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Original

Controlling the train car's center of gravity (COG) position based on train load levelling

S. Sugiono[a]* • W. S. Nugroho[b] • E. Wiryawan[c] • O. Oktavianty[a] • D. H. Sulistyarini[a]

[a]Dept. of Industrial Engineering, Brawijaya University, Malang 65145, Indonesia
[b]Dept. of Mechanical Engineering, Brawijaya University, Malang 65145, Indonesia
[c]PT. Industri Kereta Api (INKA), Madiun, Indonesia

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Abstract: The dynamic center of gravity (COG) shift of a train car affects the train's running stability. Loss of running stability results in derailments and overturns. This study proposes a novel ticketing algorithm as an effort to prevent derailment and overturn. The algorithm limits the freedom for passengers in seat choosing. Instead, the passengers will be offered recommended seat positions that account for a minimum COG shift. The novel ticketing algorithm implementation was evaluated in comparison to the existing ticketing algorithm and safety-as-priority (SAP) algorithm. Each algorithm implementation was evaluated and compared analytically through a numerical simulation approach. The dynamic COG shift on a few loading scenarios was evaluated using COG loading shift and COG shift. COG shift evaluation shows novel algorithms have smaller shifts than existing algorithms but still bigger than SAP algorithm. The loading shift showing the loss of balance during iterative load addition and load reduction has been reduced through SAP and novel algorithm implementation. In the tested loading scenarios, the Existing algorithm shows (x=2.60x10^{-5},-z=3.41x10^{-5},y=6.17x10^{-5})% shift while SAP shows (x=1.28x10^{-5},-z=-2.40x10^{-5},y=2.36x10^{-5})% and novel algorithm shows (x=1.60x10^{-5},-z=3.07x10^{-5},y=5.34x10^{-5})% Cog shift. The result suggests that the novel algorithm has made it possible to maintain train running stability while considering the passenger needs. Hence, the running safety of a train can be altered without sacrificing passenger satisfaction.

Keywords: center of gravity (cog), load configuration, ticketing algorithm, derailment

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*Corresponding author.
E-mail address: sugiono_ub@ub.ac.id (Sugiono Sugiono).
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1. Introduction

The increase in life quality has raised more concerns about the health and safety of public transport. Railway transport is popular mass transportation in Indonesia. Accidents in railway transport frequently caused many casualties. Within the last 10 years, the Indonesian railway department has reported 36 accidents of the commercial train. Of all the accidents, only one is fatal. The fatal accident was the 2nd Bintaro tragedy on December 9, 2013. The accident was a result of a collision between a train and a petrol truck (Departemen Perhubungan, 2020). However, such accidents rarely happen. Notwithstanding the severity of the accident, the frequent railway transport accidents indicate a lack of attention to safety in railway transport.

The data of Indonesian railway transport and the U.S Federal Railroad Administration (FRA) share a common. Both showed the most railway accidents were derailed trains. One-third of Indonesian commercial railway accidents are train derailments (Departemen Perhubungan, 2020). While the FRA data showed that almost 53% of U.S. railway accidents were also train derailments (FRA, 2020). More than 70% of U.S. railroad industry accident cost was spent annually for train derailment (Bridgelall & Tolliver, 2021). Train derailment is a condition where a train is out of the rail in the middle of the trip. Many factors can be presumed when a train derailed. In a 2012 study by X. Liu, the derailment causes were classified based on speed. As a result, track condition is the major contributor to train derailment in all speed classes. In the higher speed class of 25-40mph and 40-80mph, the lading problem is not listed as a contributed factor in a train derailment. However, the lading problem is always listed as a contributed factor in a derailment in the lower speed class. The lading problem contributes to more than 25% of train derailments in the speed class of 10-25mph (Liu et al., 2012). Therefore, this study evaluates track condition and lading problem as a correlated factor of a train derailment.

A fundamental view of a mechanical phenomenon is required to see the correlated factor as a unit. Train derailment occurs due to the roll moment being higher than the stabilizer moment. The roll moment is the centrifugal force that works on the center of gravity (COG). Stabilizer moment is the centripetal force directed towards COG. A train car is stable when the roll moment magnitude is lower than the stabilizer moment. If the roll moment is greater than the stabilizer moment, the train had a greater overturn chance. In the middle of both conditions, there is a critical condition when both moment magnitude equal (Matsumoto et al., 2016). In a condition so-called critical point, speed is a determining factor (Kausel et al., 2020). Hence, the critical condition can be maintained by avoiding Overspeed and setting a higher critical speed limit.

