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Research Article

Analysis of coupling system failures on freight trains

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Abstract: This paper presents an analysis of train coupling failure that led to trains break apart on the Serbian Railways over 10 years period. Train coupling failure of freight trains with single locomotives was considered. The analysis was done based on accident data combine with FMECA risk assessment. As a result distribution of failure along the train, driving regime and velocity were obtained, as well as the frequency of failure concerning the length and mass of the trains, load status, etc. The systematization of coupling failure helped to establish conditions leading to failure and to define the parameters causing it. Risk factors for coupling failure were determined using FMECA risk assessment. Preventive measures are recommended for the revision of maintenance. Risk analysis of coupling system failure can be different depending on the time of analysis (regulations, exploitation conditions) and the applied maintenance practice. FMECA analysis applied to train coupling systems based on regulation shows different permissible risk values that don't match exploitation data.

Keywords: coupling system failure; railway; risk analysis; train breaks apart

I. INTRODUCTION

The coupling system of freight trains on Serbian railways, like in other European countries, consists of a screw coupler and draw gear (**Fig. 1**), while a majority of railways outside Europe use automatic couplers. They provide mechanical connections that transmit traction forces between vehicles along the train. Train coupling failure analysis aimed to classify coupling failure cases with causes, circumstances and consequences. Analysis can determine what leads to failure increase. Since coupling failure can have a safety impact on railway traffic by causing trains to break apart, it is primary to predict coupling failure and propose measures to reduce them.

According to EU Directive 2016/798 [1], train breaks apart are classified as incidents and are not recorded in the Rail accidents database [2] to the ERA (European Union Agency for Railways). Analyzes of individual cases of train breaks apart were carried out, with an emphasis on determining the cause of coupling system failure and the root cause analysis [3-8].

From 2016 to 2020 railway operator in freight traffic "Serbia Cargo" had an average of 36,4 cases per year of coupling failures [9, 10]. Total number of accidents on the Serbian railway from 2016 decrease relative to previous years, as well as the number of coupling failures that was 40,2 cases [9, 11] per year (from 2007 to 2011). Although the total number of accidents decrease, the number of train coupling failures relatively increased by almost 14% [12].

The rolling stock of railway operator "Serbia Cargo" in 2020 was reduced by almost 43% relative to the stock of national operator "Serbian Railways" ("Serbia Cargo" legal predecessor) from 2007. The number of freight wagons was, also, reduced by approx. 53% [12]. The rolling stock (on average) is over 40 years old, and a large number of vehicles are rented from other railway operators in Europe. Also, there are a certain number of foreign vehicles, running according to the GCU (General Contract of Use for Wagons). Considering the previous, analysis of train coupling failure on Serbian railways does not have a purely national character and is not defined.

The risk of trains breaking apart, caused by coupling failure, in railway traffic is a quantitative measure of the severity, detectability and frequency. Taking measures to reduce coupling failure is to manage improvement through preventive maintenance, quality, design and operation [13].

Risk analysis of coupling failure was made based on the EN 50126 series standards [14, 15] for railway applications of RAMS management (Reliability, Availability, Maintainability and Safety). Failures are ranked according to the criticality level, known as the Risk Priority Number (RPN). Failure Mode and Effects and Criticality Analysis (FMECA) is based on Failure Mode and Effects Analysis (FMEA) with the additional critical analysis performed after the implemented FMEA.

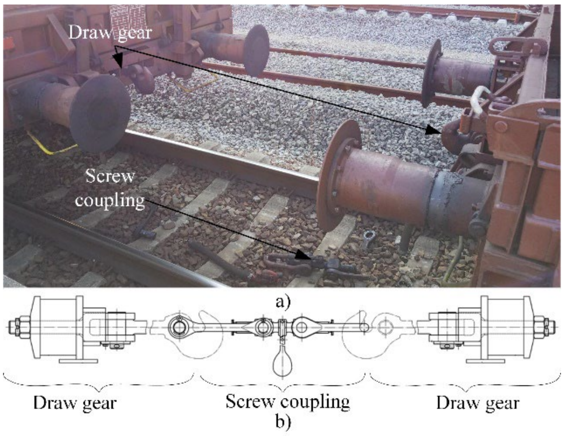

Figure 1. *Coupling system on freight trains, a) at train brakes apart, b) schematic view between 2 wagons*

