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Analytical Approach to Determining Factors that Influence Wheelchair Occupant Kinematics during a Railway Vehicle Crash

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Abstract

Design-for-accessibility is becoming a global requirement. While much has been done to achieve high levels of accessibility in rail transportation, not much has been done to improve the safety of these vulnerable users in the event of heavy braking and, in a worse case, crash. The kinematics that ensues after the crash governs the secondary collision characteristics, injury mechanism and ultimately injury severity. Fundamental analytical understanding of the factors that influence crash occupant motion is required to ensure kinematics that has reasonable accuracy. This is key in providing well informed and accurate input data and establishing realistic boundary condition; particularly when commercial software is applied like a 'black box' without delving into the fundamental dynamics behaviour. The general wheelchair occupant kinematic model presented in this paper is initially based on the ideal condition for safety as applied in road vehicles. The data and information obtained from the model equations are, however, invaluable to providing input data and boundary conditions that result in more realistic commercial software FE model results.

Keywords: Occupant kinematics; secondary collision; linear motion; angular motion; degrees of freedom; sagittal plane, wheelchair occupant.

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1. Introduction

Design-for-accessibility is becoming a global requirement. While much has been done to achieve high levels of accessibility in rail transportation, not much has been done to improve the safety of these vulnerable users in the event of heavy braking and, in a worse case, crash. The kinematics that ensues after the crash governs the secondary collision characteristics, injury mechanism and ultimately injury severity. During a railway vehicle crash, occupants tend to continue in the initial trajectory based on Newton's First Law of Motion. The kinematics that ensues after the crash governs the secondary collision characteristics, injury mechanism and ultimately injury severity. If a seat for able people (rigidly connected to the railway vehicle floor) is considered as one object, and the occupant as another object, then the crash motion would be considered as a 2-degree of freedom (DoF) problem. This is because the occupant is not restrained. However, for a wheelchair occupant, the wheelchair is not secured and the occupant is not restrained. This yields a more complex 3 DoF scenario, which requires more realistic data and information in order to accurately determine the post-crash occupant kinematics.

Fundamental analytical understanding of the factors that influence crash occupant motion is required for such accurate outcomes. This is key in providing well informed and accurate input data and establishing realistic boundary conditions, particularly when commercial software is applied like a 'black box' without delving into the fundamental dynamics behaviour. This is new research that has not been carried out for the safety benefit of wheelchair users who are relatively new occupants on railway vehicles. From crash tests in past studies, it can be concluded that during a frontal impact (at 0º to the longitudinal direction), the occupant travels in one direction (Matsika el al, 2011). Therefore, analysis is narrowed down to 2-D (planar) problem in the sagittal plane. For purposes of injury assessment in vehicles involving frontal crash, analysis of kinematics in this one plane is sufficient, and has been widely applied in both rail and road vehicles. To this effect, the approach applied was that of dynamics of a rigid body in general plane motion, which combines translation and rotation. Subsequently, the kinematics of a wheelchair occupant considered in this paper is defined by the general linear and angular momentum equations.

The accuracy of the results of any computer numerical model depends on the accuracy of the input data, and also on how realistic the initial and boundary conditions have been set. It is for this reason that this paper is dedicated to applying analytical methods to rationally identify key input parameters. The parameters drawn out of this process are used to develop crash scenarios which will be considered for crash analysis. Selection of the scenarios is also guided and informed by the results from Human Factors studies (Matsika, 2013). Additional relevant guiding information was obtained from literature review related to disability-specific human factors, wheelchair design and railway carriage interior design.

2. Methodology

The general wheelchair occupant kinematic model presented in this paper is initially based on the ideal condition for safety as applied in road vehicles as a reference starting point (Dsouza, 2010; Rodgers, 2009). Here the wheelchair is secured using a tie-down system, and the occupant is restrained using a 3-point safety belt. For this general model (and dynamic system), three subsystems are developed namely the occupant, wheelchair and railway vehicle. Free-body-diagrams are developed from which governing equations of motion are determined. The deceleration (crash pulse) is applied to the vehicle floor. Since the main focus of this research was the occupant kinematics, only the occupant and wheelchair kinematics analysis is detailed. Moreover, the vehicle is constrained to move only horizontally in an inherently non-complex motion.

The equations developed show that there are many forces being applied on several interfaces on each of the subsystems identified (occupant, wheelchair and vehicle floor). They also reveal critical factors that influence wheelchair and/or occupant kinematics and therefore influence the ultimate injury severity of the occupant in the event of a crash.

