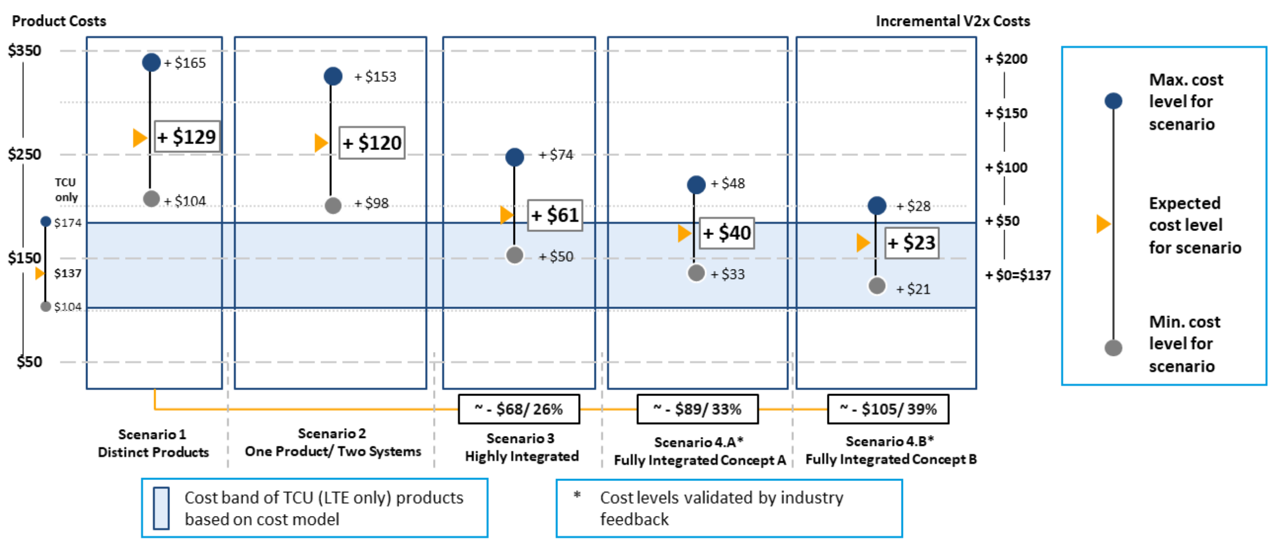


Figure 3: Scenario Specific Cost Comparison Chart (BOM + SW Related Costs)

2.4.1 Detailed Review of Product Costs

The results show that product scenario 1 has the highest incremental costs to realize V2x functionality within an automotive vehicle. The expected cost increase hereby reaches approximately the same costs as for the aforementioned TCU due to a similar product system configuration besides the actual modem chipset (LTE vs. DSRC/C-V2x). In a realistic industry scenario both products (TCU, V2x module) can be sourced and developed completely independent as limited communication & interaction between those two modules are required, if any.

Scenario 2 already provides some level of cost benefits as certain commodity components (e.g. casing, connectors) will be leveraged for the purpose of physical integration. The limits of such integration are reached very early on in the product development process as redundancy of key cost drivers (e.g. application processors, modem chipsets, GNSS/IMU, etc.) prevent further cost benefits in comparison to scenario 1. Further value-decreasing factors for this scenario are the aggravated physical compliance of such combined module (EMI, on-PCB connector) and a complex (or conflicting) product development process, potentially requiring two different suppliers to provide the main TCU and V2x sub-module. Besides the limited cost benefit and complex product integration an OEM developing automotive products with high degree of common products/components within vehicles across different global markets can leverage such design in a competitive manner. With a standardized TCU module (LTE baseband module with broad/worldwide band support) and a market specific V2x card (DSRC for one market and C-V2x for other markets) significant cost benefits can be realized by preventing double efforts for engineering, sourcing and manufacturing. Such product design as in scenario 2 requires nevertheless strong OEM and supplier commitment.

With a significant increase in degree of physical and logical integration, products designed as outlined in scenario 3 can demonstrate a significant cost advantage compared to the baseline of scenario 1. Major driver of such scenario advantage is the avoidance of component redundancy as the logical processing of both communication systems is operated in a shared environment within the main application processor (SoC). The increased benefits of shared components as HSM, GNSS/IMU and commodity elements (PCB, casing) realize attractive cost reductions so that the incremental V2x functionality cost impact can be reduced to less than 50% as compared to scenario 1. It is important to mention that within this product scenario the question around the selection of LTE & V2x modem chipset (DSRC or C-V2x) is still based on the discretion of the OEM as both communication modems are operating completely independent from each other and the hypervisor environment of the main AP should provide the appropriate separation of all functions. Physical limitations and challenges of integrating two high-frequency systems in this product scenario require intensive testing & validation activities around EMI and functional processing assurance (SW process cycle timing, etc.) to comply with standardized function requirements (e.g. amount of BSM messages sent & received, certificates processed per second, and a broadband connection requires intensive packet filtering).