II. Methods

1. FMECA method

The ranking of the severity, detectability and frequency of coupling failure for freight wagons was made according to ranks in UIC B169, RP 43 [13], where the rank have values from 1 to 10. For severity, values range from „no impact“ for 1 rank to „unsafe without warning“ for rank 10. The ranking of detectability of failures goes from „nearly certain“ for rank 1 to „nearly uncertain“ for value 10. The frequency range has values from rank 1 „little - failure is implausible“ for a value less than 10^{-9} to „very high: Failures in very short cycle which are not avoidable“ for a value more than $8 \cdot 10^{-3}$ per year for rank 10 [13].

Risk evaluation is the assessment of the obtained RPN with the limited RPN value, defined in the risk analysis process, to identify the criticality level with increased risk. If the calculated RPN is above the set limit value, it is considered unacceptable and improvement measures must be implemented. If the RPN is below the set limit value, but it is not negligible, it is considered conditionally acceptable and only economically justified measures are applied [16]. The rank of severity (S), detectability (D) and frequency (F) have values between 1 and 10, so the risk evolution in RPN range from 1 to 1000.

Some failure of mechanical components could, due to deterioration over time, become causes of severe failure. Failure means that the observed object can no longer perform the function and realize the operating conditions. The quality deteriorating of the component does not mean failure, but some failures can become failure root causes [13]. For the coupling system of freight wagons in railway operator "Serbia Cargo", consisting of screw coupling and draw gear, quantitative values of failure can be obtained, based on accidents reports.

For one or more components of the coupling system, due to the deterioration of their condition over time (wear, corrosion, etc.) or overload, severity could progressively increase. Using experience and data from an operation, taking into account the worst outcome in the failure chain for all components, the result is always coupling failure leading to trains breaking apart. Thus, the risk analysis was significantly cut by the assessment of component failures (fractures) only. Results of risk analysis of the coupling system of "Serbia Cargo" freight wagons were based on the number, equipment and technical condition of the vehicles in use from 2018 to 2020. The introduction of an Entity in Charge of Maintenance (ECM) in railway maintenance and reconstruction of the Serbian railway company in 2015 into 3 separate entities with changing and aging of rolling stock, affected characteristics of train coupling failure.

2. Method for prediction of train breaks

The relative indicator of train breaks apart in railway freight traffic is the ratio of the number of train breaks and the traffic volume in millions of tonne-kilometre. This relative indicator represents the frequency of train breaks apart reduced to ton-km per year. Based on the determined frequency of train breaks apart and their effects on railway traffic in recent years, it was possible to predict the risk of train breaks accordingly. The prediction was based on data obtained for equal or similar [16]:

- types of vehicles (wagons and engines) and their condition (quality and maintenance),
- traffic condition,
- train driving and
- external and other conditions in operation.

3. Method for train breaks data analysis

In train breaks apart analysis various methods were applied for the classification of failure cases and systematization of operational data [10]. The induction method, aiming to review the circumstances that preceded the coupling failure, was based on the investigation reports along with exploitation and maintenance experience. Based on the conducted analysis coupling failure factors were defined. The collected data and information were processed statistically to quantify the factors. Using the generalization method, the most important causes of coupling failures and the critical parts of the coupling system were determined. The analysis of coupling failure cases shows the frequency of failure so that preventive measures can be proposed to focus on reducing train breaks apart. During the analysis of train breaks apart cases, it was not possible always to determine all primary characteristics due to data deficiencies or insufficiency.

The analysis of relevant cases of train breaks apart was carried out from 2 main aspects:

- causes and
- effects.