2.1. Development of a Generic Crash Wheelchair Occupant Kinematics Model

From the video footage obtained from the crash tests carried out by Matsika et al (2011), it can be concluded that during a frontal impact (at 0º to the longitudinal direction), the occupant travels in one direction. Therefore, analysis is narrowed down to 2-D (planar) problem in the sagittal plane. To this effect, the approach applied was that of dynamics of a rigid body in general plane motion, which combines translation and rotation.

2.1.1. Description of Loadings and Constraints on a Wheelchair Occupant

Based on the experimental crash results mentioned above, the following generic kinematics diagram was developed to explain the motion of various parts of a human body during a crash involving a wheelchair occupant. Figure 1 show the generalised motion and constraints/loads as they apply to a wheelchair occupant. The parametric details are explained in Table 1.

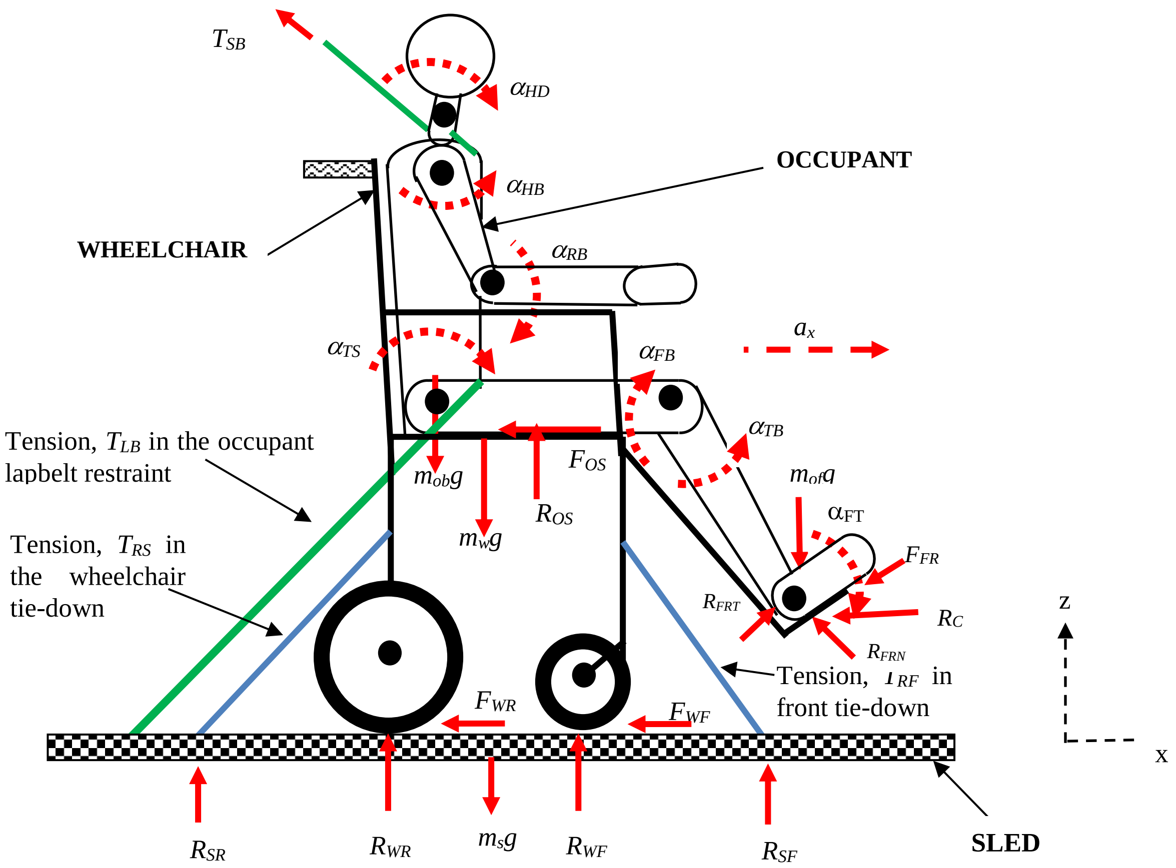

Figure 1: Generic System Motion and Loading of the Wheelchair and Occupant (Matsika, et al, 2011)

The general dynamic system shown in Figure 1 constitutes the following subsystems:

- Occupant
- Wheelchair
- Sled/railway vehicle

The deceleration (crash pulse) is applied to the sled. Since the main focus of this research is the occupant kinematics, only the occupant and wheelchair kinematics analysis will be detailed in the following sections.

