Currently, railways have great potential over other modes of transport in meeting sustainability development goals (economic, social and environmental). It is expected that railway capacity would increase at a higher rate than other modes of transport. This would result in a rise in the number of people travelling by rail. Wheelchair users are expected to be part of this population and, taking the UK as an example, are in fact increasingly choosing to travel by rail. According to the UK Association of Train Operating Companies (ATOC), disabled railcard journeys in the UK have trebled in the last 15 years. There are now 122,000 railcards in use by people with disabilities, an increase of more than 40,000 in just five years – thanks to the increasingly accessible infrastructure and rolling stock. To improve accessibility, vehicle interiors are now engineered to accommodate a wheelchair occupant.

Fixed seats on trains are designed to national and international standards as part of the vehicle dynamic system. By contrast, most wheelchairs are not intended for use as a vehicle seat and have not been designed or tested for crashworthiness. However, currently, there is a push for wheelchair manufacturers to design them to withstand high crash deceleration. In rolling stock, consideration of human factors and ergonomics has led to the development of standards to provide adequate space in the wheelchair area. To be deemed accessible, a railway vehicle should at least accommodate a

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Figure 1: A typical open space designated wheelchair space
reference wheelchair with dimensions as stipulated by the PRM TSI (the length of the wheelchair, \( L_{wc} \leq 1,250\text{mm} \), which includes foot protrusion and the maximum height \( h_{wc} \leq 1,375\text{mm} \) – see Figure 1 on page 77). When on board a railway vehicle, it is recommended that a wheelchair occupant transfers to a vehicle seat. However, the common practice is to park in a wheelchair space, either facing forward or rear, but not sideways. In the event of a crash, the main concern for occupant safety is secondary collision with interior furniture or features.

Wherever a designated wheelchair space is provided, the EC PRM TSI specification sets a length \( L_{ws} \) requirement of 1,500mm to 1,600mm (minimum) depending on the seating configuration (Figure 1 on page 77 shows an Open Space Configuration). However, to allow for easy manoeuvrability, it is recommended that the area should be as large as possible. Nevertheless, train manufacturers build to maximise the number of fixed seats. Subsequently, the wheelchair space is typically minimised to between 1,500mm and 1,600mm long. It is important to note that crash-worthiness and wheelchair space requirements have already reduced the number of fixed seats by about 10 and six, respectively. The reduction in the number of seats is in contrast with the desire for train operators to run economically because increasing the number of seats maximises space utilisation. To this effect, train manufacturers tend to minimise the wheelchair space rather than maximise it beyond 1,600mm.

While much has been done to ensure that infrastructure and rolling stock are accessible, little has been done to design the interior of trains for reduced injury severity during secondary collision. This article discusses what factors ought to be considered by rolling stock interior design engineers when developing retrofitted or new-build railway vehicles to improve wheelchair occupant safety during a crash. The factors identified include human related factors, wheelchair design and railway interior design.

**Wheelchair occupant crash dynamics**

During a train crash (primary collision), the occupant continues to travel with their initial motion (see Figure 2). This motion continues until the occupant makes contact with an object in their trajectory (referred to as secondary collision) at a relative velocity \( V_{ir} \). Common secondary collision objects include furniture such as partitions, grab poles and tables.

Since wheelchairs are not secured and the occupant is not restrained, the higher the weight of the wheelchair and occupant, the higher the impact kinetic energy will be, and therefore the injury potential.

**Human factors**

When dealing with wheelchair occupant transportation in rolling stock, the starting point is to recognise that although a wheelchair is used as a seat on board a train, it is a mobility device used by people with disabilities as an assistive technology. This subsequently takes into account Human Factors Engineering (HFE). The basic premise of human factors and ergonomics is user-centred design, based on a fundamental understanding of user capabilities, needs, and preferences. These human-related factors include anthropometry, weight, personal preferences, medical condition, and the ability to interact with wheelchair and the interior environment.

The occupant’s anthropometry is one of the most important factors affecting the occupant’s crash kinematics behaviour in that it determines that mass moment of inertia. Missing or not fully developed limbs may influence whether the occupant uses footrests, a situation that determines the pre-crash posture. Wheelchair
users with both lower extremities are likely to
place their feet on the footrest. This, however, is a
personal preference of the occupant. Crash tests
conducted involving wheelchair occupants have
shown that placing the feet on the footrest
influenced the initial occupant posture and
subsequently post-crash occupant kinematics and
secondary collision characteristics. The
occupant’s weight influences the secondary
collision kinetic energy. Their ability to interact
with the wheelchair and vehicle environment
determines the pre-crash orientation and
subsequent crash kinematics. Therefore, an
optimised crash-safe train environment should
put human factors specific to wheelchair
occupants at the centre of the design. These
factors determine pre-crash occupant posture,
which ultimately determines the occupant’s
secondary collision characteristics and potential
injury severity.