Other aspects of train breaks apart include:

- the distribution of coupling failure along the train,
- driving mode before train breaks apart,
- train speeds before train breaks apart,
- characteristics of trains that break apart (number of wagons, length and weight of the train), etc.

III. Results and analysis

4. FMECA risk assessment

The analysis of the risk of coupling failure showed that the RPN is the highest for component failure with the direct consequence of the train breaking apart. As the severity for all component failures is equal, the RPN depends on detectability and frequency. RPN value was limited at 250 according to the EN 50126 series standard [14, 15]. The most critical component failures were [16]: drawbar (RPN = 400), draw hook (RPN = 320), coupling links, screw and joint pin (RPN = 288), elastic device (RPN = 280), coupling head and hose and brake pipe (RPN = 256). Prime critical components have high frequency and low detectability in operation due to the inaccessibility of components in the preventive inspection.

5. Prediction of train breaks

Limitations of train breaks apart predictions are assigned data for particular railway vehicles and traffic conditions. For parameters change, the projection will not correspond to the attained data. The model of a prediction was made for train breaks apart of the operator "Serbia Cargo" in 2020, based on the breaks frequency from 2016 to 2019.

The average frequency of train breaks apart reduced to ton-km per year between 2016-2019 amounts to 0,0079 breaks/mil. ton-km per year [9, 15]. For the realized volume of 4,178 million ton-km freight traffic of "Serbia Cargo" in 2020, it can be predicted 33 cases of train breaks apart (**Fig. 2**). Only 24 cases in 2020 were registered. The reduction of train breaks number as much as 37% compared to the previous years is not unexpected, when it's known that decreasing trend is almost 28% for all accidents and incidents from 2010 [16]. The decrease in the number of trains breaking apart and the total number of accidents and incidents were only a partial effect of the decrease of 8% in traffic volume in 2020, compared to 2019.

Based on the presented data, it is the evident influence of the newly-formed Accident and incident analysis team within the safety management system of "Serbia Cargo" at the end of 2019. The team's focus was to re-analyze all accidents and incidents after submitting the final investigation reports. The team proposes improvement measures for increasing traffic safety. The establishment of an Accident and incident analysis team resulted in greater responsibility for all participants involved in the railway traffic. A decrease in the total number of accidents and incidents, and therefore train breaks apart, have an effect due to the implementation of measures and security recommendations of the team and the entire security management system.

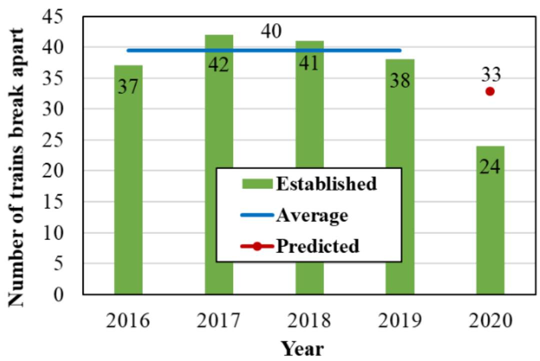

Figure 2. *Prediction of train break apart frequency*

6. Train breaks data analysis

The trains break apart is a result of coupling system failure. The official analysis of coupling system failure on Serbian railway, states that the cause of failure, in over 50% of cases, was the fatigue of material (**Fig. 3**), such as changed material structure, loss of connection parts, and other irregularities related to the material. Irregularities in driving are listed in 15% to 18% of cases as the cause of trains break apart [12]. Variations of train composition, tightness of screw coupling, as well as the vehicle condition make 9% to 20% of trains break apart causes. The increase of the material in the last ten years, as the main cause of coupling failures from 51% to 60% cases, considered independently, indicates that there has been a decrease in the quality of diagnostics in the maintenance of coupling systems.