2.1.2. Kinematics of the Wheelchair Occupant

For the occupant, the body is isolated as a dynamic subsystem with rigid parts that can rotate about respective joints. All external forces acting on the occupant are thus accounted for. The governing equations for a specific constraint situation could be developed by equating to zero any force that is not applicable. For example, if the occupant is not using a shoulder belt, then T_{SB} will be equal to zero. According to the ISO 7179/19 standard (ISO, 2001a), the angle of inclination of the lap belt to the floor (ϕ) and that of the wheelchair tie-down (front and rear) should be the same, which is 45°. The tension created in the belt appears as a resistive force in the opposite direction to the forward occupant motion resulting from the deceleration, a_x. Since motion is constrained in the x-direction,

a_x will be replaced by a_T (crash pulse) in all the analysis. The heel support reaction, R_{FRT} is present only just before the application of the deceleration a_T . Therefore, R_{FRT} may be ignored in the force analysis.

Table 1: Motions and constraints/loads that apply to Different Test Ids

Description	Denotation	Occupant Body Part
Static load	$m_{ob}g$	Upper body (general)
	$m_{of}g$	Lower limbs (general)
	$m_w g$	Wheelchair
	$m_S g$	sled
Angular Motion	α_{HD}	Head
	α_{TS}	Torso
	α_{HB}	humerous upper limb
	α_{RB}	radius upper limb
	α_{FB}	femur lower limb
	α_{TB}	tibia lower limb
Angular moment	$I_{HD}\alpha_{HD}$	Head
	$I_{TS}\alpha_{TS}$	Torso
	$I_{HB}\alpha_{HB}$	Upper Limb (Humerous)
	$I_{RB}\alpha_{RB}$	Upper Limb (Ulna)
	$I_{FB}\alpha_{FB}$	Lower Limb (Femur)
	$I_{TB}\alpha_{TB}$	Lower Limb (Tibia)
	$I_{FT}\alpha_{FT}$	Foot
Friction	F_{OS}	Between the occupant and seat
	F_{FR}	Between foot and foot rest
	F_{WF}	Between the front wheel and floor
	F_{WR}	Between the rear wheel and floor
Reaction	R_{OS}	Between the occupant and seat
	R_{WF}	On front wheels
	R_{WR}	On rear wheels
	R_{FRN}	On footrest
	R_{FRT}	On heel support
	R_{SF}	On sled rear
	R_{SR}	On sled front
	R_C	Inertia on footrest
Tension	T_{SB}	Shoulder belt
	T_{LB}	Lap belt
	T_{SF}	Front wheelchair tie down
	T_{SR}	Rear wheelchair tie down

In addition, there are forces that cancel out, but are shown solely for illustrative purposes, and may therefore also be ignored in the analysis. These are:

$$m_{ob}g = R_{os} \tag{1}$$

$$m_{of}g = R_{of} = \sqrt{R_{FRT}{}^2 + R_{FRN}{}^2} \tag{2}$$

Where, $R_{FRN} = m_{of}g \cos \beta_3$ (3)

$R_{FRT} = m_{of}g \sin \beta_3$ (4)

Where β_3 is the footrest angle of inclination with respect to the horizontal plane.

Using the momentum equations for planar (x-z plane) motion, the following set of linear and angular equations of motion are developed for the occupant (Figure 2).

Longitudinal Motion

$$\sum F_x = m_o a_x = m_o a_T$$

Equilibrium of forces in the horizontal direction gives the following expression:

$$-F_{OS} - T_{LR} \cos\phi_1 - T_{SB} \cos\varphi - F_{FR} \cos\beta_3 = m_o a_x = m_o a_T \tag{5}$$

Where,

$F_{OS} = \mu R_{os} = \mu m_{ob} g$

$F_{FR} = \mu(R_{CN} + R_{FRN}) = \mu\, (m_{of} a_T \sin\beta_3 + m_{of} g \cos\beta_3)$

$= \mu m_{of}\, (a_T \sin\beta_3 + g \cos\beta_3)$ (6)

R_{CN} is the normal reaction of the inertial foot force on the footrest plane, and μ is the coefficient of friction.

$R_{CN} = m_{of} a_T \sin\beta_3$

Replacing the expressions for F_{FR} and F_{OS}, Equation 6 becomes,

$-\mu m_{ob} g - T_{LR} \cos\phi_1 - T_{SB} \cos\varphi - \mu m_{of} g \cos\beta_3^2 = (\mu m_{of} \sin\beta_3 \cos\beta_3 + m_o) a_T$ (7)

And, m_o – total mass of the occupant which is the sum of the mass of the upper part of the body (m_{ob}) acting on the seat and the mass of the lower limbs (m_{of}) acting on the footrests. ($m_o = m_{ob} + m_{of}$)

ϕ_1 - Angle between the line of action of the lap belt tension and the horizontal plane, which by design is equal to the angle between the line of action of wheelchair tie-down and the horizontal.

