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Feasibility of a kneeling train to improve Platform-Train Interface (PTI) for passenger boarding and alighting

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Abstract: Railway operators and infrastructure companies strive to optimise the flow of passengers on and off vehicles whilst aiming to minimise accidents at the Platform-Train Interface (PTI). An ideal solution (already available in some situations) would be a step-free access to aid efficient boarding for everyday passengers and those with additional needs or reduced mobility. Out of many solutions existing today, a 'kneeling vehicle' seems a possible solution due to the opportunity to minimise the step and gap distances. In this paper, the viability of an assumed kneeling mechanism retro-fitted to a contemporary suspension architecture is assessed by evaluating the possible improvement in the step/gap distances based on a detailed model of suspension movement. It is shown that for many different infrastructure scenarios that significant improvements in the PTI are shown for a modest and achievable kneeling action. This paper also address fundamental operational concerns of a kneeling vehicle by assessing gauging (with respect to infrastructure and adjacent vehicles) and pantograph interaction.

1 Introduction and Scope

There is an ongoing trend to improve step-free access throughout UK rail infrastructure to improve customer experience by enabling both more effective 'flow' of people, and ease of access for Persons with Reduced Mobility (PRM) [1],[2],[3]. This has been supported by large investment from councils, operating companies and infrastructure managers throughout the network to achieve these goals. Through schemes such as "Access for all" introduced in 2005, 55% of stations in UK are estimated to provide step free access by 2020 [1].

Despite these investments, there remains an operational challenge at the Passenger Train Interface (PTI) where there continues to be an inconsistent experience to users in terms of the sizes of vertical step and horizontal gap to board the train. Out of surveyed stations in [1], 33% of platforms have either step and/or gap greater than 25 cm.

The properties of the PTI is perceived to have a direct effect on the rate of boarding and alighting of passengers. The movement of people on and off vehicles can be complicated by additional items such as luggage, bicycles and pushchairs. Wheelchair users infer extra requirements for boarding in terms of supporting equipment (i.e. accessibility ramp) as guided by [3] and attention from station personnel to facilitate boarding or alighting.

The ambition of seeking to improve the experience at the PTI is to ultimately reduce the dwell time of vehicles at the platform edge in order to optimise network capacity. As this is a fundamental problem in the rail industry, solutions have already been considered and implemented. A pragmatic solution to the problem would be to standardise the standing height of all platforms throughout the network such that vehicles could be designed with tighter tolerances to the platform edge. Although possible in metro systems where the vehicle and platform are often owned by the same operator, A study produced [4] concluded that the cost of rebuilding existing platforms far exceeded the potential benefits. The natural extension of this idea is to raise sections of platforms, as seen in 'Harrington Humps' throughout the UK [5], or even use actuated platform sections that can be raised to meet the vehicle, as in certain sections in New York and Hong Kong [6]. The challenge with these systems is

to ensure the raised sections match the stopped locations of doors in train bodies that are far from standardised across manufacturers, and are subject to change with variations in rolling stock. This could only be partially solved by recent introduction of automatic train stopping systems into the market.

A further solution that are used in some mass transit applications are platform mounted flexible gap fillers. Here, a brush or elastomeric type material is installed that is flexible enough to compress against the vehicle body but have suitable rigidity for passengers to place weight on. Such installations have previously been proposed through patents [7] and [8]. The idea has been extended to active gap filling mechanisms [9] where the interface material can be retracted for passing trains, or presented to stationary vehicles to aid boarding and alighting. As previously concluded with the concept of correcting platform heights, the efficacy of these systems is dependant on the precision with which they are located to the stationary vehicle, and the conformity based on variation of vehicle type.

The different solutions highlighted in which deployable structures in platforms are mounted can lead to large cost estimates when the number of platforms and the overall length of instalment are considered. Hence introducing new technologies in a vehicle has potential to be relatively more cost effective where specific routes of optimum benefit can be targeted. Opportunities for mounting components on the vehicle to aid boarding and alighting for passengers have been presented in a number of scenarios. For example, concepts such as a deployable gap bridging system [10] or forms of train mounted horizontal gap fillers [11] have been investigated.

A final option to be considered is to physically move the vehicle toward the platform to reduce the step and gap, as is now commonplace in bus and coach transport [12, 13]. Manipulating the position of a rail vehicle is not commonplace, but there have been scenarios where this has been implemented. An example is the active lateral suspension which has been actively researched for many years ([14–17]). Though this mechatronic solution is aimed at better stability during cornering, the technology can be referred to moving the vehicle body for improving PTI.

Specifically with regards to the PTI, [18] explains actively tilting an omnibus to reduce boarding offset and minimise energy wastage.

Furthermore [19] describes a rail vehicle suspension system capable of being lowered to facilitate entry and exit when the train is at rest whilst assuring normal suspension operation when the train is moving. This invention presents an augmented suspension system with an uniaxial cylinder along with the springs thereby improving only the vertical step. The horizontal gap is not addressed with such a system.

However, implementing some form of kneeling functionality with secondary suspension of the train could interfere with its braking and suspension subsystems. Since the two subsystems use the same compressed air source, utilising it for another new functionality leads to a scenario where the safety is at risk. Hence a separate subsystem to kneel the vehicle is essential.

Future vehicle design trends would suggest a move away from the current use of pneumatic systems [20] and that a traditional passive suspension systems will be replaced with active or semi-active suspensions for improvement in performance. Studies such as [21] and recently [22] highlight the benefits of mechatronic solutions that can be found by adopting disruptive technology in the secondary suspension, or using only a single stage of suspension. A move to this technology would allow more flexibility in the control of movement and enable kneeling easily.

