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Methods for reducing the specific mass of rolling stock

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ABSTRACT

In future, environmental issues will be extremely important such as use of recycle material and global warming. Reduction in air pollution can be provided with low energy consumption in the railway sector. Therefore, new and modern designs should have lightweight equipment and systems. In this paper, main reasons of high body mass are discussed in terms of safety issues such as crashworthiness, signalling and aerodynamic design, technical issues such as bogie design and body frame design, passenger comfort issues and some methods are also given to decrease specific mass of the train.There are several methods that can be applied to reduce specific train mass (mass per seat or mass per passenger space) but optimum design conditions should be clarified as much as possible and therefore, suitable material and lightweight design should be considered to obtain high performance with low cost. Use of light materials, decreasing wiring and different optimum bogie and body shell design might directly reduce the specific mass of the vehicle. Effective designs of the train leads to improved performance, reduction in energy consumption and less track damage which are very important parameters to provide efficient train operation. Because of the fact that, initial vehicle investment price and maintenance cost change with material type, easy manufacturing, modular design, use of less material which directly affect the journey time, people's comfort and people's life, are the most important parameters to be taken into consideration.

1. Introduction

The design of a new railway vehicle is influenced by several kinds of parameters which affect the train weight. These parameters depend on chosen materials, effective equipment type, aerodynamic and dynamic issues etc. which result in high mass on train in order to provide comfort and good quality riding. Specific mass of a train is defined as mass per seat for regional rolling stock type or mass per passenger per space for inner city transportation trains. Effective design of train leads to improved performance, reduction in energy consumption and less track damage which are very important elements to have efficient train operation. Because, first vehicle investment price and maintenance cost change with the parameters such as material type, easy manufacturing, modular design, material amount used. These parameters directly affect the journey time, people's comfort and people's life that are crucial issues should be taken into consideration.

An important aspect of modern industrial train manufacturers is decreasing the vibration and noise as well as reducing weight for increasing the speed, decreasing track damage and energy consumption. According to Hagiwara [1], less weight "is also effective in the reduction in kinetic energy, which increases in proportion to the mass and square of the velocity. When the velocity increases from 220 to 270 km/h, kinetic energy becomes 150% more however, when a 30% weight reduction is realized". This proves how mass reduction affects the energy consumption through increasing kinetic energy.

In this study, a special investigation was made to find out increasing factors of train weight, how the specific mass can be reduced and which methods can be applied respectively. Optimum design of the train includes safety, operational and technical issues regarding with cost efficiency and performance. In order to achieve this, lightweight train is one of the most important issues that should be considered initially because of the new metallurgical improvements and production techniques. For example, composites have been started to use in a wide range of equipment from seats to high strength and flexible bogie design.

However, there are some disadvantages of using these lightweight designs such as elastic vibration of the train. Nagai et al., [2] was stated "using light metal materials and changing vehicle body structure, has been resulting in deterioration of the car body rigidity so

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that some elastic vibrations in the car body are easily induced". Therefore, optimum structure should be designed to reach high quality and comfort for people's expectation, less cost and mass for operator's needs.

2. Literature Review

There are several studies about reducing railway vehicle weight related to redesigning of bogie, use of new material and different manufacturing techniques. Rochard and Schmid [3] suggested advantages and disadvantages of mass reduction of trains commenting on the state of art and benefits of mass reduction for high speed rail implementations. Yoon et al. [4], Park and Lee [5] studied on the strength of a bogie frame which affects safety, comfort and riding quality of passengers. Tilting bogie frame design in terms of strength and weight was investigated by Park B.H. et al. [6]. One of the significant factors in bogie mass is the choice of suspension that provides comfortable journey for passenger by preventing vibration and noise. There are two studies that discuss to improved comfort that is related to human bio-mechanical behaviour for flexible car body which means lightweight vehicle [7],[2]. Using of different types of materials for seating, interior design of the train and body shell influence the train mass significantly. Development of the ride comfort in terms of seat and car body design was observed in Korea high speed railway and rubber tired light rail vehicle [8], [9]. Environmental issue is also important in today's development to reduce energy consumption and this result in high mass on railway vehicles. Lightweight traction model of Shinkansen high speed EMUs was investigated in the way of environmentally aspects by Hagiwara [1] as mentioned in the introduction part. In future, wireless technology will be the most considerable innovation to reduce train mass. Bellavista et al. [10] studied wireless equipment in entertainment services to show lightweight. Aluminium and aluminium alloys have a wide range usage area because of having less weight. However, repair and welding are very important issues that should be considered. In that time manufacturing and welding techniques play an important role to have light weight design. Pulsed current welding on high strength aluminium alloy was concerned from the point of mechanical properties by Balasubramanian et al. [11].