φ – The angle between the shoulder belt and the horizontal plane

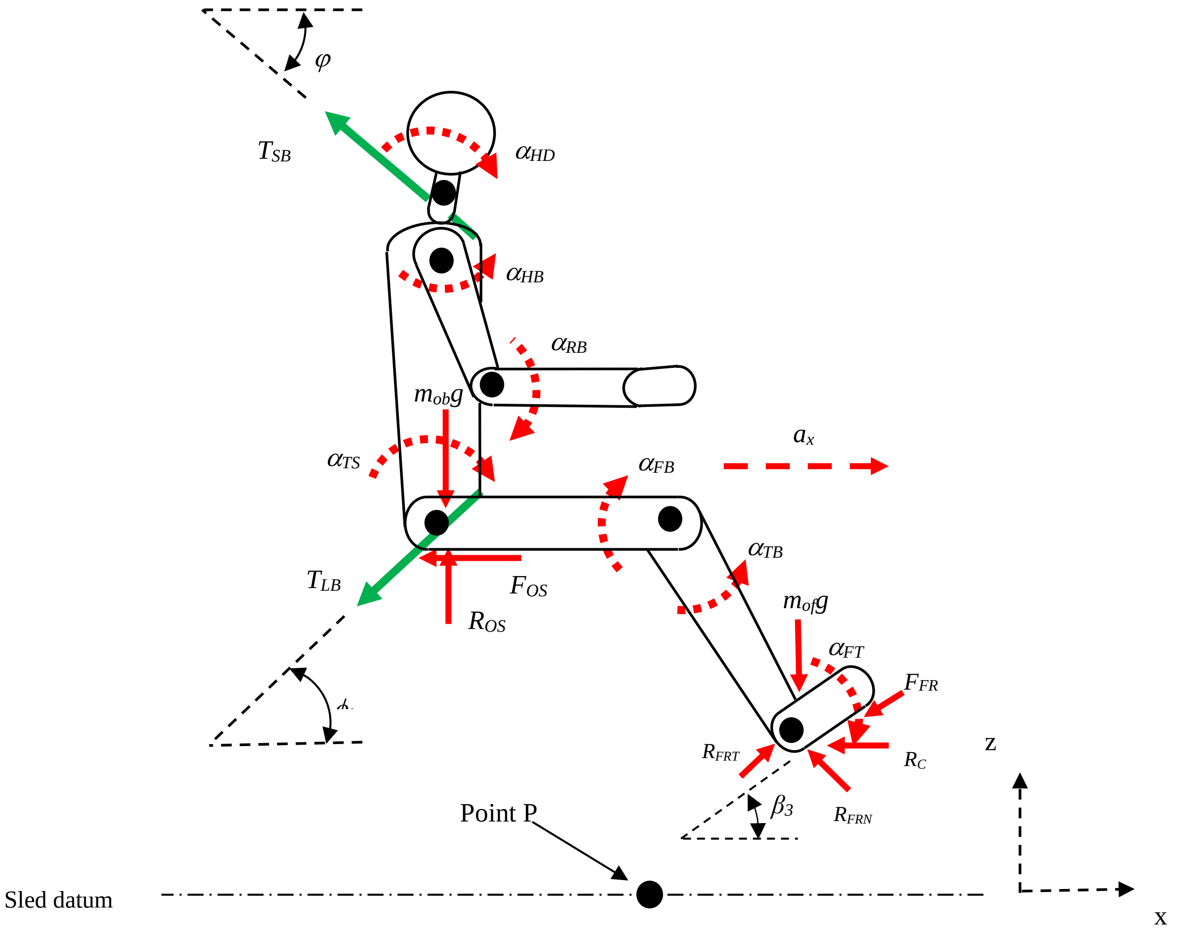

Figure 2: Occupant Kinematics Subsystem

Vertical Motion

Applying the equation of motion in space to the system in the vertical axis gives the specific equation below,

$$\sum F_Z = m_o a_Z$$

Equilibrium of forces in the vertical direction gives the following expression:

$-T_{LR} \sin\phi_1 + T_{SB} \sin\varphi - F_{FR} \sin\beta_3 = m_o\, a_Z$ (8)

Replacing the expression of F_{FR} (Equation 5) in Equation 8 gives,

$-T_{LR} \sin\phi_1 + T_{SB} \sin\varphi - \mu m_{of} g \cos\beta_3 \sin\beta_3 = \mu m_{of}\, a_T \sin\beta_3^2 + m_o\, a_Z$ (9)

It should be noted that a_z is nearly zero as long as there is contact between the occupant and the seat.

Angular Motion in the x-z plane

Applying the equation of motion in space to the system gives the specific equation below,

$$\sum M_p = I_{Go}\alpha_O + m_o a_T d$$

Where, M_p = moment about an arbitrary axis p. In Figure 2, p has been conveniently taken as the axis passing through the contact between the front castor wheel and the floor.