Kneeling trains could provide a good alternative for improving the PTI. Since using secondary suspension in a train would risk safety and other dependent functionalities, a stand-alone system should be developed to kneel a train. Considering the fact that tilting trains already exist, augmenting such a system for better boarding and alighting is a more feasible solution to a better PTI.

The concept of kneeling train could add more potential benefits as listed below [23].

- The train adapts to differing vertical and horizontal platform offsets,
- Existing train suspension resources can be utilised,
- Changes to existing rail infrastructure can be minimised,
- Other PTI solutions such as platform gap fillers could be combined.

Although literature shows that physical vehicle movement is possible, there is little assessment regarding the viability of such an action. This article aims to assess the feasibility of kneeling or tilting a train towards the platform for improved accessibility. The focus is on the ability to achieved this on an in-service vehicle as a retro-fit option as this presents a more swift route to service improvement than inferring a 'kneeling requirement' on future vehicle designs. The premise of the investigation is that some modification can be made to a vehicle that can manipulate the movement of the vehicle body through the range of motion allowable by the secondary suspension using mechanisms suggested in [13, 18]. In the first instance, the main question that arises from this presupposition is whether there is sufficient allowable movement in the suspension to allow a sufficient improvement to the user experience at the PTI.

The assessment of kneeling a vehicle was undertaken by creating a multibody simulation model of a chosen baseline vehicle in Simpack[®] and simulating the approach of a modified vehicle to a platform. The tilting mechanism and actuators are not designed in this paper, but potential actuation methods to achieve a reduced PTI were modelled as pure force components and the kneeling process simulated dynamically. The simulation environment allows the assessment of the complete range of motion possible for the vehicle body with respect to the track. The angle of tilt and achievable step and gap reduction were quantified. This information was also compared against statistical data to estimate the extent of PTIs which would then comply to standards.

Producing a dynamic simulation model allowed the assessment of not only the primary geometric concerns, but also allowed secondary problems to be addressed. Of the many issues identified, often they relate to operational concerns that arise due to the enforced lean angle. In line with the general context of the work, the key items to be addressed by this paper are:

Table 1 Standard platform dimensioning

Variable	Description	Value
a	Track semi-gauge	0.7175 m
b	Rail distance	0.73 m
c	Emergency recess width	0.3 m
d	Platform width	2.5 m
f	Platform length	variable
h	Platform height	0.915 m

Table 2 Modelled platforms and their dimensions

Platform	Height[m]	Radius of curvature[m]	Cant[mm]
Straight	0.915	∞	-
Curved	0.915	3000	-
London Waterloo	0.82	114	110

- To assess the maximum extent of kneel possible for a given vehicle and its suspension.
- To qualify the improvements in step and gap for comfortable boarding and alighting by passengers.
- To identify the possible infringement of gauging limits for the platform edge, adjacent vehicles and pantographs.

The following section (Section 2) presents details of the experimental setup and the results observed (in terms of step and gap improvements) for different operational scenarios. Section 3 assesses further experimental data to quantify the effect on gauging due to the kneeling function. The achieved benefits are assessed against operational concerns in the discussion part of this paper in Section 4

2 Assessment of kneeling benefits

This section describes the simulation environment along with the vehicle model and different platform configurations used in it. The actuation methods and test scenarios are described. The benefits of the kneeling train are measured in terms of improvements in step and gap distances which are tabulated for different conditions. It could be inferred from these improvements that they lead to better passenger flow in and out of train, thereby reducing the dwell time and risk of accidents at PTI.

2.1 Simulation model

In simulation, two main systems are modelled which are the platform and train. They are explained in the respective sections below. The train modelling is similar to the vehicle simulation model developed in [24] though the parameters are from class 158 vehicle.

2.1.1 Platform: In this feasibility study, three types of platforms are modelled. The first two types are a straight and a curved platform which conform to the geometrical standards. The model of a standard straight platform is shown in Fig. 1. The different distances are detailed in Tab. 1 which are according to UK standards [25].

Some of these standards such as platform height could not be applied to old platforms where in certain cases any alterations could also not be made. To investigate such a real case, measurements from London Waterloo station was used. This station is partly straight and curved with an extreme horizontal radius of curvature 114 m at one location. The platform is 820 mm high which is lower than the standard height shown in Tab. 1, thus making a good sample for a non-ideal platform. A track cant (110 mm) is also included in the curved platform model [26]. These details are summarised in Tab. 2.

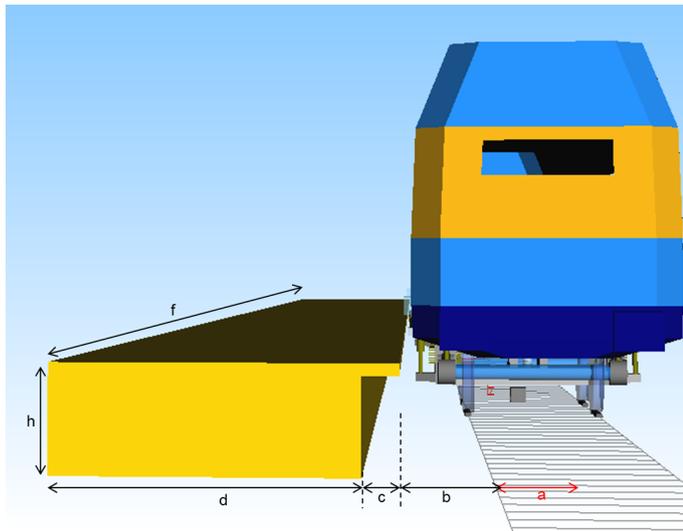


Fig. 1: Dimensioning a standard platform

2.1.2 Train: A Diesel multiple unit (DMU) a typical commuter vehicle of class 158 with contemporary suspension design has been modelled in this study, whose main parameters can be found in Tab. 3. The vehicle model is made up of the outer body and model of the truck.

