Use cases and conceptual system specification for Self-Propelled Wagon

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Introduction and aim

The objective of this contribution is to present the analysis of the technical enabler “Self-Propelled Wagon” within the modern trends of the freight train digitalization. This document starts with an analysis of the state of the art and after the stakeholder needs analysis, it introduces the most significant use cases. As a result of the preliminary calculations, a conceptual system specification for Self-Propelled Freight Wagon (SPFW) is disclosed.

A state of the art review for the SPFW concept has been carried out as well as identifying and analysing essential use cases; Private yard load automation, Challenging Tractive Power and Braking Scenarios, Coordinating groups of self-propelled wagons and Autonomous loading/unloading. In order to understand the needs of operators, infrastructure managers, suppliers, and research centres, stakeholder needs analysis was carried out through conducting a physical workshop for Nordic railway stakeholders and an online survey at a European level. Moreover, this study presents, as a result of the state-of-art analysis, the needs analysis and identified use cases, a conceptual analysis on the impact of self-propelled objective on the digitalization of the freight trains, introduces a high level system architecture as well as a preliminary test.

State of the art

The state of the art with respect to self-propelled freight wagons (SPFW) shows sporadic developments over the past decades. Simple self-propelled wagons have existed for around 100 years, but recent technological advances with respect to remote control and sensing, artificial intelligence and energy storage have led to a surge of developments in recent years. In general, the incorporation of some sort of propulsion into a wagon is done in order to reduce the number of locomotives at various stages of a wagon’s travel and operation, thus reducing capital and personnel expenses as well as increasing flexibility in the movements of the wagons.

In Figure 1, below, three commercial references are presented and recognized for the development self-propelled wagon or similar projects.

Figure 1: From left to right: IntraMotev “ReVolt”, RZV Čakovec “Self-Prop Rail”, Parallel Systems transport unit prototypes [1],[2],[3]

First of all, Intramotev, an American company is developing self-propelled battery-electric freight cars as “ReVolt” shown in Figure 1 above. The main goal of Intramotev is to distinguish itself by its focus on integrating “cutting-edge" battery technology, autonomous driving algorithms and regenerative braking to revolutionize rail transport. This aims also to reduce diesel consumption from locomotives in the course of mainline operations. The current state of development at Intramotev is unclear in Europe, but a reference has been deployed on Iron Senergy’s Cumberland mine in Pennsylvania. Few details about the actual design or capabilities have been published. [4]

On the other hand, RZV Čakovec and collaborators devised a self-propelled wagon equipped with a 55 kW diesel generator and hydraulic transmission, enabling it to go up to 100 km/h under remote control around work sites. The drive works via friction wheel applied directly to the rail, thus obviating any need for modifications to the bogies themselves. A prototype was displayed at the InnoTrans in 2014 but any further developments or use of this prototype are known after the conclusion of the project [2] [5].

Parallel Systems, a California-based start-up founded by former SpaceX employees, is developing an ambitious self-propelled freight wagon concept. This concept actually forgoes the traditional freight wagon altogether and consists of pairs of independently mobile drive units or carriers, each roughly in the format of a traditional bogie and joined together by a subframe/carrier, upon which normal intermodal containers can be placed directly. These electric rail carriers are autonomous and self-sufficient in terms of energy supply, traction and braking, are claimed to have a range of approximately 800 km between charges and are intended to supplant conventional rail and road freight over distances of up to 1600 km. The units are not intended to be mechanically coupled, but would, as the company has demonstrated with their existing prototypes, drive together in physical contact through their centre buffers, thus minimizing aerodynamic drag and occupied track length [3].

All these entities are linked to self-propelled wagon initiatives through their respective focuses on different aspects of the technology and infrastructure required to make autonomous rail freight a reality.

While the above references stem from commercial entities, an example of research project into SPFW comes from the RWTH Aachen. A classical approach to achieving many of the benefits of self-propelled freight wagons is simply equipping an existing freight wagon with the equipment necessary to propel itself, as represented by the FlexCargoRail concept in Figure 2.