I_{Go} = moment of inertia of the occupant about the centre of gravity. A further discussion on mass moment of inertia of human beings.

Moments acting on the occupant subsystem about the axis p yield the following expression,

$$-T_{SB}\cos\varphi\, h_{SB} + T_{SB}\sin\varphi\, L_{SB} - T_{LB}\cos\phi_1\, h_{LB} - T_{LB}\sin\phi_1\, L_{LB} - F_{OS}\, h_S - m_{ob}gL_{CG}$$
$$+ R_{OS}L_{CG} + m_{of}gL_{FR} - R_{of}L_{FR} - (F_{FR}\cos\beta_3)h_{FR} + (F_{FR}\sin\beta_3)L_{FR} = I_{Go}\alpha_o + m_o a_T h_{CG} \quad (10)$$

Where L_{SB} – the horizontal distance from the front wheel axis to the vertical line passing through the top of the seat belt/shoulder contact point.

L_{LB} – the horizontal distance from the front wheel axis to the point where the lap belt goes round the occupant

L_{CG} – the horizontal distance from the front wheel axis to the vertical line passing through the centre of gravity of the upper part of the occupant (where m_{ob} passes).

L_{FR} – the horizontal distance from the front wheel axis to the vertical line passing through the centre of application of the footrest load reaction.

h_{SB} – the height from the floor to the top of the seat belt/shoulder contact point.

h_{FR} – the height from the floor to the line of application of the friction force between the feet and footrest.

h_{LB} – the height from the floor to the point where the lap belt goes round the occupant.

h_S – the height from the floor to the occupant/seat contact (the seat height).

Feet Motion

The force induced by the deceleration acts on the ankle. When the resultant force passes through a line beyond the edge of the footrest, a clockwise moment ($m_{of}a_T e$) is created about an instantaneous contact point (Figure 3). This unbalanced force is responsible for the angular motion of the feet that was observed at the edge of the footrest in experimental tests (Matsika et al, 2011). Foot rotation occurs only for the condition $0 < e$.

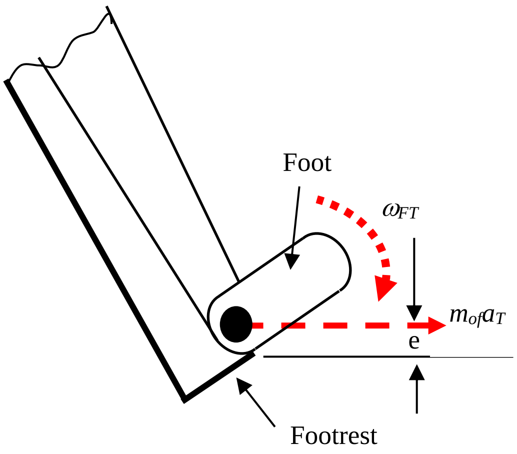

Figure 3: Foot rotation at the footrest edge

The moment created on the foot about the horizontal axis passing through the ankle, M_F, is given by Equation 11,

$$M_F = m_{of}a_T e \quad (11)$$

2.1.3. Kinematics of the Wheelchair

In this section, the wheelchair is isolated as a single rigid body dynamic subsystem (Figure 4). All external forces acting on the wheelchair are accounted for. The governing equations for specific constraint situation could be developed by equating to zero any force that is not applicable. For example, if the rear tie down is not applied, then T_{SR} will be equal to zero. The tension created in the rear tie-down appears as a resistive force in the opposite direction to the forward motion of the occupant which results from the acceleration, $a_x = a_T$.