3. Main Reasons of High Vehicle Mass

3.1 Safety Issues

Safety issues have to be considered in modern railway vehicle design in order to protect people not only from environmental conditions but also crashes and effects of vibration and noise. In the acceptance of a railway vehicle, primarily, safety properties should be evaluated which is related to whether train is acceptable to run passenger with minimal impact such as; passenger life, comfort, motion sickness and environmental conditions. Manufacturers and operators should handle the safety conditions in consideration of cost which influences the design of the train directly. Although there are several designs and equipment reducing risk of the vehicle, they may lead to the overweight trains.

3.1.1 Influence of Crashworthiness on Vehicle Mass

Crashworthiness is the main design element of a car body shell to protect passenger from harmful effect of train crashes. Body shell materials have become important to reduce train weight. Strength, fatigue resistance, corrosiveness, fixing and environmental characteristics of materials are important parameters increasing the train mass. According to Kim and Choi [9], a body shell should have sufficient strength, toughness and endurance to balance weight changes due to the acceleration, deceleration and passenger movements. Moreover, he found out that body shell for a light rail vehicle "should be designed to satisfy the requirements for weight reduction directly associated with construction cost".

3.1.2 Influence of Signalling on Vehicle Mass

Railway vehicles must have signalling system to serve reliable train operation and provide safety conditions. To sustain a high reliable train operation, signalling system of the train should be made from high quality wiring and labour. Using of wire to transmit signal increases the body mass. Figure 1 shows the signalling wiring system between the vehicles including open train, connected train sets and closed train. If the vehicle bus has a multifunctional property it can be used as a train bus at the same time. Otherwise both train bus and vehicle bus should be used cooperatively in the same vehicle. These different types of wiring designs have various effects on the vehicle mass. According to Kirrmann and Zuber [12], there should be standard data communication for passenger information and to control train which should be provided to configure it for coupled trains. This wiring complexity leads to high mass.

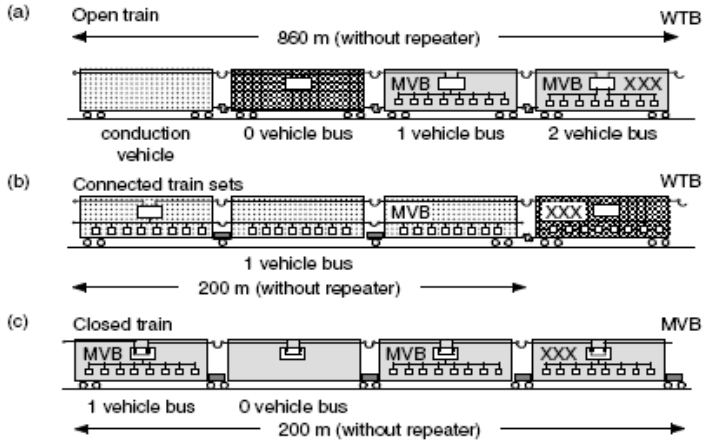

Figure 1. Signalling wiring system between vehicles [12]

3.1.3 Impact of Aerodynamic Design on Vehicle Mass

Aerodynamic design of the train is significantly important for carrying passengers in a safe way. Body shell of the train should be designed with optimum strength due to the train pressure effect, cross-wind effect and tunnel aerodynamics. Vehicle body should be strong as much as possible to eliminate pressure or cross-wind effect laterally. Trains must be designed to be tough and light weight as possible that should be taken into consideration by collision energy management.