As demonstrated in scenario 3 an intelligent physical and logical integration of TCU and V2x functionality in one product leads ultimately to reduced product costs (compared to the baseline outlined in scenario 1). Leading LTE semiconductor suppliers of modem chipsets used for consumer electronics and automotive use cases are currently actively developing modules that provide LTE and C-V2x functions in one semiconductor package (following 3GPP Release 14 standardization efforts) targeting a commercial release in the near term. The achievements of cost reductions so far have been independent from the type of V2x communication system used within the final product, but with scenario 4 the additional overall cost improvements will only be realized if we focus on a communication configuration which is a combination of LTE and C-V2x.

Scenario 4 with their sub concepts A & B (reflecting different industry player product integration options of communication and sensor elements) enable significant cost reductions not only compared to the baseline of scenario 1 but even towards scenario 3 by reducing the need for separate communication modem of the V2x function, thus reducing also complexity of the product design (e.g. packaging efforts for PCB) and decreasing even further the amount of secondary components such as antennas that are now shared by the integrated LTE/C-V2x communication systems (assuming antenna specifications suitable for shared functionality). The logical separation of processing environments is still realized through the hypervisor and virtualization of the HW and SW environment within the main application processor.

The author of this study is aware of similar activities to provide integrated LTE/DSRC solutions (in various levels of semiconductor package and module integrations) but it is believed that DSRC only or mixed modules (LTE and DSRC modem in single communication chipsets package but not integrated as single semiconductor similar to C-V2x) will ultimately be challenged by C-V2x based systems due to their massive economies of scale and therefore cost improvements driven by 3GPP and future 5G standardization efforts (consumer handset LTE chipset volume outperforming annual automotive modem demand by far; several 100 million versus 20-30 million units per year [2017]).

Both scenario concepts A & B and their expected product cost range are also now within the cost band of today's automotive TCU solutions (blue area on chart of Figure 3), leading the way of providing V2x functionality in an almost cost-neutral, or at least cost-sensitive, way thus decreasing the impact on consumers of such equipped vehicles.

2.4.2 Non-Monetary Decision Factors of Automotive Technology Selection

Up to this point, the investigated scenarios have been compared purely based on the cost levels driven by their corresponding bill-of-material configuration. Within realistic product development environments this point of view is one of many to estimate an automotive product providing all critical functions at reasonable costs. However, OEMs and Tier1s must take other factors into account when considering alternative configurations such as availability of technology in the market developed by Tier 2 or Tier 3 suppliers or the complexity of development itself.

For that reason, each scenario has been rated according to the two following domains able to capture the aforementioned factors:

- **Market Alignment:** Current activities of industry players (along value chain) to develop and provide either technology, resources, components that are required to realize product, including willingness of OEMs and their suppliers to develop product. Includes factors such as cost impact of final product, availability of components, ability to execute on product development in an effective manner.

- **Engineering & Packaging Complexity:** Effort (time, financial resources) required to develop automotive grade product solution with industry standard product development processes & activities. Includes resources to define system/ product requirements creation, actual SW/HW/system implementation, testing & validation and product lifecycle management.

In contrast to the BOM cost analysis, these two domains have not been rated or evaluated in the same lever of detail but represent a critical summary of industry experts' feedback that has been obtained for this study. Their input was summarized and transformed into a qualitative scale from unfavorable to beneficial (see Figure 4).

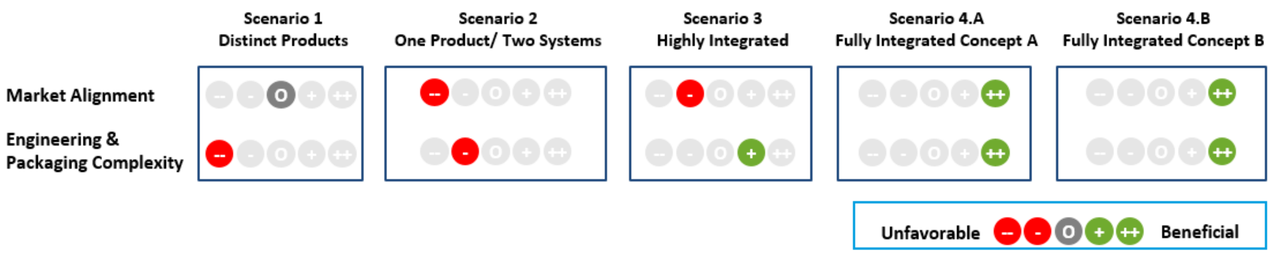


Figure 4: Scenario Specific Rating Overview

It points out that the scenario 4 (concepts A&B) received the highest rating in both domains whereas scenario 1 and 2 could not reach an overall positive position. Apparently, the ability to integrate V2x functionality into existing TCUs to a significant degree (advanced physical integration on semiconductor level) resonates well with automotive stakeholders responsible for such technology introductions. The positive feedback regarding market alignment circled mainly around the increasing availability of C-V2x technologies and products driven by latest announcements, beginning test trials and the availability of a long-term roadmap of functionality heading ultimately into future LTE and 5G releases.