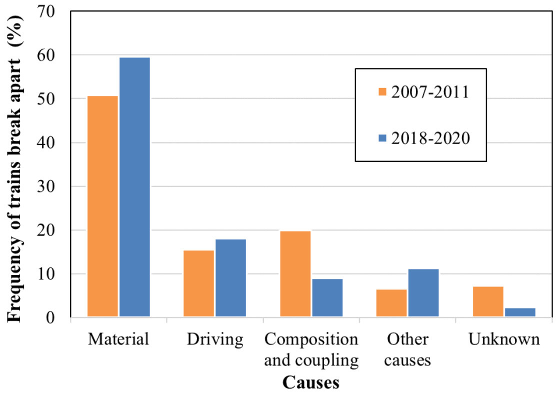

***Figure 3.** Causes of trains break apart*

In 55% cases the reason for coupling failures were parts of the draw gear and coupler in 37% of cases (**Fig. 4**). The failure of other parts was significantly less - about 8%. From 2018 the failure of draw gear elements has increased to 64%, while the failure of coupler elements has decreased to 27% [12].

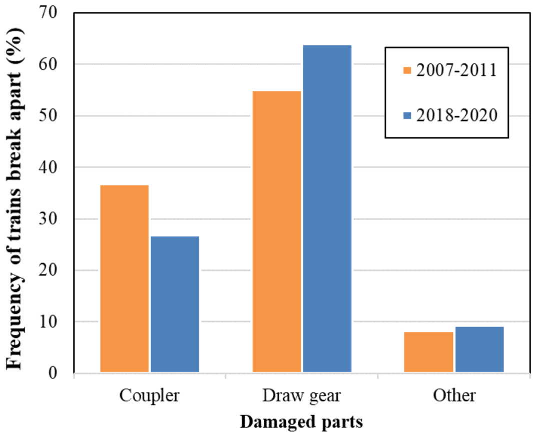

***Figure 4.** Damaged parts when trains break apart*

The consequences of the coupling failure and train breaking apart are direct costs of the material (spare parts and repair), but can also include indirect costs (delay of a broken train and other trains on the the line). Additional costs are related to traffic disruption and organizational change. From 2007 to 2011, the direct material costs of breaking trains apart were up to 1000 euro, and the traffic closure on the rail line section lasted on average 3 to 4 hours [9]. Similar was from 2018 to 2020, with direct material costs between 400 and 900 euros, and the traffic closure between 4 and 5 hours (**Fig. 5**) [9]. These consequences do not include the total costs of keeping trains and the engaged train route, which do not happen at every break, but can amount to 3000 euro and higher.

The conditions of technical inspection and the level of the technical quality of wagons in the exchange between railways in Europe are defined in Annex 9 of GCU. Annex 9 refers to all the damages caused by the accident, and new fractures (without fatigue signs), to inadequate handling of train by the railway operators. Therefore coupling failure can have significant financial consequences as all fractures during train breaks, in which there are no clear traces of fatigue, or wear on broken parts, are considered the responsibility of the railway operator.

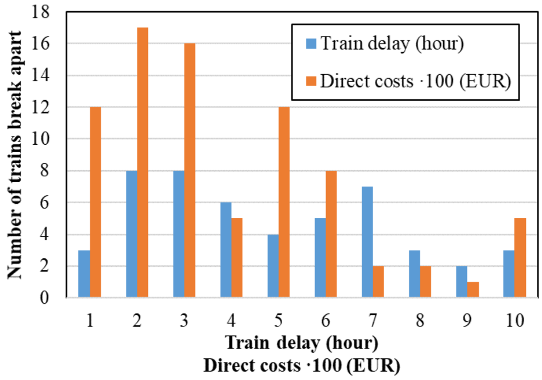

***Figure 5.** Train delay after the break*

A decade ago, as many as 59% of cases of coupling failure on freight trains were on the first third of the train length (**Fig. 6**) of which 26% are coupling failures between the locomotive and the first wagon, and 33% between the first wagon and the first third of the train length. Only 18% of train coupling failures were between the first and second third of the train length. A rather different distribution of coupling failure was in recent years, where in 38% of cases coupling failures were on the first third of the train length (Fig. 6), of which 16% are coupling failures between the locomotive and the first wagon. Almost 40% of coupling failures were on the second third of the train length compared to just 11% on the last third [9].