3.2 Technical Issues

So far, safety issues increasing vehicle mass has been argued. In this part technical design parameters that lead to high vehicle mass are presented particularly related to bogie and frame design.

3.2.1 Influence of Bogie Design on Vehicle Mass

A bogie, carrying all body and passenger load, is a key structure in wheel-rail interaction. Moreover, a bogie consists of bogie frame, wheel, axle, suspension systems, and traction-brake equipment which are subjected to static and dynamic loading. Owing to the fact, the bogie frame should be not only as strong as possible but also flexible to compensate dynamic loading in the curves. Park and Lee [5] claims that bogie mass "should be as light as possible at higher running speed. Therefore, the strength of the bogie should be carefully calculated and analysed by the international standards such as UIC and JIS." Classical optimization problem is that fatigue constraints obstruct to designate simple algorithm which is not proclaimed as an analytical function for minimizing weight of vehicle [5]. Finite element model can be used for preventing time waste and to try new design bogie frame strength in terms of design variables such as material type. Figure 2 shows a bogie frame model which is ready to analyse to measure design variables effect.

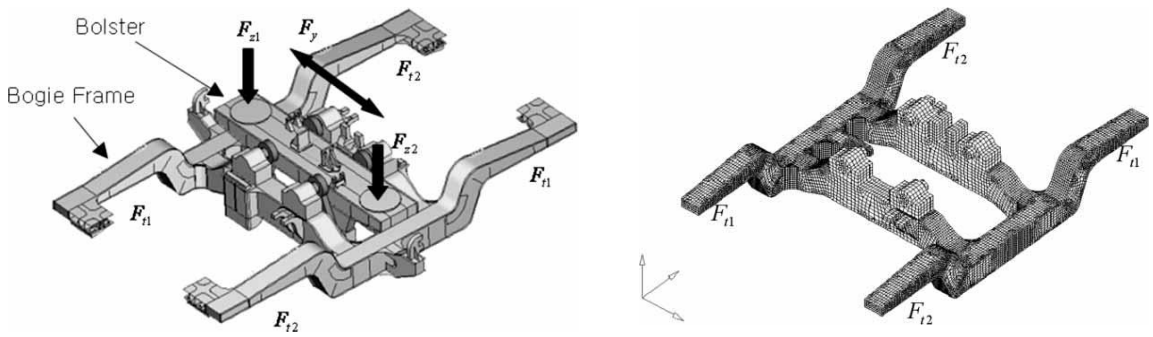

Figure 2. Bogie Frame Model [5]

Primary and secondary suspensions of the train are designed for steering bogie as stabile. There are new technological improvements which lead to not only an increase in the passenger comfort and but also a decrease in vibration and noise. Tilting trains can be given as an example of using these suspensions. Figure 3 shows the tilting bogie and its mechanism.

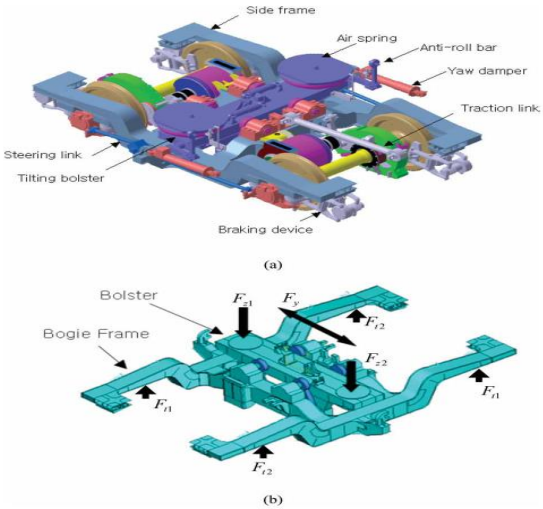

Figure 3. (a) Tilting bogie and (b) tilting mechanism [6]

3.2.2 Influence of Body Shell Design on Vehicle Mass

Body frame design considers material type and design features which are in development with advanced technology. Use of variety of aluminium material alloys, composite structures and different manufacturing techniques lead to reduction in body mass which is important for less energy consumption and environmentally friendly trains.