The truck model is constructed using a multi-body physics based simulation. This allows the key components such as wheelsets to be modelled as lumped masses and interconnecting components as springs, dampers, bearings etc. Properties such as rolling contact could be modelled using non-linear equations or defined graphs in order to calculate forces exerted. The truck model contains the suspension elements along with the bogie and wheelsets. The different components include anti-roll bar, vertical and lateral bumpstops, lateral suspension, anti-yaw dampers, air springs modelled as shear springs. These components are collectively termed as secondary suspension which connects the bogie to the bolster on which the vehicle body is mounted. Among these components the bumpstops are modelled with non-linear characteristics.

Apart from them, the primary suspension is mounted between the wheelsets and the bogie which is modelled as a set of spring and dampers. The wheel axle guides also has stiffness associated with it, which together with the primary spring is responsible for yaw stabilisation of a wheelset. The wheelset contains an axle on which wheels are mounted on either side. In a broader perspective, secondary suspension is responsible for passenger comfort and primary for stability of vehicle. The rail-wheel contact patch has also been modelled using Hertzian contact stress model with a value of 0.3 for coefficient of friction. The rails have a standard cross-section of UIC60 and wheels are defined from standard S1002 profile.

2.1.3 Measurements: In the design of vehicle body, the important locations are the positions of door step from which the step and gaps are measured. Figure 2a shows how step and gap distances are measured between the points on the train and platform. On the vehicle body, the doors are located vertically at 1.1 m above rail level (arl) and laterally 1.35 m from midpoint between the rails. The mid-points of doors are indicated as d_1 and d_2 in Fig. 2b and located longitudinally at 1.8 m and 2.5 m from either end of the class 158 vehicle. It can be observed that the door positions do not coincide with the bogies. The distances are measured at markers placed at floor of the doorstep on the vehicle according to the coordinates described above.

With respect to the platform, the edge of the standing surface of the platform towards the track is the measurement line. This can also be inferred with respect to Fig. 1 as the edge corresponding to dimension $(a + b)$ from the midpoint of track and at height h above the rail level.

Table 3 Main parameters of vehicle model

Parameter	Value
Total vehicle mass	39 tonnes
Total primary yaw stiffness per axle	15 MNm/rad
Car body width	2.8 m
Car body height	3.6 m
Secondary suspension	
Height of airbags	0.3 m
Longitudinal and Lateral stiffness	118 kN/m
Vertical stiffness	177 kN/m
Roll and Pitch stiffness	296 kNm/rad
Yaw stiffness	49 kNm/rad
Primary suspension	
Longitudinal and Lateral stiffness	493 kN/m
Vertical stiffness	987 kN/m
Roll and Pitch stiffness	49 kNm/rad
Bogie	
Bogie mass	2469.6 kg
Semi-pivot spacing	8 m
Wheelset	
Wheelset mass	1106 kg
Wheelbase	2.6 m
Wheel radius	0.45 m

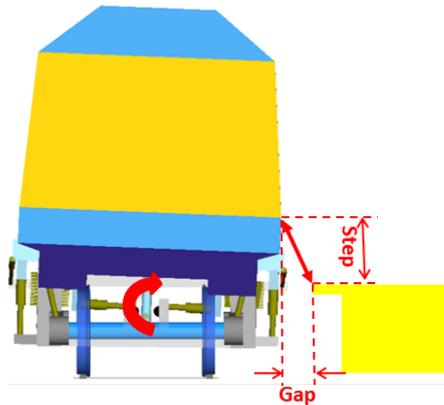
Markers are also positioned at bottom edges and roofs of the vehicle and at edges of pantographs to discover their interference with components of railway infrastructure as shown in Fig. 2b. The bottom edges of the vehicle are at 1.3 m above rail level and four edges of the roofs are at 3.2 m and 3.7 m above rail level which are labelled cr_1-cr_6 at the rear side and correspondingly cf_1-cf_6 at the front side. Along the lateral and longitudinal directions, these markers are at the extreme edges of the vehicle. On the pantograph the important feature to be detected is the loss of contact between the catenary and the carbon strip. In order to detect it, markers are placed on the farthest ends of the carbon strip labelled as p_1 and p_2 in Fig. 2b.

2.1.4 Actuation: The step and gap could be minimised by a combination of vertical and horizontal actuation, or a tilting actuation. In the former case the vertical movement could be achieved by controlling the volume of compressed air in the secondary suspension air bellows, thereby adjusting the vertical step as described in [19]. A horizontal actuation could not be performed by any component which are available in today's trains. If the airbag is considered as an actuator to tilt the vehicle, the suggested method is to pump a defined volume of air from bellow on one side of the vehicle to another. By virtue of this movement, the vehicle body can be tilted towards the desired side, but still maintaining the total volume of air within the suspension system constant similar to [13, 18]. In simulation environment, inflation and deflation of air bellows has been simulated by modifying their stiffnesses. This method of actuation has been analysed here for the sake of comparison with the other actuation which is described below.