A large number of coupling failures between the locomotive and the first wagon leads to locomotive damage. Over 50% of damaged locomotives can't be repaired in operation, thereby increasing the expenses of the incident and can lead to traffic closure.

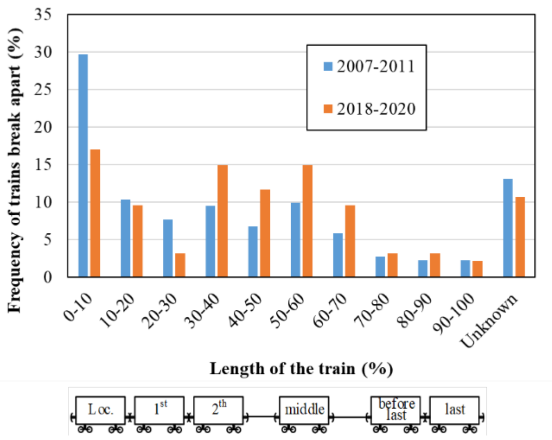

***Figure 6.** The distribution of trains break apart along the train*

Coupling failure between the locomotive and the first wagon mostly occurs during traction, while other cases mainly occur during braking or changing of direction. From 2018 to 2020 decrease in the number of coupling failures in the front part of the train, and increasing in the middle of the train (**Fig. 6**), was caused by a larger number of coupling failures during maneuvers (pushing) that were taken into account.

Braking, from all driving modes, has the most significant effect on coupling failures, mostly due to large longitudinal forces, and from 2007 to 2011 caused 56% of cases of failures. In recent years, from 2018 to 2020, the effect of braking as the cause of coupling failures decrease to 41% (**Fig. 7**). Pulling has same effect on coupling failure (20% to 23%), while maneuvering caused more coupling failure recently [12].

Ten years ago coupling failure mostly occurred at train speed between 10 and 20 km/h (34% cases - **Fig. 8**) [9], while recently most coupling failures occurred at speeds up to 10 km/h (39%). The number of coupling failures decreases with increasing speed, so as many as 58 ÷ 65% of coupling failures occur at speeds less than 20 km/h (**Fig. 8**) [12].

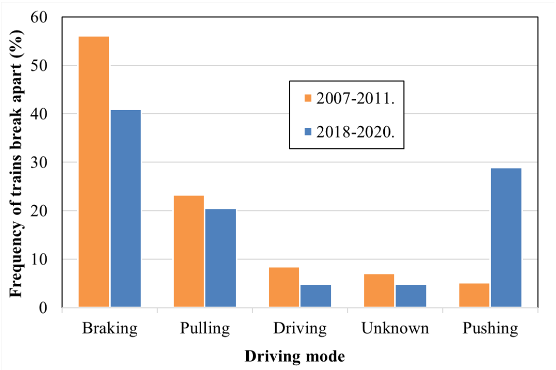

Figure 7. *Driving mode before trains break apart*

Almost 50% to 70% of train coupling failures occur in the station area or switchyards because of a more frequent number of starts and stops (therefore traction and braking), which implies low speeds in stations and nearby.

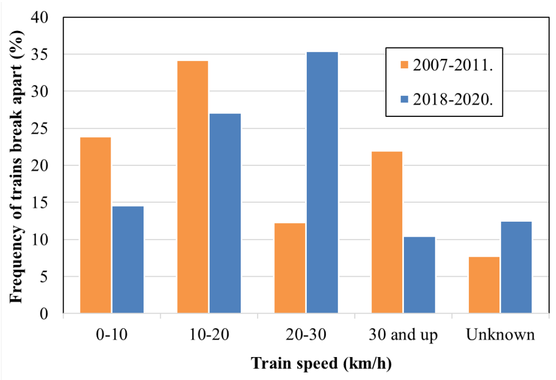

Figure 8. *Train speed before trains break apart*

The frequency of coupling failure can be influenced by train parameters, like the number of wagons, the length and weight of the train, the state of loading, the schedule of loaded and empty wagons in the train, and others. The coupling failure occurs in freight trains with a small number of wagons (8 to 15) and a large number of wagons (43 to 51). In the last few years coupling failures occurred most frequently in trains with 20 to 35 wagons (**Fig. 9**).