The critical condition occurred when the quasi-static response of the track changed to the dynamic response as the speed increased. The dynamic response is the generation of the surface seismic wave that propagates vibration throughout the entire train body (Kouroussis et al., 2014; Norén-Cosgriff et al., 2018). This vibration applies forces in various directions and magnitudes to the wheel flange. The lateral-to-vertical (L/V) force ratio of a wheel flange is modified by those forces (Wicaksono et al., 2019). As a result, the wheel angle of attack (AOA) changes dynamically during running. Moreover, the axial force and AOA get bigger during the sharp curve. As this happens, the flange may climb to the sideway of the track making the train derail. This phenomenon is called flange climbing derailments (Matsumoto et al., 2019). The change of L/V ratio and AOA is uncertain and uncontrollable during running. Therefore, the train running stability depends on external factors. Load configuration is one of the factors that affect train running stability (Li et al., 2016). However, load configuration is commonly neglected in a passenger train. In this study, the passenger and luggage load configuration effects on a train running stability will be analyzed.

This study proposes new flange climbing derailment prevention by controlling COG based on load levelling. The load that levelled consists of passenger and luggage load. Therefore, the new ticketing algorithm that prioritizes safety is needed to plan the load-level configuration. This study also proposes a novel ticketing algorithm that prioritizes safety but also notices passenger comfort. The seat positions are recommended by the system based on minimum COG shift percentage, passenger group, and passenger special needs. Accordingly, the passengers are still able to choose seats in a limited fashion. The effectiveness of the novel algorithm will be evaluated analytically in comparison with the existing ticketing algorithm and the safety as a priority (SAP) algorithm. The vertical to lateral load ratio will be used to assess running quality by taking the weight distribution of the loaded car into account.

2. Materials and methods

2.1. Ticketing system development

In this study a novel ticketing algorithm that balanced the individual needs of each passenger with train safety was developed. The effectiveness of the algorithm was compared to the SAP algorithm and the existing algorithm. The existing train ticketing algorithm consists of simple steps for the passengers to buy train tickets as shown in Algorithm 1. There were no safety requirements listed on algorithm 1.

As the opposite of the existing ticketing algorithm, the SAP algorithm was fully prioritizing safety over passenger needs. Thereby, the passengers do not have the right to choose a seat. As seen on Algorithm 2 the COG shift optimizer will find a seat for a passenger. The only control that a passenger has was the seat confirmation before payment.

Algorithm 1. Existing train ticketing algorithm

```
1. Passenger choose train
2. Passenger see the available seat
3. Passenger pick a seat
4. Passenger pay and confirm the seat
```

Algorithm 2. Safety as priority algorithm

```
1. Passenger choose train
2. Passenger pick a train
3. COG shift optimizer find the best scenario to add a new passenger
4. Passenger confirm the seat and pay
```

In between the flexible existing ticketing algorithm and the rigid SAP algorithm, a balanced ticketing algorithm was developed as in Algorithm 3. The novel algorithm was designed to maintain flexibility for the passenger to choose seats. However, the flexibility was reduced due to the COG shift optimization. The COG shift must be minimized as in the SAP algorithm.

Algorithm 3. Novel algorithm

```
1. Passenger choose train
2. Passenger list the preferences and special needs
3. If a passenger come in a group set a passenger as a reference point run space reservation algorithm
4. COG shift optimizer find the best scenario to add new passengers
5. Match the scenario with the preferences
6. Passenger confirms and pay
```

The seat reservation technique on the Novel algorithm for a passenger that comes in a group must be able to place them in a narrow distance. The placing distance was prioritized over COG optimization. Hence, Algorithm 4 was placed prior to COG optimizer in algorithm order on Algorithm 3. The ticketing algorithms were evaluated analytically through vector calculus analysis on some loading scenarios.