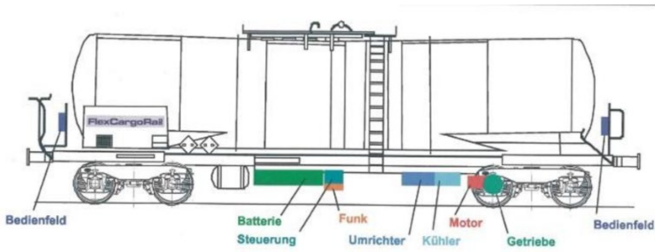

Figure 2: Representation of the components under the wagon body [6]

The objective of this project was to link one wheelset of that wagon with a fully decouplable electromechanical drive system, which can also haul another wagon together [7]. The FlexCargoRail concept fulfils many of the requirements for basic shunting and last-mile-operations, however it requires significant modifications to the wagon and at least one bogie and may thus not be suitable for some common types of wagons. Aspects of the development of this concept have been carried forward in the Wagon4.0 project, which additionally focuses on the technologies needed for automated and autonomous operations.

Use case definition

Four essential use cases for self-propelled wagons in freight operations have been identified and analyzed for this report. All of them have been analyzed, detailed theoretically and simulations and preliminary work has been started by the partners involved in them. Further work and results, for the one selected for the implementation, will be disclosed at the end of the project funding this research.

The **first use case** focuses on private yard load automation, where traction motors, converters, and batteries could be integrated into existing freight wagons to automate yard operations. The main interest of the partners involved in this use case is the definition and design of a proper motor that cope with the requirements of the use case and fit into the characteristics of the axle/bogie proposed. As we are seeking to retrofit an existing axle/bogie, the aim is to be as non-invasive as possible, so a direct-drive motor solution that can be directly coupled into the existing axle is being designed. The fact that it is a direct-drive system allows to avoid additional mechanical components, reducing the complexity and cost of the new drivetrain. The definition of the braking system is modified to work with decoupled wagons and, as a complement for both subsystems, communication elements need to be integrated for speed control, braking and the link with the management of this yard. As a result, this process eliminates the need for shunting locomotives, reducing operational time and labor costs. Preliminary tests of some of these functions are planned in a private yard in Asturias, Spain, with an alternative site in Gijón.

The **second use case** addresses challenging tractive power and braking scenarios, exploring two scenarios: "Power Booster" and "Power Peak Shaving." This is the only one that is foreseen on main lines, as the others are meant for yard operation.

The "Power Booster" scenario aims to enhance traction capabilities on uphill gradients by using self-propelled wagons to supplement locomotive power. This allows the train to maintain a constant speed and maximize line capacity, even on steep inclines. By distributing the traction force across multiple wagons, the overall strain on the locomotive is reduced, which can prevent slowdowns and improve the efficiency of freight transport on hilly terrains. Additionally, this distributed power approach can enable longer or heavier trains to operate without the need for additional locomotives.

The "Power Peak Shaving" scenario focuses on reducing power demands from locomotives during peak loads on the electrical grid. In this scenario, battery-powered bogies are used to provide supplementary power when the electrical substations are overloaded. By communicating with the electrical grid, the system can detect power peaks and adjust the power output of the locomotive and the self-propelled wagons accordingly. The locomotive reduces its traction output while the battery-powered bogies increase their traction output, ensuring that the train's overall power needs are met without overloading the grid. This approach not only alleviates power peaks but also enhances the stability and efficiency of the electrical network.

The **third use case** involves coordinating groups of self-propelled wagons to demonstrate automated shunting operations. The method optimizes the coordinated motion of wagons to maximize efficiency and minimize shunting duration. Traditional shunting operations involve moving one wagon at a time, which is time-consuming and labor-intensive. In contrast, the envisioned process involves concurrent shunting, where multiple wagons move simultaneously. This approach significantly reduces the total shunting time by 40-60% compared to traditional sequential shunting. The optimization algorithm ensures that the wagons move in a coordinated manner, avoiding collisions and near-collisions. By allowing several wagons to move at the same time, the overall efficiency of yard operations is greatly improved, leading to faster train assembly and reduced operational costs.