The favorable rating of highly & fully integrated (scenarios 3 & 4) products regarding engineering & packaging complexity has been driven by the general understanding of automotive development processes to bundle adjacent & symbiotic functions into one product or domain to prevent conflicts within development activities as well as prevent un an unnecessary occupation of talent to develop similar functions & components. Also, subsequent processes, such as testing & validation, benefit from such integrated products as the actual efforts can be reduced in a real-world setting (e.g. limited redundancy of specifications/ requirements and reduction of actual T&V work across value chain).

3 Conclusions and Recommendations

The analyses within this study have been performed to identify the cost realities of potential V2x product scenarios in an automotive environment so that eventually key decision makers within the industry are able to leverage the identified key factors and data points to define or refine strategies around their V2x product portfolio for future vehicles.

The results of this study clearly indicate the importance of physical and logical integration of products with adjacent functionality (such as LTE and V2x features) as a strategy to avoid costs especially in a high-volume demand area such as automotive. The actual consolidation of HW components is the initial and major step to achieve a far-reaching cost improvement strategy.

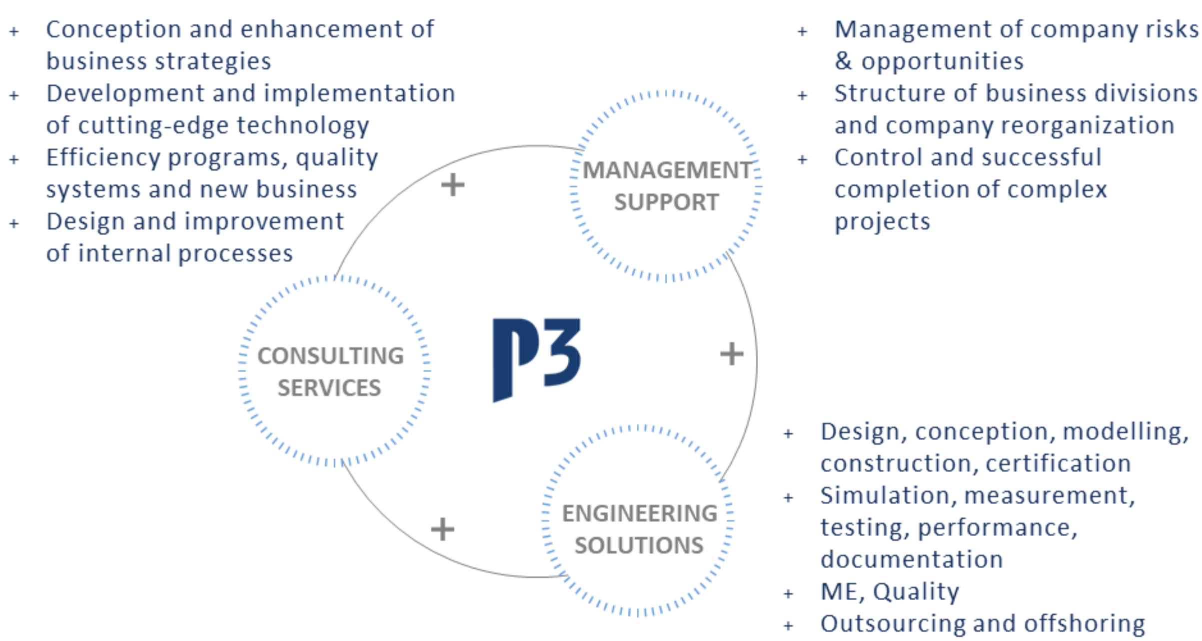
Even though the realization of V2x functions within a vehicle in scenario 1 (distinct products) is feasible (regarding technology, product development and market introduction) with today's means, it will receive additional scrutiny by various stakeholders within OEMs to justify the almost 5x higher incremental costs of V2x functions compared to the most favorable product option. This cost increase is not just limited to the product itself (hardware and software) but eventually includes also the indirect cost factors and complexities that exist in various processes of realizing such a product. This affects efforts (timing and monetary resources) for development and testing & validation.

OEMs are already (or will soon) equip their vehicles with a TCU as a standard option even if the consumer will not activate any additional connected services functions after purchase. This baseline is important as we have seen different incremental costs levels across the investigated scenarios. Future V2x product strategies should reflect the focus on keeping this increment as low as possible to reduce the financial impact on consumers.

4 About P3

P3 provides global management consulting and innovative engineering to its clients through a broad range of services from strategy and benchmarking through validation and launch, including prototyping, program and supplier management, systems engineering, and automated testing systems. P3's unique blend of business experience and technical expertise results in custom solutions that reduce time to market and lower development hurdles.

In recent years, P3 has expanded into app development, data analytics and visualization, and software development, driven by the needs of their clients'. P3's North American headquarters is located at their Mobility Innovation Center in Southfield, MI with their global headquarters located in Aachen, Germany. P3 has over 3,800 employees at 40 locations in 15 countries.



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