Algorithm 4. Space reservation algorithm

```
1. Find cars with available seats more than the space needed
2. For each car check the seating order (check seat distance) distance = seat number referenced – seat number reference
3. Pick a car with the best seat order. With minimum closest order
```

2.2. Railcar body stability analysis

The train running safety with the loading protocol based on the existing algorithm, SAP algorithm, and novel algorithm were compared. The comparison variables are railcar COG response to iterative loading shift and the COG shift percentage. The COG shift simulation was performed by creating three loading scenarios using each algorithm. The model used in the simulation was depicted in Figure 1. The model was an Indonesian economic railcar model. The rectangle form of the wagon shown in Figure 1 indicates the COG was located at the center. The distance of a point in Figure 1 to the COG position was determined using considerations in Table 1. The angles relative to COG were determined using the radial arc in the center of Figure 1. The COG was modelled in 3D space using a standard vehicle coordinate system. The vehicle system coordinate axes comprised of x for longitudinal, z for vertical, and y for lateral (Cai et al., 2011). Therefore, the shift calculations were performed on the x, -z, and y axes. All passengers were considered to have 70kg body mass in 9.821m.s^{-2} gravity acceleration loaded on a 41-ton railcar.

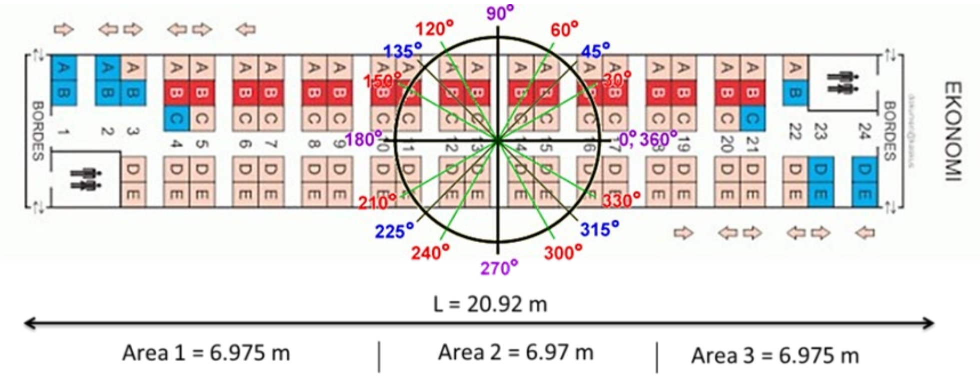

Figure 1. Train model used in the simulation.

The effect of load addition on a railcar body on the train stability was determined analytically using iterative COG shift analysis. The COG was modeled as a sphere in a three-dimensional space. The initial COG was in the center of the railcar due to its square block morphology. As a load was added, the COG was shifted towards the load. Otherwise, as a load was removed the COG shifted towards its initial position (Sharma & Kar, 2021). These are mathematically formulated in Equation 1 and Equation 2. The shift percentage relative to initial COG has also been calculated using the formula in Equation 3. The COG shift was calculated for every coordinate. The COG on each coordinate was considered as a unit vector. To obtain the total shift magnitude along with its direction, Equation 4 was employed. All calculations were performed iteratively except for the vector length.

Table 1. Figure interpretation agreement.

Figure Interpretation Agreement		
seat width (m)	0,4	
seat before (m)	13	5,2
space [between seats] (m)	6,5	
half-length [L/2] (m)	10,46	5,26
space width [vacant space on seat] (m)	0,809231	0,809231

$$COG = \frac{Wd}{W+w}\ [m] \qquad (1)$$

$$COG = \frac{Wd}{W-w}\ [m] \qquad (2)$$

$$Shift = \frac{COG_t}{COG_0}\ [\%] \qquad (3)$$

$$\overline{COG} = \sqrt{(COG_x)^2 + (COG_{-z})^2 + \left(COG_y\right)^2} \qquad (4)$$

The COG iterative loading shift and the percentage of COG shift were evaluated on predefined scenarios. The iterative COG calculation was performed each time the passenger was added to the train. This condition is called passenger loading. There are 45 passengers loaded onto the train in each scenario. Each scenario corresponds to each algorithm. The scenario for the existing algorithm was every passenger prioritizing seats around the window. Therefore, the seats next to the windows were loaded first. The SAP algorithm does not affect any scenarios because it only had one order to load the passengers. The SAP algorithm load order was through the nearest point to the COG. The nearest point to the COG in the corresponding railcar model was at the center. The scenario for the novel algorithm was the passengers prioritizes grouping. The passengers were considered to come in inseparable groups such as family, partners, or friends. Thus, the scenarios were evaluated to assess the developed novel algorithm.