The **fourth use case** investigates autonomous loading and unloading of freight wagons. It includes autonomous entry and exit from yards and terminals, and the use of specific technologies found in the state of the art, like AutomaticCarConTrain (AMCCT) and Innofreight's SUM for transshipment. The focus is on intermodal wagons, enabling autonomous transshipment of intermodal loading units and reducing the need for manual intervention. The envisioned process aims to streamline operations, reduce costs and enhance efficiency in freight handling. For intermodal terminals, the self-propelled wagons could autonomously disconnect from the train at a siding and enter the terminal. The intermodal loading units are then autonomously transshipped using enabling technologies such as the mentioned AMCCT or SUM. For yards, similarly to what it is proposed for the first use case, the wagons autonomously unload and load on-site or at the final destination. After loading or unloading, the self-propelled wagons autonomously reconnect to the outgoing train at a siding. This process, here again, reduces the need for manual labor and increases the efficiency of freight operations by allowing for continuous and automated handling of goods. The use of autonomous technologies in loading and unloading also minimizes the risk of human error and enhances the safety of freight operations.

Needs analysis

To understand the needs of operators, infrastructure managers, suppliers, and research centres, both a physical workshop and an online survey was conducted. The aim was to gather comprehensive insights from stakeholders in the rail freight industry.

Workshop

The ¨Nordic Perspective for Future Rail Freight¨ workshop, organised by Lindholmen Science Park in Gothenburg, was held on 2023-03-22. This event sparked extensive discussions and provided valuable insights across a wide range of stakeholders. The stakeholders were grouped into four teams. Four questions were asked to each team coming from a variety of sectors in rail freight industry.

The questions were broadly framed to assess the interest and curiosity of rail freight industry partners regarding the topic of self-propelled wagons. As a result, the use cases have been prioritized by the participant, resulting in the ones that have already been presented in the previous section of this document.

Another question was related to expectations from SPFW as a potential user. Below are the listed answers:

- Last mile service from the mainline to the industrial area
- Self-loading and unloading
- Reduce the train time and the need of feeder and shunting locomotives
- Infrastructure way of thinking: Trains occupy tracks and they should move as much as possible
- Needs to be safe and reliable
- Knowledge of the tracks (lack of energy), speed that you have to have going up a hill with a certain load
- Cheap
- Battery for the part of the track that don't have electricity

With regard to SPFW, general takeaways from the workshop were that there is broad interest in SPFW, especially in the context of other developments such as the impending implementation of the Digital Automatic Coupler (DAC), and that there are many use-cases in which various stakeholders could benefit greatly from an independent electric drive system in freight wagons. However, it was also put forward that legislative work may be needed in order to support this initiative, as capital costs will be an issue for operators wishing to implement this technology.

Survey

The survey was conducted among stakeholders from the freight transport industry, with a special focus on the requirements and processes in shunting and last-mile operations. The survey consisted of 16 questions on the topics of infrastructure and operations. The survey aimed to collect important parameters for the use case, such as distances, gradients and operating times.

An overview of answers concerning time and distance are shown in the table 1 below. Unfortunately, only a limited number of usable responses were received to this survey, but these were very helpful in determining the performance data and requirements in the specifications.

Question	Minimum	Maximum	$n_{Answers}$
Maximum speed	15 km/h	40 km/h	4
Maximum gradient	4 ‰	9 ‰	2
Maximum distance with own drive	1 km	10 km	6
Track in the train formation between shunting operations	50 km	400 km	7
Time in which the wagons are uncoupled from the train set	24 h	168 h	5
Time of the car at the destination	6 h	168 h	6
Number of start-ups	3	12	5
Smallest radius	90 m		1
Permanently coupled wagon units	1	4	6

Table 1: Summary of survey responses

These answers are also very useful in order to adapt the design of components such as batteries and motors, since some of the main input parameters to define the requirements for these components are the needed operation time and distance. The required power/torque for the motor, and thus for the battery, can be calculated from the desired speed profile of the wagon, so optimizing this target speed profile could result in significant weight and cost savings. Adjusting the vehicle's maximum acceleration would reduce the previously mentioned power requirements, thereby requiring a smaller and therefore cheaper battery and motor.