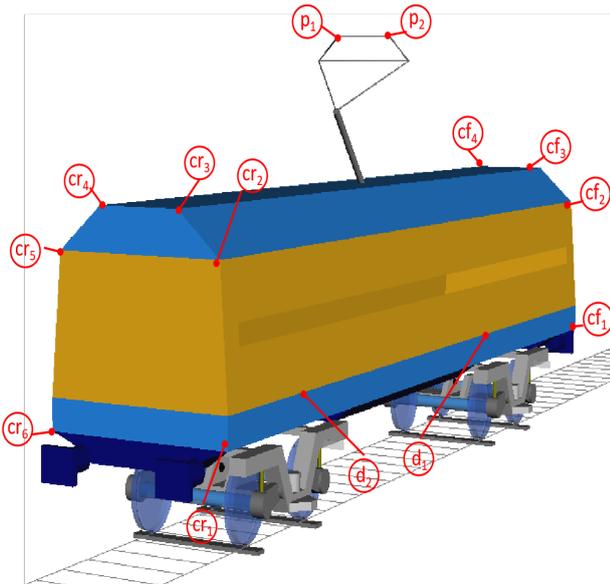
Apart from using the airbag for tilting purpose, this motion can also be achieved by a custom designed mechanism, which is similar to the system mounted on certain vehicles to improve their performance while driving through curves [21]. The tilting motion is simulated by an idealised actuation as a torque applied on the vehicle body. This torque is applied at the midpoint between air bags of secondary suspension. The actuators and the associated mechanism to be developed are part of future research, as the present investigation

Table 4 Variations in simulation model

Platforms	Actuation	Running conditions
<ul style="list-style-type: none"> • Straight • Curved • London Waterloo (without cant) • London Waterloo (cant towards platform) • London Waterloo (cant away from platform) 	<ul style="list-style-type: none"> • Kneeling • Airbag (vertical motion) • Airbag (tilt) 	<ul style="list-style-type: none"> • Stationary kneel • Dynamic kneel



(a)



(b)

Fig. 2: (a) Definition of step and gap measurements (b) Positions of markers in the simulation vehicle

is based on geometric viability of the proposed motion. Figure 2a shows the tilting torque at the secondary suspension and the car body tilted by 2.35° due to it.

2.2 Variations on principle of operations

The two main test scenarios with which a kneeling train has been tested are in a stationary and dynamic kneel scenarios. In a stationary kneeling scenario the vehicle is actuated to kneel after it has come to a complete stop at the station. One concern in this strategy is the time required to tilt the vehicle and for it to centre itself before accelerating which is defined as the dwell time. In applications such as urban transport network where time is also a critical factor, this poses as a

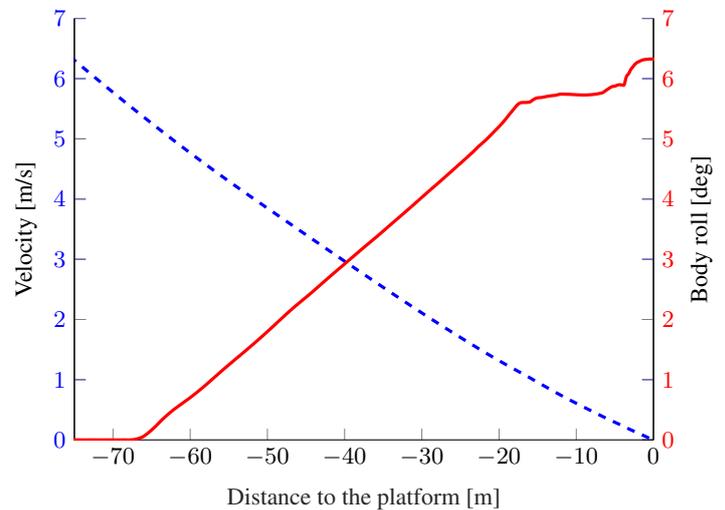


Fig. 3: Example of a dynamic kneeling scenario

disadvantage. However this scenario has been analysed as a geometric analysis before building up the complexity in the following test scenario.

This can be overcome with a dynamic kneeling scenario, where the train is actuated to kneel while it decelerates on approaching the station. The distance to the platform from which kneeling starts is a parameter in this scenario, apart from deceleration profile of the vehicle. While leaving the station the vehicle centres itself from the knelt situation during its acceleration.

Figure 3 shows a proposal of a dynamic kneeling scenario. The graph plots the vehicle velocity and kneeling action through the body roll angle against the distance before the platform. In this example the kneeling action has started at 70 m before the train enters the platform. The roll angle from -70 m until -20 m increases smooth and monotonically. Between -20 m and the edge of the platform the rate of body roll angle is reduced to avoid discomfort to passengers getting ready to alight. It can also be observed that in the latter interval the roll angle is not smooth. This is because of an inherent open-loop system which delivers a smooth actuation force from the actuator, which on interaction with the non-linearities in the suspension system translates into an irregular roll angle profile. In a control system point of view, the roll angle could be solved as an optimisation problem with an objective of minimising roll acceleration for passenger comfort reasons considering the available time to roll as a parameter.

Table 4 summarises the different variations with which the simulation model has been tested. Though they form different combinations, only results from the important ones are presented in subsequent sections and discussed.