3. Results

3.1. The effect of passenger load configuration on COG shift

The passenger load contribution to the COG shift was evaluated based on COG shift percentage. The run of each scenario results in simulated seat choice by the passenger. Tables 2, 3 and 4 are used to present the result of simulated seat choices for every scenario. The simulated seat choices of the existing algorithm are presented in Table 2. Each table consists of a No. column to represent the passenger number and a seat column to represent the picked seat.

Table 2. Existing algorithm seat choice.

Existing Algorithm Seat Choice									
No	Seat	No	Seat	No	Seat	No	Seat	No	Seat
1	1A	10	10A	19	19A	28	8E	37	17E
2	2A	11	11A	20	20A	29	9E	38	18E
3	3A	12	12A	21	21A	30	10E	39	19E
4	4A	13	13A	22	22A	31	11E	40	20E
5	5A	14	14A	23	3E	32	12E	41	21E
6	6A	15	15A	24	4E	33	13E	42	22E
7	7A	16	16A	25	5E	34	14E	43	23E
8	8A	17	17A	26	6E	35	15E	44	24E
9	9A	18	18A	27	7E	36	16E	45	7C

Differing from the existing algorithm, the SAP algorithm chooses a seat for a passenger. The only consideration is the minimum COG shift. Therefore, the SAP simulated seat choice result in Table 3 has a narrower configuration than the simulated choice of the existing algorithm in Table 2. The first 40 passengers were placed close one to another around the center of the railcar. The rest 5 passengers were placed symmetrically by placing on top-left followed by bottom-right, followed by top-right, and followed by bottom-left.

The novel algorithm was developed to prioritize safety but also take every passenger's needs into consideration. Therefore, a novel algorithm limits the passenger seat choices but does not restrict the passenger to choose a seat if they have special needs. Hence, the result of the novel algorithm simulated choice in Table 4 has shown no difference with the SAP algorithm. The only difference is the last 4 passenger placement. This is due to the group prioritizing scenario that considers a group of a passenger is inseparable. It is shown that passenger no. 41 and 42 along with passenger no. 43,44, and 45 have come in a group. Therefore, they cannot be placed apart from each other. This kind of special need was prioritized in this simulation over the COG shift minimization.

Table 3. SAP Algorithm seat choice.

SAP Algorithm Seat Choice									
No	Seat	No	Seat	No	Seat	No	Seat	No	Seat
1	10A	10	11B	19	12C	28	13D	37	14E
2	11A	11	12B	20	13C	29	14D	38	15E
3	12A	12	13B	21	14C	30	15D	39	16E
4	13A	13	14B	22	15C	31	16D	40	17E
5	14A	14	15B	23	16C	32	17D	41	9A
6	15A	15	16B	24	17C	33	10E	42	9E
7	16A	16	17B	25	10D	34	11E	43	18A
8	17A	17	10C	26	11D	35	12E	44	18E
9	10B	18	11C	27	12D	36	13E	45	9B

Table 4. Novel algorithm seat choice.

Novel Algorithm Seat Choice									
No	Seat	No	Seat	No	Seat	No	Seat	No	Seat
1	10A	10	11B	19	12C	28	13D	37	14E
2	11A	11	12B	20	13C	29	14D	38	15E
3	12A	12	13B	21	14C	30	15D	39	16E
4	13A	13	14B	22	15C	31	16D	40	17E
5	14A	14	15B	23	16C	32	17D	41	9A
6	15A	15	16B	24	17C	33	10E	42	9B
7	16A	16	17B	25	10D	34	11E	43	8A
8	17A	17	10C	26	11D	35	12E	44	8B
9	10B	18	11C	27	12D	36	13E	45	8C

The final COG shift percentage (the 45th iteration) has shown a significant difference of each passenger loading scenario on COG shift in every coordinate. The numerical simulation results were summarized in Figure 2. The existing algorithm shows the biggest COG shift percentage on all coordinates. As the reverse, The SAP algorithm shows the smallest COG shift on all coordinates. The longitudinal (x) and vertical (-z) shifts on Novel algorithm implementation were modest. However, the lateral (y) shift was as significant as the existing algorithm.