At the end of the survey, open questions were proposed to give the opportunity to the answerer to tell their wishes and expectations for the future developments in rail freight transport. They would like more hump yards. They expect an energy source on the freight wagon, a possibility of automation and an increased flexibility. Moreover, a cost reduction will be appreciated. Finally, there were wishes related to the DAC5 and all related "train functions", such as parking brake, wagon mobilisation instead of bleeding, automated brake test, train integrity, etc.

The purpose of the stakeholder workshop and survey was to determine needs from operators, infrastructure managers, suppliers and research centres and to get an overview of the last-mile operations of a wagon. The stakeholder workshop successfully identified critical insights into the potential and needs for self-propelled wagon in the rail freight sector. The outcomes highlight the potential for self-propelled wagon to revolutionize freight operations through increased efficiency, flexibility and sustainability, provided that administrative and resource challenges are addressed correctly. The online survey help understanding the real conditions and the yards and thus optimize the requirements for the SPFW. The values given by the survey's answers allow us to get the range values in term of time and distances travelled by a wagon.

Conceptual analysis of the impact of the self-propelled wagon on digitalization of freight operation

Self-propelled freight wagons are seen as one of the most promising ways to revolutionise freight transport and improve the efficiency and safety of the transport system in the long term. They stand to contribute to the digitalisation of freight transport by automating and optimising processes.

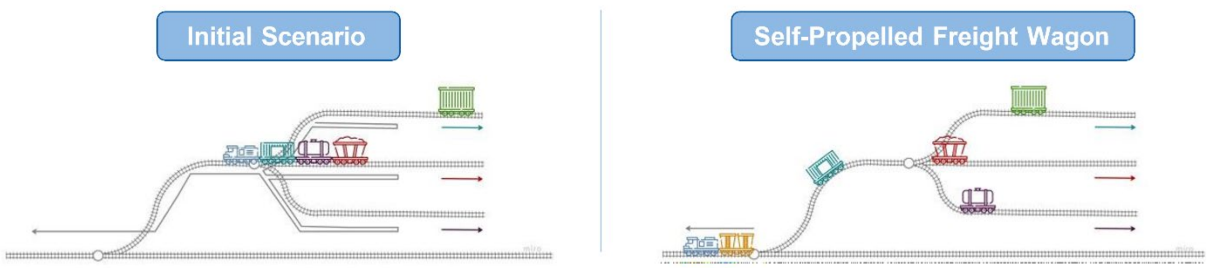

Figure 3: Logistical simplification through self-propelled freight wagons [8]

Thanks to the integration of IoT technologies and sensors, self-propelled freight wagons enable a range of improvements in the logistics industry. They can track the transport and supply chain, improve the efficiency of freight movements and increase safety. The control of freight wagons by automated systems enables the avoidance of human error and can improve the punctual and efficient delivery of goods. This technology could also compensate for the shortage of lorry drivers and marshalling-yard workers, and the declining attractiveness of the driving profession, thereby increasing the availability of transport. Figure 3 shows the logistical efficiency of self-propelled freight wagon compared to a classic locomotive.

However, the introduction of self-propelled freight wagons also requires a corresponding infrastructure to enable the networking and data transmission of the vehicles. In addition, further tests and developments are required to improve IoT and automation technology in order to ensure reliable operation and safety.