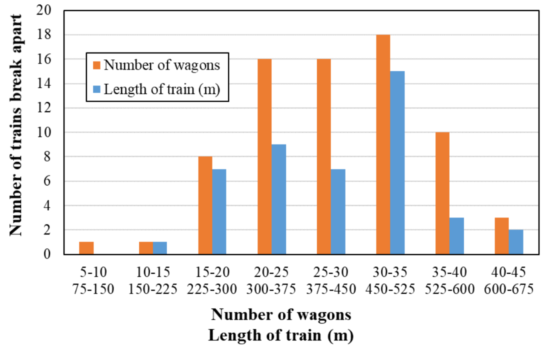

Figure 9. *Number of wagons and length of trains of trains break apart*

Consequently, as average freight train in the last ten years had 26 to 27 wagons [9], length of broken trains ranged from 152 m to 720 m. The average length of trains breaking apart was about 400 m. It can be concluded that the frequency of train coupling failure increases with train length over 500 m (**Fig. 9**).

The masses of trains that have coupling failure range from 336 t to 2333 t (**Fig. 10**). The average gross weight of one train in 2009 was 926 t [9], and of a train that break apart 1354 t, similar to the last few years.

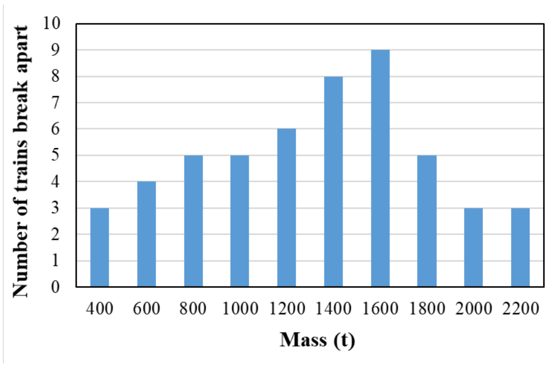

Figure 10. *Mass of trains break apart*

The frequency of coupling failure is somewhat higher for trains with all loaded wagons (27%) related to 16% for trains with all empty wagons. Trains with diverse lodes (both loaded and empty wagons) have 25% frequency of coupling failure, but in almost a third of cases loading data were not available.

IV. Conclusions

The cause of the train breaking apart is coupling failure. Separated parts of the train are automatically stopped, but failure could lead to an increase in stopping distance and passing through a signal or crossing. Although it seems that consequences of coupling failure have relatively low severity in everyday practice, as a safety precaution, all measures must be applied to reduce causes of train break apart. Taking measures to reduce or eliminate the causes of coupling failure is to manage the risk of the train breaking apart usually by preventive maintenance, quality, design and operation.

The characteristics of train coupling failure observed over a decade show a decrease of locomotive damage and frequency of coupling failure in the front part of a train, as well as an increase of coupler and draw gear fatigue. Since coupling and draw gear are standard constructions, and also inspected with regular maintenance, the percentage of failure caused by material fatigue is extensive. Significantly, the frequency of coupling failure due to train driving has not decreased.

To increase the safety of railway traffic, monitoring and analysis of common safety indicators must be performed. Risk assessment should be performed by the railway infrastructure management or railway undertakers and through the review of changes in the railway network and analysis of railway safety in the previous period and the need to implement measures to reduce risk.

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AUTHOR CONTRIBUTIONS

M. Vukšić Popović: Conceptualization, Data analysis, Finite element modelling, Writing.

J. Tanasković: Review and editing, Supervision.

Z. Starčević: Data collection and analysis, Review and editing.

N. Međedović: Data collection and analysis, Review and editing.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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