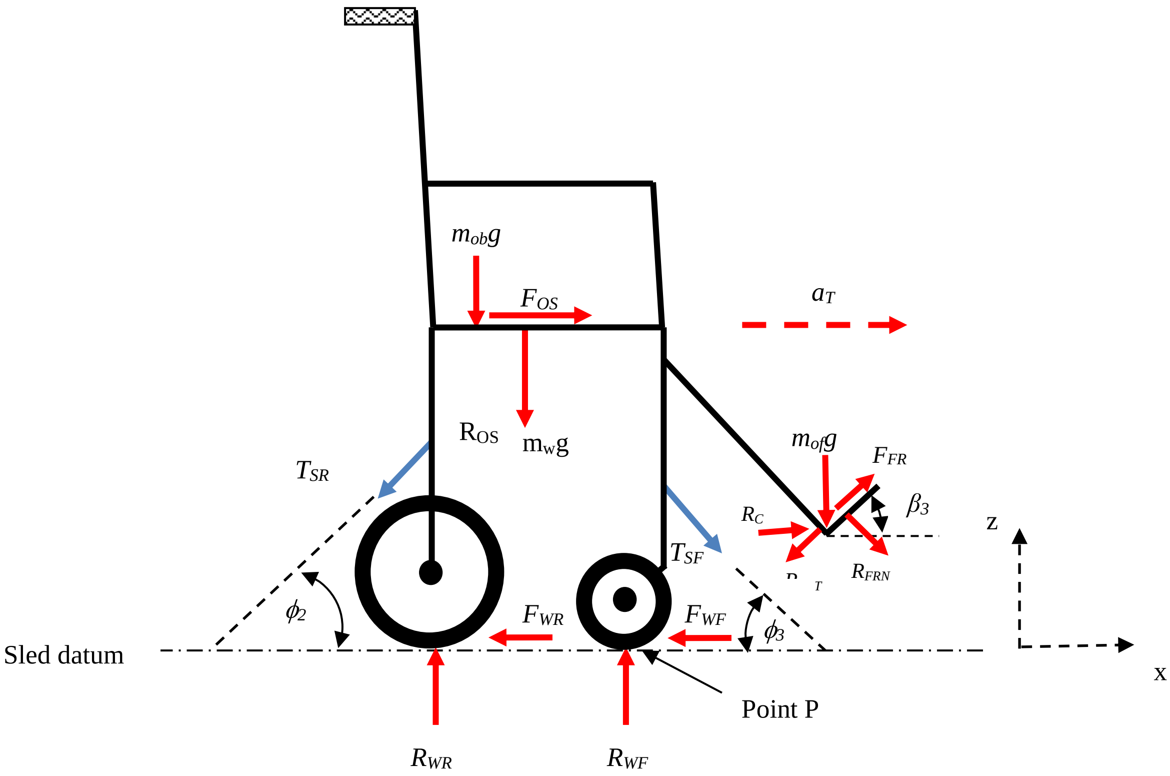

Figure 4: Wheelchair Kinematics Subsystem

Using the momentum equations for planar (x-z plane) motion, the following set of linear and angular equations of motion are developed for the occupant. Treatment similar to the occupant above produces the following equation:

Longitudinal Motion

$$-T_{SR}\cos\phi_2 + \mu m_{ob}g - \mu R_{WR} - \mu_r R_{WF} + T_{SF}\cos\phi_3 + \mu m_{of}(a_T\sin\beta_3 + g\cos\beta_3)\cos\beta_3 = m_w a_T \qquad (12)$$

Where, m_w – mass of wheelchair

ϕ_2 – Angle between the line of action of the tension of the rear wheelchair tie-down and the horizontal.
ϕ_3 – Angle between the line of action of the tension of the front wheelchair tie-down and the horizontal.
$F_{WR} = \mu R_{WR}$ (frictional force taking that the brakes are applied on rear wheels)
$F_{WF} = \mu_r R_{WF}$ (rolling resistance force taking that the front castors roll freely)
μ_r is the rolling resistance coefficient

Vertical Motion

$$-m_{ob}g - m_{of}g - T_{SR}\sin\phi_2 - T_{SF}\sin\phi_3 - R_{SB}\sin\varphi - m_w g + \mu m_{of}(a_T\sin\beta_3 + g\cos\beta_3)\sin\beta_3 = m_w a_z \qquad (13)$$

Angular Motion in the x-z plane

$$R_{WR}L_{WB} - (T_{SR}\cos\phi_3)h_{SR} - (T_{SR}\sin\phi_3)L_{SR} - m_{ob}g\,L_{CG} - m_w g\,L_{WG} - F_{OS}h_S + (T_{SF}\cos\phi_3)h_{SF} + (T_{SF}\sin\phi_3)L_{SF} + (F_{FR}\sin\beta_3)L_{FR} + (F_{FR}\cos\beta_3)L_{FR} - R_{of}L_{FR} + m_{of}gL_{FR} - m_{of}a_T h_{FR} = I_w\alpha_w + m_w a_T h_{CGw} \qquad (14)$$

Where, L_{WB} – Wheelbase

L_{SR} – the horizontal distance from the front wheel axis to the vertical line passing through the rear tie-down anchorage point on the wheelchair

L_{SF} – the horizontal distance from the front wheel axis to the vertical line passing through the front tie-down anchorage point on the wheelchair.

L_{WG} – the horizontal distance from the front wheel axis to the vertical line passing through the centre of gravity of the wheelchair

L_{CG} – the horizontal distance from the front wheel axis to the vertical line passing through the centre of gravity of the occupant.