2.3 Step and gap improvements

In this section the results are presented from the kneeling test scenarios applied to the straight and Waterloo platforms described above in Tab. 2. From Tab. 5 it can be observed that a significant improvement in PTI step and gap distances can be achieved by kneeling a train. In the simple case where a vehicle is knelt at stationary conditions on a

Table 5 Improvements in PTI due to kneeling actuation

Test scenario	Kneel angle [deg]	Reduction in	
		Step[mm]	Gap[mm]
Stationary kneel (straight platform)	7.7	185	81
Dynamic kneel (straight plf.)	6.7	160	53
Dynamic kneel (curved plf.)	6.32	159	89
Dynamic kneel- canted track (Plf. and cant in same direction)	7.52	207	117
Dynamic kneel- canted track (Plf. and cant in opposite direction)	0.36	15	24

Table 6 Improvements in PTI due to air bellows only

Scenario	Kneel angle [deg]	Reduction in	
		Step[mm]	Gap[mm]
Vertical motion	-	33	-
Tilting motion	2	47	5

straight platform, step and gap are reduced by 185 mm and 81 mm respectively. Because these improvements are measures of deflection, the absolute positions of platform edges or doorstep are not important. Hence a stationary kneeling scenario at a curved platform also achieves the same improvement.

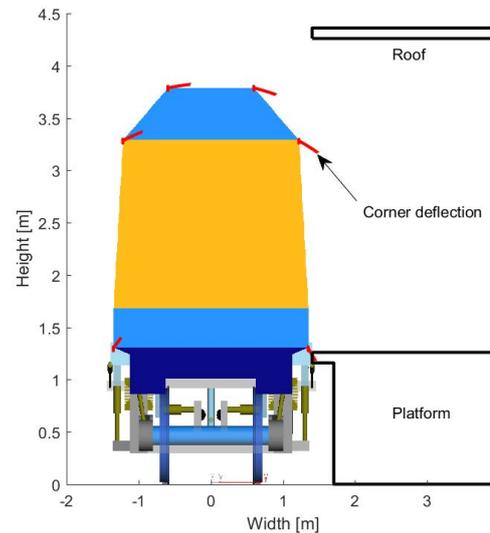
In cases of dynamic kneel, the train is assumed to be at cruising speed of 30 m/s at 50 m ahead of the platform from which the vehicle starts to decelerate. In all the cases The table shows maximum kneel angle that the suspension would allow for a defined vehicle deceleration profile into the platform. When compared with the stationary kneeling situation in a straight platform, dynamic approach could not achieve higher reduction in step and gap distances. The vehicle could be tilted only upto 6.7° , due to interference of longitudinal and lateral forces in a dynamic kneel.

It can be observed from dynamic kneel scenario in Tab. 5 that the gap reduction in a curved platform is larger than a straight platform for similar kneel angles, due to curvature of Waterloo platform inward towards the train. The canted tracks modelled according to values in Tab. 2 in a station with curved platform capture the scenarios where the platform curvature is toward or outwards the train. In former case, the cant augments the kneeling action thereby reducing the step and gap further as shown in the table. When the track cant inclination is opposite to the kneeling direction, only a small reduction can be achieved.

In the alternative actuation method just by using the airbags of secondary suspension, only a small reduction in step and gap could be achieved as observed from Tab. 6 when the vehicle is stationary. The absolute height of airbag in the simulated vehicle is 60 mm, and by completely deflating its height can be reduced by about a half. This is the maximum vertical step which could be achieved. If a control strategy can be developed whereby airbag on one side is completely inflated and the other side deflated, a tilt angle of about 2° is achieved. Though these values are smaller compared to those achieved by a tilting mechanism, a retrofit of the concept can be realised by using the existing components in the vehicle. The use of airbags for tilting motion might compromise on safety as presented earlier and could be used only as a proof-of-concept before a complete mechanism for tilting has been developed.

3 Gauging Assessment

A key area identified as a risk towards implementing a kneeling functionality in a train is problems concerning the space surrounding the vehicle. Gauging covers a series of techniques which ensures that sufficient space exists around a moving train to provide safe operation [27]. As presented in section 2, the step and gap distances at

**Fig. 4:** Gauging at Platform Train Interface (PTI)

PTI improve significantly due to a kneeling train. However it needs to be analysed how such a kneeling action affects the infrastructure and nearby vehicles. Three such areas have been identified and they are described in the following subsections. An interference would be detected when the path of the markers as shown in Fig. 2b would intrude into the boundaries of the infrastructure while actuating.

3.1 Vehicle-Infrastructure interaction

Two regions should be observed with regards to gauging at the train and station infrastructure interface. The first area is whether the floor or step of the vehicle could come into contact with the platform. The second area is between the roofs of the vehicle and platform. According to RSSB standards [25], the height of roof is 3 m from surface of the platform and other fittings such as lights, signals or sign posts are located at least 2 m away from the edge of platform. Hence the latter structural elements need not be considered for gauging analysis.

For the gauging analysis an extreme PTI situation from statistical data is selected, where the train and platform are so close to each other. The nominal step and gap in this situation are 55 mm and 35 mm respectively. This scenario is depicted in Fig. 4, where apart from train the platform structures are also drawn. The deflections of vehicle corners are drawn as red lines, when the train kneels up to 4.73° . When the two areas mentioned above are looked into, it is clear that there is no contact in the second area between the roofs. But the floor of vehicle touches the platform as seen from the bottom right corner of the train.

In this extreme PTI scenario example, the safe kneel angle is only 2.5° . It can be inferred from this example that the kneel angle should be adapted towards each platform-vehicle combination. This observation should be addressed by developing other strategies, one of which could be to sense the position of platform with respect to vehicle and actuate accordingly.