Moreover, the digitalization of freight trains will lead to special requirements for usual freight wagons components. Indeed, an on-board energy storage system is needed in order to feed all the subsystems and increase the efficiency of freight wagons. The presence of this kind of system can also enable the use of energy recovery systems such as braking energy recovery for instance. Through this system, the productivity can be improved and the operating costs reduced. Regarding coupling systems, the DAC offers significant advantages for the entire logistics process for freight wagons by improving effectiveness, flexibility, monitoring, safety and automation, and is a perfect complement to a self-driving ability, as the combination would allow complete shunting movements to take place without any personal human interaction with train hardware.

An autonomous freight car requires a vehicle control unit (VCU), which operates in a similar way to a normal train. The VCU is responsible for monitoring and controlling the various electronic systems of a vehicle, playing an important role in ensuring safe and efficient operation of the vehicle, but also helping with maintenance. One of the main tasks of the VCU in the context of a SPFW is to monitor and regulate speed and braking power. The VCU can also contain additional sensors and monitoring systems that are necessary to control and regulate the operation of an autonomous freight train such as the communication modules. This means the VCU is the main gateway for every communication between the wagon, the wayside systems and the user. Furthermore, a VCU also enables the storage of maintenance data on the network, which can help to optimize maintenance activities and prolong the lifespan of the train.

Last but not least, communication systems are also affected by the digitalization of freight trains. However, it is important to differentiate two types of communication systems for self-propelled freight wagons:

- The onboard communication system Freight Ethernet Train Backbone (F-ETB), which controls the communication between the wagons inside one trainset
- The FDFT-Link that connects the single wagons to the to the wayside

The communication network between SPFW offers several advantages, including greater insights and the ability to quickly retrieve data in the event of an accident or emergency. The stored data can include information such as the location of the cargo, its weight and dimensions, and other relevant details. In the event of an accident, this data can be retrieved quickly and used to assist emergency responders such as firefighters in understanding the nature of the cargo involved and taking appropriate safety precautions.

Communication with trackside systems enables the position of autonomous trains to be accurately determined in real time, which can help reduce the distances between them. By decreasing the spacing between trains, rail operators can increase the capacity and efficiency of their networks, allowing for more trains to run at a higher frequency.

Conceptual system architecture

As a result of the analysis shown in this paper, up to now, and considering the freight system architecture agreed within the FP5 TRANS4M-R project (Deliverable D2.3 [8]) and the relations due for the self-propelled wagon concept, the next figure (Figure 4) presents the interfaces that are defined for this element.

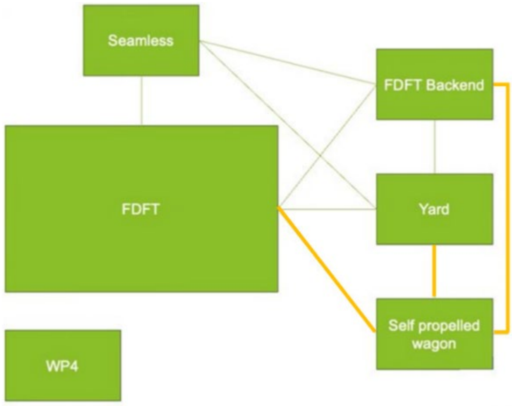

Figure 4: Interfaces of the SPFW to the other subsystem of the freight system architecture

Emphasizing the use cases where the SPFW operates in yards and terminals, the links in bold represent the relationships with the FDFT function on-board and with the Yard automation management system. These links are performed by means of the communication system that the SPFW need to be equipped with. There are two ways from the Yard Automation Management System (YMS) down to the operation on its control. The first and priority is by the on-board Automatic Shunting Operation element, which will be the link with any GoA level yards where the wagon would be operated from the YMS. As a secondary option, in a non-operative yard automated area or for validation or test purposes, the control could be taken remotely by an operator. This is why a remote controller element is proposed to be added, at this stage, prior to the confirmation of these technologies by the operators and infrastructure managers.

The next figure depicts which elements are on-board the wagon, with the blue blocks representing the additions provoked by the self-propelled wagon concept.

