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Assessment of quantitative methods for the safety-performance evaluation of next-generation train-centric railway operations

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The railway transport demand of passengers and goods is continuously increasing. This situation leads to the railway network saturation and the consequent need for a larger infrastructure capacity where train services operate efficiently with higher frequencies and less delays. A cost-effective solution is the deployment of next-generation railway signalling systems which can shorten the train separation and provide substantial capacity benefits to railway customers. Moving Block (MB) is a railway signalling system enabled by the European Train Control System - ETCS Level 3. It considers trains being outdistanced by an absolute braking distance. This distance is needed by the train behind (i.e., following train) to slow down from its current speed to standstill. However, with the significant increase of railway demand that is forecasted by the European Commission in the future, there is a need to shift to a more advanced railway signalling system that can drastically reduce train headways. Virtual Coupling (VC) is a recently introduced railway signalling concept that envisages consecutive trains to run at a very short distance, similar to car platoons –as proposed by the automotive industry. The main difference between VC and MB is that the former can allow the trains to move dynamically and synchronously in platoons at a relative braking distance from each other by means of a vehicle-to-vehicle communication. A relative braking distance is defined as the safe separation to coordinate the speed of a train with the one ahead while considering its braking characteristics. Additionally, VC can lead to an improved customer satisfaction since it can provide a more flexible train service in line with passengers' travel needs.

As the deployment of new railway technologies requires official approval from the railway industry, a well-specified strategy can foster investment decisions for technological developments and the overall system migration process. Therefore, it is crucial to guarantee that the proposed railway technologies can enhance operational efficiency and ensure safety to passengers and freight transport. Although next-generation train-centric signalling systems can provide substantial capacity benefits to railway customers, several uncertainties arise in the safety validation of the VC technology. Several attempts have been made for evaluating the safety and availability of multi-aspect signalling and ETCS railway signalling systems. However, to the best of our knowledge, no quantitative assessment for the safety of train-centric signalling and especially for VC has ever been performed to allow a more reliable impact assessment of next-generation signalling systems. It is therefore crucial to address the following question: Which quantitative approach is suitable to assess both the safety and performance of next-generation train-centric signalling systems?

In this paper, we first identify the system components that constitute next-generation train-centric signalling systems (i.e., MB and VC). We then investigate different quantitative safety methods adopted in the literature to identify the most appropriate one for the evaluation of the safety of MB and VC while ensuring the performance benefits of each signalling system. The results showed that a Fault Tree Analysis (FTA) provides a rational framework for modelling the possible scenarios leading to system failure. It also allows modelling and analysing safety critical components in engineering systems. In addition, a FTA is flexible and efficient as it graphically shows the logical relations between the basic events and top event. However, the FTA has limitations when modelling complex systems especially when it comes to handling dependences. In addition, with the application of a FTA, it is difficult to express complex situations in real-world conditions. This method also does not take into account the system efficiency and can become very complex when considering a certain level of detail. Stochastic Activity Networks (SAN) are a graphical, high-level language for describing system behaviour. This method is a stochastic generalization of Petri Nets which is defined for modelling and analysing real-time systems. To this end, our results showed that the combination of a FTA with SAN can address the complexities imposed by train-centric signalling components and is an effective approach to evaluate the safety-performance effects and behaviours of the MB and VC systems in real-world conditions. Future works will include measurements performed on MB and VC case studies to validate the results of the FTA-SAN approach.