Direction of travel
During a frontal crash, an occupant is projected
forward with reference to the decelerating train.
Therefore, the seating orientation and location is
important in determining the occupant
kinematics and which interior furniture/feature
the occupant would impact in a secondary
collision. A train is bi-directional; therefore,
secondary collision would occur either with
the front parts of the occupant’s body if the
wheelchair occupant is facing the direction of
travel, or the rear parts of the occupant’s body if
they are facing the opposite direction. In some
older vehicles, however, sideward facing is
unavoidable due to lack of wheelchair turning
space inside the vehicle.

Wheelchair characteristics
Figure 3 (opposite) shows some of the
wheelchair parameters that influence user/ wheel-24
chair and wheelchair/space interaction. Not indicated
are three angles which are critical to the dynamic
response of the wheelchair and its occupant
during a crash. These are the angles of inclination
of the footrest, seat and backrest. Wheelchair
occupant crash displacement increases with
decreasing footrest inclination, seat and back-
rest angles. In addition, wheelchair crash
motion characteristics are influenced by the
coefficient of friction between the wheels and
the floor, particularly when the wheelchair
brakes are applied.

Notably, compared to manually powered
wheelchairs, electric powered wheelchairs offer
superior control capabilities and have greater
potential to address human factors concerns
specific to the disabled. They have better control
and therefore parking characteristics than
manually powered ones. This determines pre-

Rolling stock interior design, wheelchair users expect a
bottom-up approach – this would ensure that
most human related factors are incorporated in
the designs. Therefore, there is a need to
effectively engage wheelchair users through
information dissemination.

Law and legislation
When developing future legislation and rolling
stock interior design, wheelchair users expect a
bottom-up approach – this would ensure that
most human related factors are incorporated in
the designs. Therefore, there is a need to
effectively engage wheelchair users through
information dissemination.

Secondary collision objects
and occupant proximity
Rolling stock interior design furniture and
features surrounding a wheelchair occupant
constitute secondary collision objects in the
event of a crash. The pre-crash proximity to
the occupant, geometry and mechanical
properties of these objects determine the
potential injury severity created by secondary
collision. Figure 2 (page 78) implicitly shows that
the higher the initial distance between the
department and secondary collision object,
the higher the potential impact velocity.
Therefore, the pre-crash proximity of the occupant prior
to the crash determines the relative impact velocity (V_{rel})
and injury potential.

The characteristics of occupant secondary
collision are strongly dependent on the

In the UK, studies have found that various
organisations and disability groups did not wish
to use wheelchair securement and occupant
restraint systems on board trains. Most were
unwilling to use them because they were
considered to be time-consuming, and posed
potential difficulties with the release of such
systems in an emergency. Therefore, any train
interior design aimed at improved crash-
worthiness should consider these challenges.
configuration of the wheelchair space. In the Open Space configuration, frontal collision secondary collision objects in the wheelchair parking space include partitions, grab poles and the floor. Where a fixed bay table is fitted, the main frontal collision object is the table itself. Positioning of furniture with respect to a wheelchair occupant influences how and where the furniture collides with an occupant. It also determines the occupant’s displacement and impact velocity; therefore how much kinetic energy the occupant carries.

injury. Subsequently, the geometrical and material characteristics of the secondary collision object are key parameters when designing wheelchair space for minimised injury severity.

Flow chart of factors influencing design of wheelchair space

Figure 7 shows how design factors discussed above relate to the wheelchair occupant crash injury potential. It postulates that human factors specific to wheelchair users should be the centre and how the occupant interacts with the wheelchair and railway vehicle interior.

Conclusion

A crashworthy wheelchair railway vehicle space design should consider the complex interrelation between human factors, wheelchair design, train operations and secondary collision objects/furniture. For this reason, to comprehensively and effectively define occupant safety when transported by a train, it is imperative that the subject of crashworthiness incorporates wheelchair occupant human related factors. This will also assist in developing crash-safe future designs of carriage interior furniture, accident investigation and subsequent recommendations aimed at preventing wheelchair occupant injury. Incorporating wheelchair occupant-specific human factors would also enhance their acceptability of any legislative and technical measures that are aimed at increasing occupant safety.

To improve wheelchair railway vehicle crash safety, the design of the railway vehicle interiors should aim at optimising the dimensions of the wheelchair space rather than maximising them. It reflects a compromise between accessibility which tends to maximise the wheelchair space and crash safety which improves with reducing the initial distance between the occupant and secondary collision objects. Appropriate geometry and material properties of these objects should also be determined. This would result in an optimum design, which interior design engineers need to target. The design should also incorporate the operational constraints of train operators. As part of the PRM TSI, the EU needs to develop a standard that specifies a wheelchair environment that ensures occupant safety comprehensively and effectively define occupant safety and also optimised for crashworthiness.

References

1. Images obtained from the Report ‘A Survey of Occupied Wheelchairs and Scooters’ conducted in 2005. Research conducted on behalf of Mobility and Inclusion Unit of the Department for Transport, United Kingdom

Biography

Dr. Emmanuel Matsika, a mechanical engineer, is a Researcher at NewRail where he conducts research on EU Projects aimed at improving safety and security of passenger railway vehicles, and enhancing performance of railway freight vehicles. His PhD research was on railway vehicle crashworthiness, focusing on crash safety of wheelchair occupants.