3.2 Pantographs

The Pantograph is an important component of the vehicle in an electric multiple unit (EMU). In simulation the pantograph has been modelled on top of the DMU vehicle model, just to investigate the effect of kneeling. The pantograph influences gauging of the vehicle due to nature of its construction extending outside the body of the vehicle. The catenary wire which supplies electric power to the train is laid in a zigzag pattern in the horizontal plane. The range of horizontal stagger of catenary in UK is ± 20 cm. In the vertical plane it hangs between the poles due to its elasticity. Moreover the wires are laid higher near the level crossings and lower in tunnels and under bridges. According to standards [28] the maximum, nominal and minimum heights of contact wire are 5.7 m, 4.7 m and

4.1 m (arl) respectively. This implies that the wire can be found in a two dimensional rectangular space which is 40 cm wide and 160 cm high.

In the context of kneeling train, two main situations arise with respect to the pantograph. When the vehicle kneels to the platform, the pantograph should not lose its contact with the wire. This is termed as risk of dewirement. Conversely, when the vehicle centres itself from a knelt position, the wire should not be entangled below the contact surface of the pantograph. Hence the deflections of ends of the carbon strip which is 916 mm long on pantograph head should be observed. The results shown in Fig. 5 correspond to a case when the train is tilted by 4.73° . As it can be observed from the plot, the left side of pantograph head intrude into the contact wire zone. This implies a possibility of pantograph head inclining away from the wire and hence causing dewirement. This effect is more pronounced at higher pantograph positions as shown in Fig. 5c.

3.3 Inter-vehicle gauging

Subsequently, gauging between stationary vehicles on adjacent tracks in a station is analysed. The centerline of the adjacent tracks are separated by 1693 mm as mentioned in [26] such that a passing clearance of 305 mm is present between the vehicles.

In the present example, only the vehicle on right kneels to the right by 4.73° . The analysis result is shown in Fig. 6 where the corner deflection lines of the kneeling train are shown in red. It can be observed that the kneeling vehicle does not collide on the adjacent vehicle. It was also found that should a train kneel toward an adjacent vehicle to the maximum amount anticipated of 7° , contact would still be avoided inclusive of a margin of error. In the most extreme case whereby both adjacent vehicles kneel toward each other due to a simultaneous fault, then vehicle contact is possible.

4 Discussion

4.1 Assessment of PTI improvements

The simulation study shows that the PTI could be improved by a small but significant quantity by kneeling a vehicle within the current limits if secondary suspension movements.

To assess the quantifiable improvement in the PTI interface, an assessment against standards for step-free access is made. This point of comparison is chosen as there is a clear definition for the dimensions required to be considered step-free [25]. An interface is defined

as step-free if it has as a step height of 50 mm and a horizontal gap of 75 mm.

It is assumed that a reduction or an optimisation in step and gap by manipulating the vehicle body would improve boarding and alighting, but it has been found to be difficult to quantify the benefit of achieving certain 'optimum steps', if indeed an optimum step could be defined in this scenario. The assessment against step-free access is therefore useful to highlight some potential performance benefit to a kneeling action, and a wider study of optimising vehicle body movement to achieve prescribed step heights could be pursued.

In order to realise the operational benefit of this vehicle movement, the quantified PTI improvements from Table 5 can be juxtaposed with statistical data of the current experience of step height and horizontal gap across the UK network. A statistical distribution of step and gaps are shown in the histogram in Fig. 7 and are sourced from [2], which comprises data measured from 5700 platforms in UK. This data relates simply to the number of instances of each interface and not to passenger numbers, so good or bad dimensions may be under or even over represented dependant on the flow of passengers across them. In these graphs the blue striped zone on the left denotes the percentage of cases which currently comply to step-free access standards. It can be observed that negligible cases comply to the requirements in terms of stepping height (0.07%), whereas nearly a third of cases (31%) comply to the standard for gap.

It was shown in Tab. 5 that considering a 'dynamic kneeling' scenario in straightforward conditions, a lean angle of around 7° can be achieved. This results in a possible step improvement of around 170 mm and a gap improvement of around 55 mm. This improvements at the PTI due to this result is superimposed to the distribution in Fig. 7. As a result, the additional number of instances that would now comply to step-free access standards is shown by the green, dotted zone. The impact on step-free access is significant as the improvements in step and gap result in nearly half (51%) would comply to step requirements, and more than three-quarters of the cases (78%) would comply to gap.

Evidently this is an idealised scenario where a full benefit may not be realised at each PTI, but clearly a wide reaching improvement of some form can be assumed due to the number of interfaces in which a quantifiable benefit would be seen. These results also do not consider the number of interfaces where a large step may be reduced to a manageable step as the operational benefit is difficult to quantify, but some benefit to situations where step-free access is not possible may be assumed. Furthermore, these benefits are measured to the first step mounted on the vehicle and does not consider any