According to Zinno et. al. [13], the essential structure of body design should be taken into consideration in terms of fire resistance, toughness, environmental issues and fatigue strength respectively. For this reason, body mass of vehicle will increase to sustain safety and comfortable train journey. Development of aluminium alloys and composite materials influences these conditions. Moreover, although glasses of vehicle is an important feature that gives relax journey to people mentally, it rises weight due to high density ratio. Therefore, optimum design of the vehicles has become more important compared to automobiles in the way of "the longer rail car geometries and lower strength-to-weight ratios result in lower crash decelerations of the occupants" [14].

3.3 Passenger Comfort Issues

All purposes, safety and technical issues of vehicle design, is to provide passenger comfort and riding quality. Air conditioning, passenger information services and electrical sockets for chargeable equipment and more comfortable seats result in overweight trains. Figure 4 illustrates a representative of a comfortable train.

Figure 4. A view of passenger comfort [15]

As discussed previously, choice of material type is considerably important for optimum vehicle design. According to Thompson and Jones [16], the train body material should keep "above the frequency range to which humans are most sensitive (approximately 2 to 10

Hz). This is one reason for the trend towards light, stiff materials such as aluminium extrusions in the manufacture of rolling stock". In addition, the active suspension system should be evaluated. Schandl et al. [7] demonstrated how the active vibration system influences the lightweight metro train made from aluminium extrusion. Using of finite element method, five eigenmodes of the train are shown in Figure 5. According to the first figure, the vertical bending in 8.5 Hz, the second one is diagonal distortion in 9.4 Hz, the third one is torsion in 9.9 Hz, the fourth illustration is related to vertical bending in 11.8 Hz and the last one shows lateral bending of body shell in 12.6 Hz.

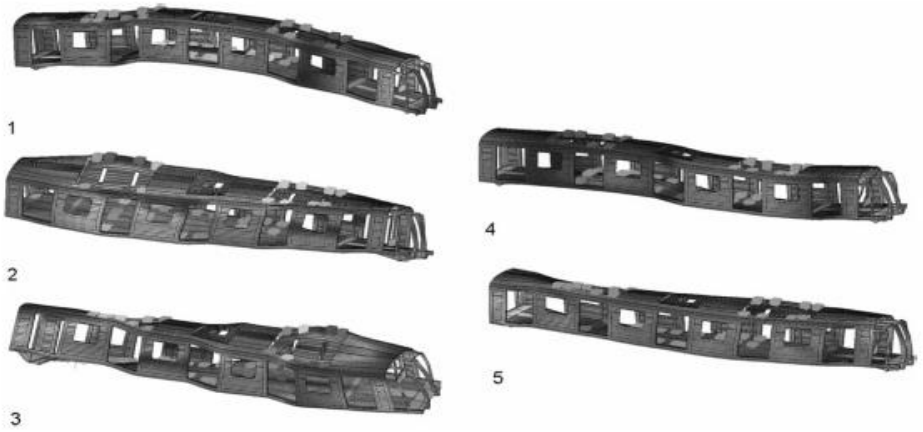

Figure 5. Mode shapes of the fully equipped metro car body [7].

4. Methods to Reduce Train Mass

4.1Suitable Material

In the above part, the reasons increasing vehicle mass are given. In this section the methods that might lead to a reduction in vehicle mass are discussed.