The significance of each algorithm implementation effect on COG shift reduction was analyzed further by finding the vector length of the final COG shift in 3D space. By taking x, -z, and y shifts in Figure 2 as unit vectors, the vector length was calculated using Equation 4. The vector length calculation result is presented in Figure 3. The vector length calculation collapses the unit vector direction into a single direction with a corresponding length (Bollen et al., 2017). Hence, the vector length of COG shift will be used as a guide to determine the railcar heading direction propensity. The vector length of the existing algorithm is the largest among all passenger loading algorithm implementations. The novel algorithm implementation has reduced the COG shift magnitude but still has a higher shift than the SAP algorithm.

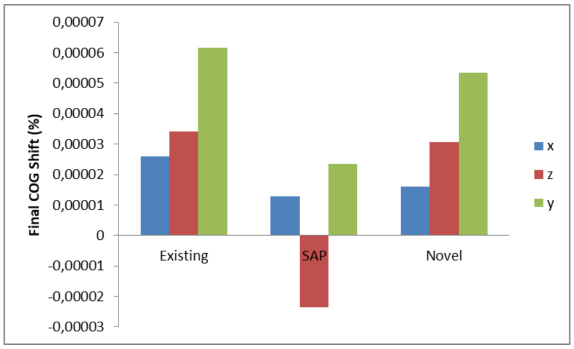

Figure 2. COG shift percentage on the last iteration.

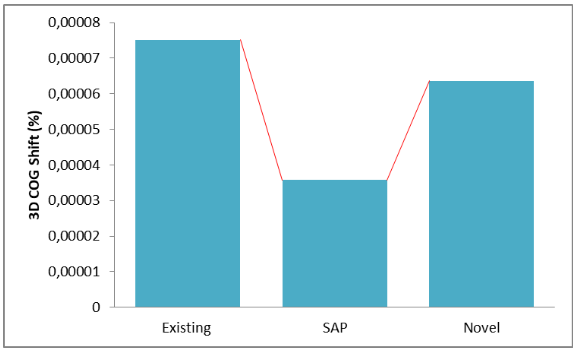

Figure 3. COG shift-vector length.

3.2. The effect of Loading on railcar COG shift

Besides the effect of the passenger loading on the final COG shift, the iterative loading shift pattern was also analyzed. This pattern shows the effect of load addition and load removal from a railcar. The effect of a load addition on vertical COG shift can be interpreted by reading the surface diagram in Figures 4(a), 5(a), and 6(a) from right to left. For load removal, the diagram can be read in the reverse direction. The lateral COG shift can also be interpreted by looking from the top view of the surface diagram in Figures 4(b), 5(b), and 6(b). Both vertical and lateral iterative loading shifts are valuable to explain the effect of each algorithm on railcar stability.

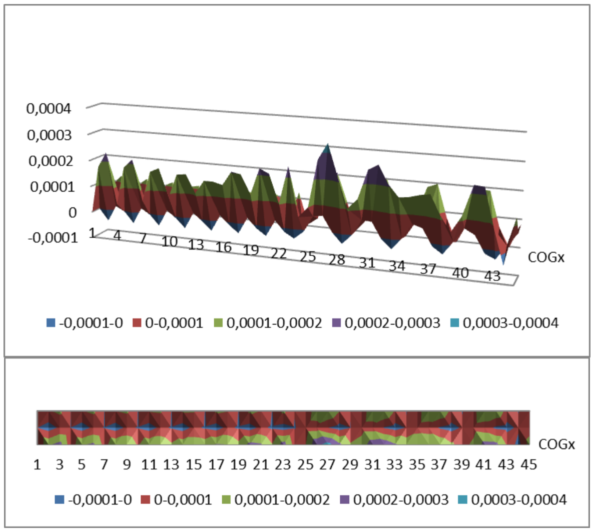

Figure 4. Existing algorithm COG Iterative shift: (a) vertical, (b) lateral.

The passenger prioritizing windows scenario which is simulated using the existing algorithm has made the passenger fill the seats next to the window first. This indicates the random seat occupation through existing algorithm implementation. The effect of the implementation of the existing algorithm was clearly depicted by its iterative loading shift in Figure 4. The surface diagram in Figure 4(a) shows the loading of passengers 26 to 28 has the biggest impact on vertical COG shift. Meanwhile, Figure 4(b) shows that the load addition has incrementally shifted the lateral COG. This is indicated by the blue region in the middle of Figure 4(b) that gets wider as the passenger loaded onto the train.