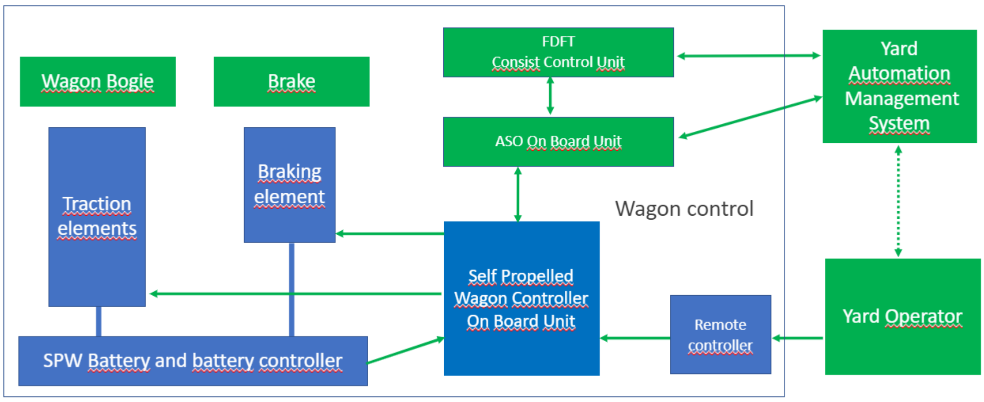

Figure 5: Internal subsystems and Interfaces of the self-propelled wagon to Yard

This Figure 5 highlights the critical components and their interactions within the self-propelled wagon system. The on-board elements will need to include the propulsion system, braking system and communication modules, which are essential for the autonomous operation of the wagon. There are new components introduced by this concept, such as advanced sensors, control units and energy management systems. These additions are crucial for enabling the autonomous functionalities and ensuring seamless integration with the existing yard and train management systems.

The proposed data, functions and orders shared between the self-propelled wagon controller and other systems include destination and route information, predicted energy requirements for shunting and last-mile operations, train composition and weight estimates, mode of operation and assisted power demand for demanding traction scenarios.

The Yard Automation Management System can control the mode of operation and remotely manage the wagon's acceleration and braking. The SPFW controller provides battery and energy status updates to the ASO and shares its position and perception data during remote control mode with the yard system. Some of these data and functions are not currently implemented but are anticipated as part of future developments. For instance, predicting energy requirements for shunting and last-mile operations is a proposed function that does not yet exist. The task where this paper has obtained the input is still working on the next phases and aims to gather data to develop algorithms for this purpose in future calls, potentially within the FDFT Backend.

Conclusions

As a conclusion for this document, the state-of-the-art review identified several commercial and research initiatives focused on new wagons or autonomous bogies, which require significant investment. Practical proposals for integrating these technologies into the current freight system architecture were prioritized, providing valuable insights for the proposed high-level system architecture.

Stakeholder needs were analyzed through a workshop and an online survey, revealing critical insights into the potential and needs for self-propelled wagons. These insights highlighted the potential for increased efficiency, flexibility, and sustainability in freight operations, provided administrative and resource challenges are addressed.

The use cases concluded that self-propelled wagons can streamline operations by eliminating shunting locomotives and reducing manual labor, resulting in faster and less costly processes. They highlighted a conflict between powertrain requirements for last-mile delivery and traction support, which could be mitigated by an integrated traction system in selected bogies. Significant efficiency gains were demonstrated with concurrent shunting, achieving substantial time savings compared to sequential shunting. The need for self-propelled wagons, autonomous coupling/decoupling, and transshipment technologies was identified, with only a few technologies meeting the requirements.

Overall, the study provided a conceptual analysis of the impact of self-propelled wagons on the digitalization of freight trains, introduced a high-level system architecture, and outlined a preliminary test and validation plan. Future work will focus on developing deployable, cost-efficient solutions, implementing and pre-testing concepts, and demonstrating the functionality of a preliminary traction system design for self-propelled wagons. This preparatory work will serve as the basis for future demonstrators in upcoming calls after 2025.

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