It is very important to know that material type directly affects train mass. Body frame, bogie frame, wiring, seat materials etc. should be considered not only for sustaining reliable train operation but also reducing the specific mass of trains. The rolling stock can be divided into three groups including body frame and shell material, bogie frame material and interior design material.

When body frame and body shell materials are considered to reduce vehicle mass, several materials can be recommended. One of these popular materials, which is in extensive use for rail vehicles, is aluminium and its alloys. The main advantage of aluminium is the fact that it is lightweight (2750 kg/m^3). On the other hand, some drawbacks decrease the use of aluminium. Having low stiffness and limited strength are two significant characteristic in design conditions. The most important disadvantage of aluminium is fire resistance problem due to having a low melting point, <700 C. With the help of manufacturing techniques, repair and welding problems might be removed and this may lead to cheap and environmentally friendly vehicles. ALJOIN is one of the projects in European countries to increase crashworthiness in the integrated joints along the railway vehicles. One other alternative method of welding aluminium structure is friction stir welding, invented and patented by TWI, which has been used Hitachi trains in Japan (Figure 6). Therefore, providing excellent strength on aluminium extrusion body shell has high quality, less weight with minimal distortion.

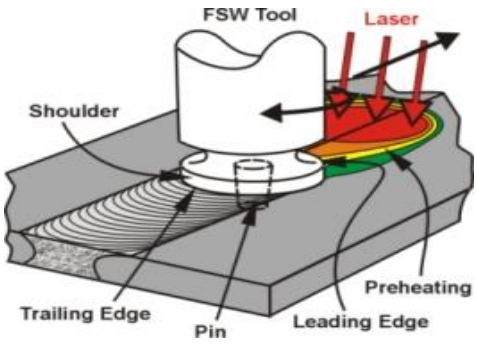

Figure 6. Friction Stir Welding [17]

The other kind of material type is composites that is started to use in a wide range. Main characteristic of composite materials is to be lightweight and strong compared to other type of metal structures. Even though these advantages provide a usage area, low stiffness, less fire resistance and high toxic fumes cause several problems in crashworthiness. According to O'Neill, composites are remarkable materials that have been used for nose of railway vehicles to have not only lightweight design but also complex body geometry because of the aerodynamic issues [18].

The following point is body design of rolling stock which is mainly about material type of body shell and frame. Design of body structure is critical for crashworthiness with lightweight. Due to the energy management in collision times, the sandwich structures (Figure 7) have become more of an issue for energy absorption and distribution with lightweight material type.

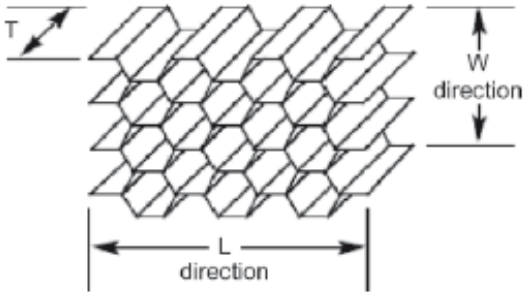

Figure 7. Specimen geometry of sandwich structure [13]

Sandwich constructions provide less weight, good dynamic properties and high strength that used for energy absorption and interior panels of the train. Therefore, not only high quality material properties but also thermal and acoustical insulation can be obtained. Energy saving is related to weight saving that according to TIFAC, "weight savings of up to 75 % can be reached in non-structural and up to 50 % in structural components" [19]. Hexcel states that floor structural panel in Schindler Wagon AG have 20% less weight than aluminium extrusion structures [19]. Use of this material for non-structural elements such as interior panel of the vehicle provides 35% less weight compared to conventional structures [19]. Therefore, energy saving can be acquired through lightweight material and design.

It is known that bogie should be made from steel or welded structures which are heavy and rigid with damping and suspension equipment. However, there is a new development that bogie can be made from composite materials which have some problems as modularity, fixing and economic issues. Material science and manufacturing technology will be developed considerably to have stiffer, stronger and solved fixing problems. Therefore, it is possible to have lightweight bogie design with flexible features and less track damage with less vehicle's mass.