L_{FR} – the horizontal distance from the front wheel axis to the vertical line passing through the centre of application of the footrest load reaction.

h_{FR} – the height from the floor to the line of application of the friction force between the feet and footrest.

h_{SR} – the height from the floor to the rear tie-down anchorage point on the wheelchair.

h_{SF} – the height from the floor to the front tie-down anchorage point on the wheelchair.

h_S – the height from the floor to the occupant/seat contact (the seat height).

These equations developed above show that there are many forces being applied on several interfaces on each of the subsystems identified (occupant, wheelchair and sled floor). One particular observation is that the loads on the footrest are applied on a plane that is at an oblique angle to the global x-direction. The footrest angle, β_3, plays an important role in determining the foot's angle of attack against a secondary collision object. Therefore, β_3 has a potential to determine the kinematics resulting from secondary collision, and the ultimate injury mechanism. During a crash a wheelchair occupant may or may not be placing their feet on the footrest (Matsika, 2013)

The equations that have been developed in this section apply only to rigid bodies for an instantaneous condition. In reality the occupant and/or wheelchair are in continuous motion with respect to time, representing a transient condition. Further, an occupant is made of deformable material. With many variables identified changing constantly with time for a deformable body, either multi-body or finite element approach should be applied to solve crash tests.

3. Analysis of factors influencing occupant kinematics

The accuracy of the results of any computer numerical model depends on the accuracy of the input data, and also on how realistic the initial and boundary conditions have been set. Selection of the scenarios is guided and informed by the results from the socio-technical studies and experimental crash tests. Additional relevant guiding information was obtained from literature review related to disability-specific human factors, wheelchair design and railway carriage interior design. Here a wheelchair occupant railway vehicle crash scenario (R_{cs}) is defined as initial conditions constituting a combination of core variables related to the occupant (W_o), wheelchair (W_c), and carriage interior configuration (C_c) and any additional variables, lambda (λ) (Matsika et al, 2013). Therefore,

$$R_{cs} = f(W_o, W_c, C_c, \lambda) \quad (15)$$

Where the core variables are defined as,

W_o – occupant characteristics such as anthropometry, gender, and weight.

W_c – wheelchair design characteristics such as weight, stiffness, dimensions and angular position (tilt, recline and footrest angle)

C_c – railway carriage interior configuration (open space wheelchair area or having an object such as a fixed table)

λ - may represent the following:

- Occupant facing orientation with respect to direction of travel (same direction, opposite direction, transverse direction and an oblique angle either in the same direction of travel or in the opposite direction)
- Angle of inclination of the occupant in the vertical plane (influenced by the angle of inclination of the wheelchair seat, railway vehicle floor and rail track).
- Wheelchair securement
- Occupant restraint

As mentioned earlier, the injury severity of an unrestrained wheelchair occupant depends on the likelihood of an occupant being displaced and involved in secondary collision with carriage interior furniture. Being accessibility driven, the wheelchair space environment takes into account functional design and human factors. Subsequently, the key variables that influence occupant kinematics and injury severity are the occupant displacement (excursion) and geometry of interior features involved in secondary collision. As such, selection of the reference case was based on a combination of the above stated variables that would produce the maximum displacement of the occupant. Other factors that would influence the occupant kinematics, and can be analytically incorporated includes:

Facing Direction

During a railway vehicle crash, it is likely that the occupant will be facing the direction of travel for the following reasons:

- By design, a railway vehicle is bi-directional, meaning that even if an occupant seats against an upright pad (rigid) support, the pad is effective only in one direction.
- Results from a Human Factor study (Matsika, 2013) showed that most wheelchair occupants tend to face the direction of travel. Because the wheelchair is not secured in a pre-determined location, the occupant is free to face their preferred direction.

Therefore, for all numerical simulation analysis only forward facing was considered for the above mentioned reasons, and also because it represents the worst case scenario.

Wheelchair Securement and Occupant Restraint

Currently, both the EU PRM TSI, and UK RVAR 2010 do not require a wheelchair to be secured, nor the occupant to be restrained. Therefore, during the analysis, the wheelchair was not secured, and the occupant was not restrained.

Occupant Selection (W_o)

A generic person with all limbs is selected for the analysis. This is not withstanding the possibility that a wheelchair occupant may have some of the limbs missing. For investigating motor vehicle frontal impacts, a dummy with all limbs is used (Dsouza and Bertocci, 2010; Dvorznak et al, 2005).