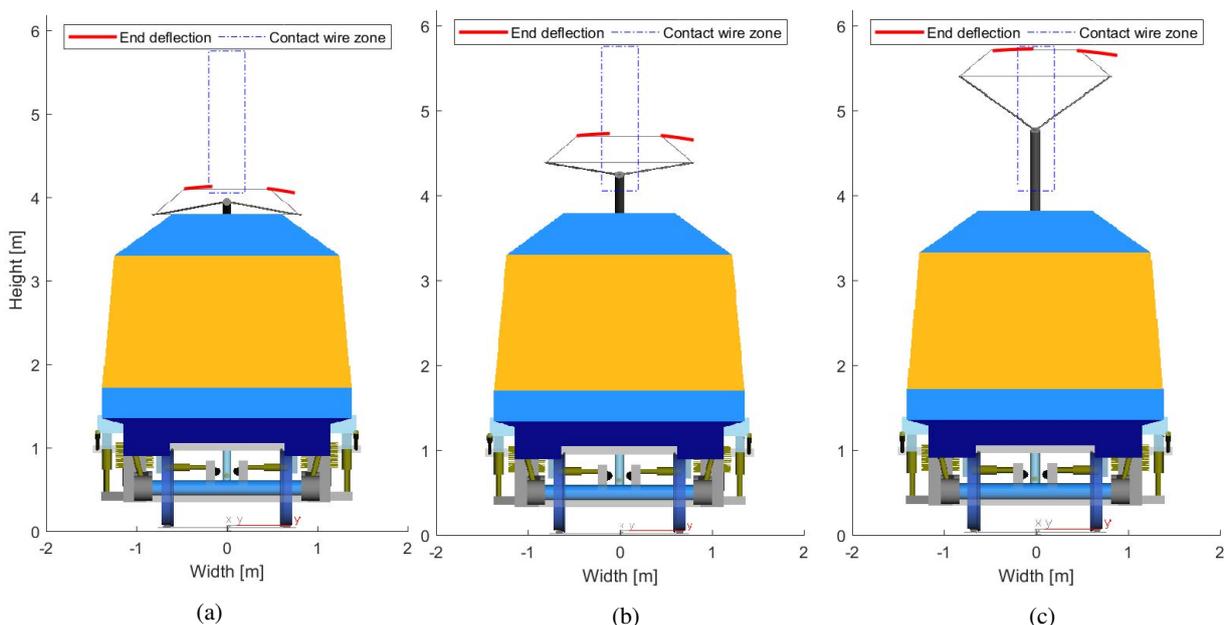


Fig. 5: Kneeling motion affecting pantograph deflection at its (a) low (b) nominal and (c) high positions

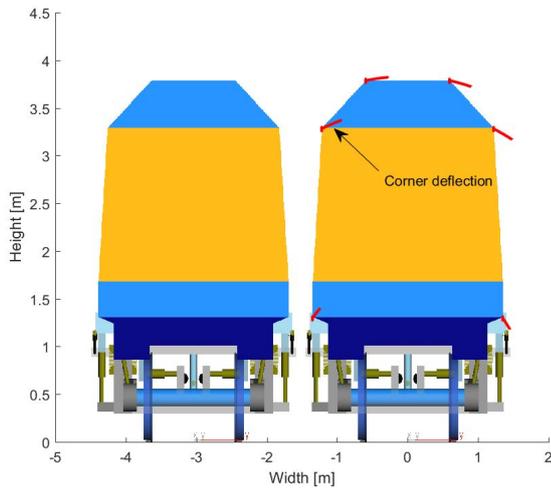


Fig. 6: Gauging between adjacent stationary trains

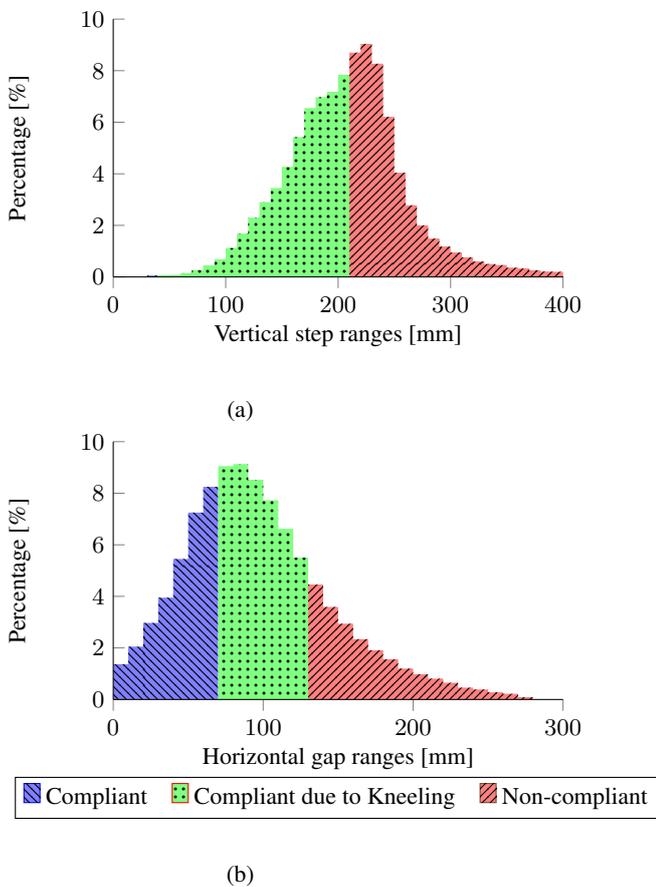


Fig. 7: Statistical data showing improvements in (a) step and (b) gap due to kneeling train

secondary step or access variations that may be present due to the internal design of the vehicle.

4.2 Discomfort due to tilt angle

The European regulation suggests a maximum ramp gradient of 6.84° for a PRM to board single deck carriages measured when vehicle is stationary [3]. The permitted track cant at stations in UK which have curved platforms is 110 mm [26] which corresponds to 4.2° and 5.73° in curves on existing or upgraded lines. Hence it can be inferred that there are stations constructed with a defined canted

track which means that tilt at such stations are already an accepted norm. The maximum tilt angles which can be realised due to tilt mechanism and the airbag actuation are 7.52° and 2° respectively as shown in tables 5 and 6. Thus the proposed tilting mechanism could provide the necessary roll angle in accordance to the regulations mentioned above.