4.2 Subsystem Signal Filet

Interior design of the train and wiring for signalling can be discussed as the third part. Use of composite materials in a wide range for seats and upholstery is important which should be light for modularity and easy repair. However, the assembly point of seats is very important for passenger safety due to the fixing problems. Wiring is another mass source that should be avoided as much as possible to decrease system wiring complexity. There are plenty of signals that should be transferred to provide system unite and control. The train mass can be reduced by using new design of wire or wireless technology. There are two kinds of wiring system to respond train standardization. One of them is "Wire Train Bus" uses WG22 which "shared the established UIC cable with the wire carrying the signals for controlling lights, loudspeakers, and doors in international vehicles" and "twisted shielded wire pair capable of carrying data at 1 Mbit/s" [12]. The other type is "Multifunction Vehicle Bus" which operates 1.5 Mbit/s. In this system, optical fibres, 120-ohm twisted wire pairs and RS-485 with 120-ohm cable are used for cost effectiveness, environmental sensitiveness, better robustness and low attenuation [12].

4.3 Optimum Design

In this section, the effect of design parameters on bogie, body shell in terms of shape and equipment type is discussed.

Bogie is a very important part of the rolling stock that should be not only light but also strong for fatigue particularly in welding connection points. Material amount can be reduced by using different design techniques in order to decrease bogie weight. If the axle boxes of train are changed the position from outer side of the wheel to inner side which is called inboard bearing wheelset, the bogie weight can be reduced. Figure 8 shows the comparison of bogies for conventional and new design.

Figure 8. Comparison of two bogie designs [20]

In conjunction with this kind of design, Bombardier Inc. states that bogie weight was reduced up to 30% and unsprung mass was decreased in 25% compared to conventional bogies respectively. Decrease in the weight and unsprung mass resulted in low track forces and damages. Therefore, it led to less energy consumption and track access charges. Moreover, low weight frame and wheelset reduce the stress level on welding points and axles. Maintenance is another important feature for this design that inboard bearing lubrication point should be placed for easy access. Also, bearings should be controlled by heat detection system at certain times.

5. Conclusion

Lightweight trains have many advantages such as improved performance, low energy consumption and low track damage. However, specific mass of the train has been increased day by day with the developments in technology. Despite the improvements in mechanic, material, electric and electronic science the train mass has been gone up rapidly because of the safety, technical and passenger comfort issues.

In this study, main reasons of increasing body mass are claimed in terms of safety issues such as crashworthiness, signalling and aerodynamic design, technical issues such as bogie design and body frame design and passenger comfort issues and some methods are also given to decrease specific mass of the train.

Aluminium alloys, composite materials and use of those with different design by the help of manufacturing techniques contribute to weight reduction that results in low braking energy and less track damage. In future, innovation in lightweight technology provides higher train performance in consideration of safety, technical and passenger conditions of the vehicles. Bogie and body frame design of the train are another significant parameters of the weight reduction that directly influences the performance and cost. Small size bogie design which includes less material decreases body mass considerably but it should be evaluated to provide optimum performance conditions related to route, infrastructure and people expectation. Tilting mechanism results in fast vehicles and less journey times. On the other hand, use of heavy equipment such as actuators in order to provide safety and comfortable journey leads to track damage and high energy consumption. Wiring is an alternative way of reducing train specific mass that causes not only complexity for train movement but also overweight trains. Computer and electronic innovations will enable to use of lighter wiring or wireless equipment for signalling and train protection systems.

In conclusion, environmental issues will be extremely important such as use of recycle material and global warming in future. In the railway sector, air pollution can be reduced with low energy consumption. Thus, new and modern designs should have lightweight equipment and systems. There are several methods that can be applied to reduce specific train mass but optimum design conditions should be clarified as much as possible and therefore, suitable material choice and lightweight design should be achieved to provide high performance with low cost.

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