Wheelchair Design Characteristics (W_c)

In this research, Figure 5 postulates that the occupant posture is determined by the wheelchair's initial geometry:

- The back rest angle, recline (β_1)
- Seat inclination, tilt (β_2)
- Foot rest inclination, legrest/footrest elevation (β_3)

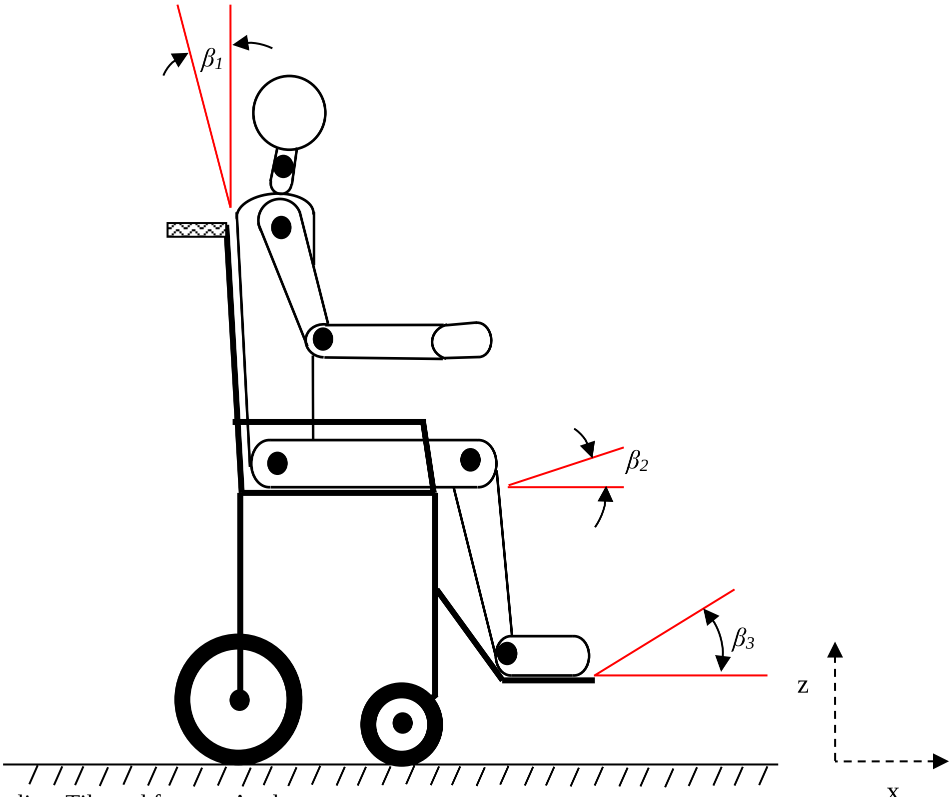

Figure 5: Recline, Tilt, and footrest Angles

Carriage Interior Configuration (C_c)

The wheelchair parking space plays an important role in establishing the dimensions for occupant kinematics. Under the EC, the PRM TSI (EC, 2007a) applies to passenger carriage building standards. However, in UK, all non-interoperable railway vehicles need to comply with the RVAR 2010 (the revised RVAR 1998). Both regulations, however, require that for stability, the wheelchair should be positioned either facing the direction or opposite the direction of travel. Nevertheless, in older railway vehicles, it is common to find wheelchairs facing transverse or even at oblique angle. The EC standard sets a minimum requirement of 1500mm to 1600mm. To allow for easy manoeuvrability, however, it is recommended that the area should be as large as possible (DfT, 2005). Nevertheless, train manufacturers build to maximise the number of fixed seats. Occupant impact with interior furniture (object) results in secondary collision. The mechanical and geometrical characteristics of the object has a huge bearing on the injury severity. Potential injury increases with increasing object strength and/or stiffness and its sharpness.

4. Conclusions

The equations developed using an analytical approach applies only to rigid bodies for an instantaneous condition. In reality the occupant and/or wheelchair are in continuous motion with respect to time, representing a transient condition. Further, an occupant is made of deformable material. However, the approach has been used to identify key factors and parameters that would serve as input to a multi-body or finite element approach. The factors could guide the setting of input parameters, and boundary conditions that yield more realistic results.

The equations show that there are many forces being applied on several interfaces on each of the subsystems identified (occupant, wheelchair and vehicle floor). They also reveal critical factors that influence wheelchair and/or occupant kinematics and therefore influence the ultimate injury severity of the occupant in the event of a crash. These include:

- The angles of inclination, recline and foot rest
- Friction between the occupant and the seat; feet and foot rest; wheelchair and floor
- Geometry and mechanical properties of secondary collision objects
- Direction of travel taking account of the fact that a railway vehicle runs bi-directionally
- Wheelchair securement and occupant restraint

Properly determining these values would help increase the accuracy of the occupant kinematics, and ultimate injury levels. It is worthwhile pointing out that this paper does not aim to make recommendations to legislation and design standards. It does however enhance the process of analysing injury severity, and therefore supports the efforts to improve design for crashworthiness.

Acknowledgements

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