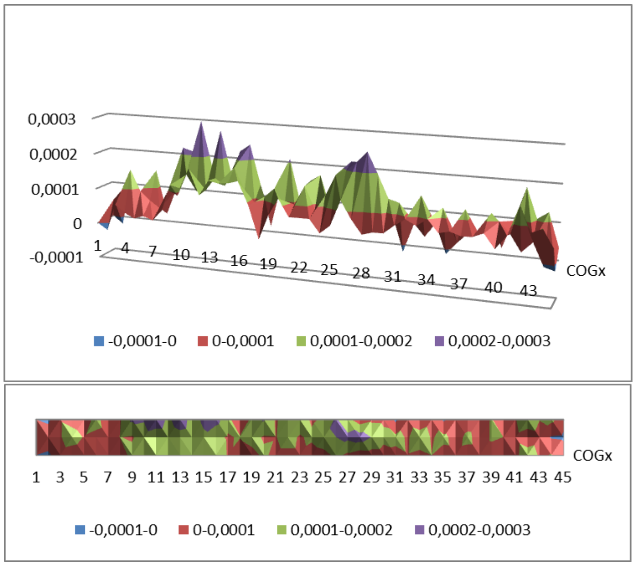

Figure 5. SAP algorithm COG Iterative shift: (a) vertical, (b) lateral.

The SAP algorithm has a significant impact on keeping the COG shift in the vertical and lateral directions. This can be seen based on the vertical shift magnitude of the COG. The largest vertical shift of the SAP algorithm was smaller than $3x10^{-5}$m which smaller than the largest existing algorithm vertical COG shift (see Figure 5a). There was also no significant lateral COG shift that occurred due to SAP algorithm implementation.

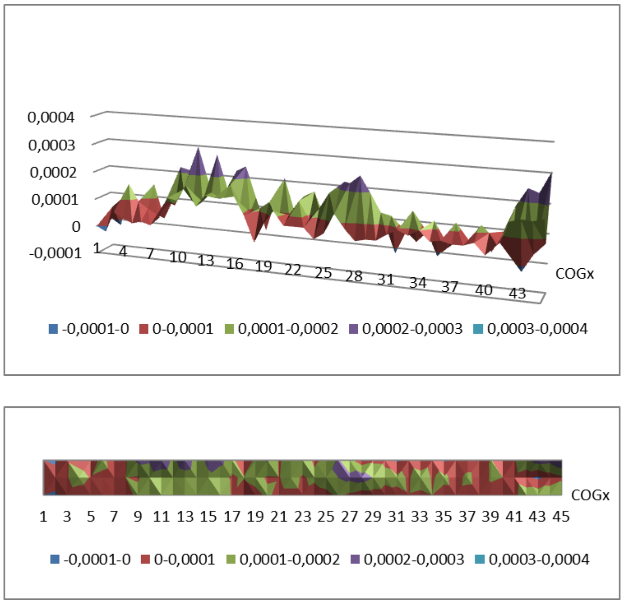

Figure 6. Novel algorithm COG Iterative shift: (a) vertical, (b) lateral.

The novel algorithm iterative loading shift pattern has a similar fashion to the SAP algorithm. The only difference was on passenger 41 to 45 loading due to the group policy. The peak of vertical COG shift was on the loading of passenger 45 (see Figure 6a). In Figure 6(b) the lateral shift also had a similar fashion with the SAP algorithm except for the passengers 41 to 45. The lateral effect was started to be seen on the 43rd passenger loading. The shift lateral cog shift value was larger than $3x10^{-5}$m which is the biggest among other passenger loadings.

4. Discussion

The numerical simulation of a railcar loading through the implementation of a newly developed novel algorithm has unveiled the impact of passenger loading order to train running stability. Analysis of the COG shift, COG vector length in 3D space, and the iterative loading shift has been employed to evaluate the algorithm implementation. The results have a possibility to unlock new factors that define train running safety and train running quality. There are many factors that affect train running safety. COG stability is one of the most important factors that define train running safety (Chung et al., 2019).

The numerical simulation result has shown that the COG shift is controllable by proper load configuration. The only way to control and minimize the COG shift is by using a strict loading configuration. This has been proved by SAP algorithm implementation. The COG shift, COG vector length, vertical, and lateral COG iterative loading shift are the minimum among all loading configurations. Therefore, the SAP algorithm is the best algorithm to be implemented in freight train loading or cargo loading. The application of the SAP algorithm for human passenger ticketing needs further evaluation.