However more than the tilt angles, the roll acceleration due to the tilt is the important parameter to avoid motion sickness to passengers [29]. Because the kneeling train is a novel concept, there has been no study to analyse the effect of tilt angles on the discomfort. As mentioned earlier in section 2.2, an optimisation problem could be solved in future works to achieve a smoother roll acceleration and roll angle among other objectives.

4.3 Gauging considerations

The variance of platform heights and shapes are well documented and can be wide ranging both across different platforms/stations as well as along the length of the same platform [4]. Furthermore, the rolling stock fleet is diverse in terms of the vehicle body geometry and access placings so a simple solution of standardising a kneeling angle is not possible. In some simulations, it was shown that contact with the platform occurs before the limit of kneeling motion is complete, particularly in a curved platform situation either with the centre of the vehicle body presented a risk on convex curves, or on the vehicle corners in concave curves.

Observations from these analyses on Gauging suggest that a control system is necessary to adjust the extent of kneel based on each platform the train encounters. It is likely that this approach will involve a case-by-case approval or feedforward information of each vehicle to each platform so that expected platform/rail geometry is known in advance, in addition to feedback control of vehicle position to account for variations in these measurements.

The analysis of the pantograph in electric vehicles shows a clear risk that dewirement could occur with current configurations of pantograph and overhead line equipment. Mitigation strategies are however possible. The pendolino method to compensate for a lean action is to mount the pantograph system on a trolley-based mechanism which is free to move laterally in order to maintain the contact with the catenary irrespective of vehicle lateral movements. It could also be mitigated by tighter control of overhead line equipment through stations, or even by only tilting vehicles within the train that do not have a pantograph.

4.4 Route Suitability

A further point arising from this analysis is that the benefit of a kneeling vehicle should be assessed on a route-by-route basis. Based on the statistical analysis in Fig. 7, it is unclear if sufficient benefit can be achieved at all PTIs to justify the cost and complexity of the introduction of a kneeling mechanism. The largest impact would be seen in routes that require many stops as opposed to a point-to-point service. It can be envisaged that the biggest cost benefit would be on busy commuter routes that experience large footfall over a number of stations. Amongst other reasons, this supports the case for a kneel-on-approach strategy as a dwell time increase to allow the vehicle to kneel and self-right would be contrary to the requirement to speed boarding and alighting.

Though the dynamic kneel scenario minimises dwell time, more parameters influence its implementation. Apart from the deceleration of vehicle when it arrives at the platform, a realistic force actuation profile for the tilting actuator should also be designed. The effect of different force profiles on the achievable improvements in step and gap and also on vehicle dynamics can be considered in further research.

As presented before it is desired to develop a stand-alone tilting mechanism so that other existing subsystems and their functionalities are not affected. But as a proof-of-concept, the idea could be implemented using air bellows of secondary suspension to study the relation between kneeling with ease of passenger flow and dwell time requirements.

5 Conclusion

In this paper a novel method for improving the PTI in a passenger vehicle is assessed. A tilting motion has been studied which will kneel the vehicle towards the platform thereby minimising the vertical and horizontal distances between the platform and the vehicle, which are called step and gap respectively.

The work here was focussed on a largely geometric assessment of vehicle body movement. The promising results have prompted a wider debate on many operational considerations and technical issues to authorise a safe kneel on platform approach. Some of these have been highlighted as part of the discussion, but not yet addressed in full detail.

The performance of such a system has been analysed with model of a baseline vehicle with different driving scenarios in a simulation environment. The different scenarios include decelerating conditions of vehicle when approaching a platform, curvature of the platform. In all scenarios, a significant benefit at PTI could be achieved. The extent of the benefits achieved from an idealised actuation scenario that could push the vehicle body to its full range of movements has been compared against the use of manipulating air content in the airbags of the secondary suspension. The latter method provides good kneeling effect but not significant when compared to a dedicated, idealised tilting mechanism. Though the kneeling function could be realised through the air bellows and it provides options for a retrofit, the range of movement possible is limited and provides only a small operational benefit. There is a possibility that contemporary suspensions with inboard air-bag configurations would provide a larger moment arm and allow more movement than the vehicle modelled, but in this circumstance the improvement of step by 47 mm was not deemed sufficient. To achieve a reasonable degree of improvement, some modification to the secondary suspension would have to be made in order to actuate the system beyond the current offerings of the available components.

Within the simulation, the surroundings of the vehicle including platform, adjacent vehicles and pantograph interaction was investigated with respect to a kneeling train. It was concluded that a control system is necessary to mitigate the risks involved colliding against the floor of platform. A proposed controller would use both information at the anticipated infrastructure geometry plus measurement information from proximity sensors at strategic locations. The sensors could act either as the signal for a control feedback, or as safety overrides for pre-emptive action. Further mitigation action is necessary to prevent dewirement risk on the pantograph head, such as a movable trolley which are installed in tilting EMUs, or strategic placing at the overhead line equipment.

Future works should study the impact of kneeling train on improved passenger flow to provide a subjective assessment on improvements. Furthermore a detailed analysis on operational and technological implementation should be considered. Since this feature is at a conceptual stage, potential failure modes should be identified and prevention mechanisms should be developed. The final area of development is to fully understand the lifecycle cost saving of implementing a kneeling function by the development of a business case. This requires thorough estimates of the cost of implementation, and an analysis of the cost savings inferred due to resultant reduction in platform dwell time.

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