The SAP algorithm may be the best algorithm to minimize the rollover or derailment risk, but it has interference with the passenger needs. The interference of strict protocol or rules with a human has a psychological impact on a person. The feeling of restraint possibly increases the abandonment of the passenger to the specified rule (Wang et al., 2020). Hence, the specified ticketing system must be provided with flexible protocol. The developed flexible protocol must be in line with the emotional and physical side of a human being. Because, each person has an emotional need and physical need that is expected to be fulfilled by the public transport provider (Camacho et al., 2017). Thus, more evaluation of the railway operation pattern that is expected by the most passengers in an area is needed.

Besides the basic emotional and physical needs of a human being that are owned by a passenger, every passenger comes with their special needs. A simple example of this need is a passenger with a common illness. An example of a common illness is metabolic syndrome, 20-25% of adults in the world are exposed to metabolic syndrome (Saklayen, 2018). Some people with metabolic syndrome also have nocturnal polyuria or nocturia (Ohishi et al., 2021). Nocturia is the condition where a person frequently urinates more than a normal person (Robinson & Suman, 2018). Consequently, the humanist approach to this problem is to allow people with nocturia or similar special needs to choose a seat near the toilet. This will be interpreted as an understanding for a passenger. The understanding is interpreted as a kindness for most people (Wang et al., 2014). Hence, to ease the passenger by providing their needs has the same effect of showing kindness to them.

Another psychological impact to be considered is a group of passengers. The separation of a passenger from a group will result in disappointment. Passengers are the consumers of the railway transport company that expect good service. A disappointment of a consumer reflects the bad quality of the provided service (Grujičić et al., 2014). Consequently, the implementation of the SAP algorithm on a passenger train will reduce the service quality of the railway transport company. Even more, the passenger that comes with a family group is more inseparable. Most of the time, a family group consists of infants, toddlers, pregnant mothers, elders, and some people that need support. The physical impact that can be seen is they need support from their family member or their occasional supporter. Support from a stranger or unusual supporter that does not know their usual needs may reduce their satisfaction (Jarling et al., 2018). Also, a missing member of a family especially kids or elders is triggering panic situations among family members (Jo et al., 2020). Therefore, based on psychological consideration SAP algorithm is not suitable to replace the current existing ticketing algorithm.

Despite the psychological analysis, the iterative loading shift has uncovered the great potential of the novel algorithm to maintain the train stability. The novel algorithm still reduces the COG shift significantly even when allowing the passenger to come with a group. The iterative loading shift also implies the small difference between the SAP and the novel algorithm implementation. This makes the novel algorithm effective to maintain train running stability. In conjunction with that, the COG shifts due to the passenger load configuration were insignificant to derail the train in normal conditions. The values of the COG shifts were small enough to be neglected daily operation (under 4 significant figures). However, in some conditions, the small COG shift may trigger accidents. The extreme overturn with a sharp angle of attack on wheels may result in an excessive lateral force that causes derailment (Wu & Wilson, 2006). Therefore, COG minimization is needed to face such extreme cases.

Based on the numerical simulation using various passenger loading scenarios and with the accordance of the psychological analysis, the novel algorithm is the best algorithm to be adopted as a replacement of the current existing algorithm. However, this study also has a limitation. The use of numerical study with a single predefined scenario is a major drawback to evaluating the implementation of each algorithm on COG shift minimization. Despite that drawback, this study has eliminated the SAP algorithm for future evaluation of COG shift on a train with human passengers due to its rigidity. Further evaluation of novel algorithm implementation on running safety and running quality also must be conducted in the future. Thus, this study successfully develops a railcar loading protocol that balanced the trade-off between transport safety and service quality.

5. Conclusions

The newly developed novel train ticketing algorithm has the potential to increase train running safety without sacrificing its service quality. The train running safety evaluation was determined through numerical simulation with predefined scenarios. The service quality was evaluated through psychological analysis. SAP algorithm favors the train running safety by providing the smallest COG shift. However, its rigid nature has made it inapplicable for the human passenger train. The novel algorithm is the best choice to replace the current existing ticketing algorithm due to its flexible nature. The novel algorithm prioritizes passenger needs over COG minimization. Thus, the development of a passenger loading protocol that balanced the train running safety and the railway operation service quality is possible.

Conflict of interest

The authors have no conflict of interest to declare.

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