

Occupant Trajectory Model using Case-Specific Accident Reconstruction Data for Vehicle Position, Roll, and Yaw

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ABSTRACT

In the fields of accident reconstruction and injury biomechanics, it is often of interest to know details of an occupant's ejection from a vehicle during a rollover. Current occupant trajectory models do not account for vehicle yaw and yaw rate. Such considerations are compulsory if the occupant's rest point has a non-trivial deviation from the vehicle's roll path. Moreover, many existing models use a single, generic function for the roll rate for all analyses. Such approaches intrinsically model all rollovers as identical events, regardless of the underlying uniqueness a particular accident may exhibit.

The objective of this work is to model the trajectory of an occupant ejected from a vehicle in a rollover event. In particular, we model the vehicle's longitude, latitude, roll, yaw, and time derivatives thereof, based on data extracted from a particular accident reconstruction. We model the occupant moving in the vehicle and possibly ejected at any time during the rollover. For each admissible ejection time, we construct an occupant trajectory, landing point, and point of rest (POR). We illustrate the effectiveness of our model with a case-study where significant yaw occurs during the rollover.

Our new model, when compared with existing approaches, provides an improved understanding of occupant ejection. Additionally, the new model eliminates spurious ejection solutions predicted by previous formulations. Finally, the new model is tailored to the underlying accident reconstruction data, producing a simulation that is based on the uniqueness of a particular rollover event.

INTRODUCTION

The vehicle dynamics of rollovers has been studied by numerous researchers in the absence of consideration of

the occupants [Carter, 2002; Cooperrider, 1998; Thomas, 1989]. Others have examined the kinematics of occupants in rollover accidents, but have not modeled ejections of occupants [Orlowski, 1985; Parenteau, 2001]. Occupant trajectories have been researched in the context of pedestrian-vehicle impacts and motorcycle accidents [Aronberg, 1990; Searle, 1983; Searle, 1993; Wood, 1991]. These models apply to the airborne phase and sliding phase of a particle, and determine the launch velocity with a known total distance from launch to point of rest. In the context of rollover accidents, the launch velocity can be calculated as a function of vehicle and occupant kinematics, however, the time and vehicle location when the occupant is ejected is unknown. It is useful to predict when in the roll sequence an ejection occurred to understand details of the injury biomechanics, such as how far the occupant was thrown from the vehicle, or if there was post-ejection vehicle-ejectee contact.

A successful model of occupant ejection in rollover accidents incorporates the reconstruction information with the occupant's point of rest to determine the time of ejection, the ejection velocity, and subsequent trajectory. Funk and Luepke have published a model of occupant ejection in rollovers [Funk, 2007]. This model includes the vehicle dynamics in the longitudinal direction and takes into account roll angle and roll rate. Rather than use case-specific data for the vehicle roll angle and roll rate, Funk and Luepke assume a prescribed functional form, while noting other roll functions could be used. Their model does not consider yaw effects or lateral distance to the occupant's point of rest.

Previous published occupant trajectory formulations lack the inclusion of roll and yaw data derived from a case-specific accident reconstruction. Moreover, these models predict possible ejection points based solely on a trajectory that is along the vehicle's longitudinal roll path. Solv-

ing for the possible ejection times in the longitudinal direction produces a set of possible ejection points. These ejection points are not all feasible, however, when the vehicle does not have linear roll path, when the vehicle has non-trivial yaw characteristics, or when the occupant's point of rest deviates from the path of the vehicle. By incorporating the yaw effects, the set of predicted solutions can be pared down to a subset of solutions that matches the point of rest in both the longitudinal and lateral directions.

Extending on our previous work [Hovey, 2007], the objective of this work is to develop a comprehensive model for occupant trajectories following ejections in rollover accidents. This model uses case-specific reconstruction data to determine candidate ejection times and the corresponding ejection velocities and trajectories of the ejectee.

METHODS

The occupant trajectory model is composed of a vehicle model and an occupant model. The vehicle model describes the motion of the vehicle from its point of trip to point of rest. From trip to rest, the vehicle translates longitudinally and laterally in the ground plane, and rotates with roll and yaw. During the rollover, the occupant is initially in the vehicle, is ejected from the vehicle, moves through the air free from the vehicle, lands on the ground, and comes to rest. The occupant model describes the motion of the occupant throughout three phases: (1) moving within the vehicle, (2) moving through the air, (3) moving on the ground.

VEHICLE MODEL The vehicle is modeled as a body that translates, rolls, and yaws in the ground plane. For the present formulation, changes in elevation of the ground plane and vehicle are ignored. Vehicle rotation along the pitch axis is also ignored.

Reference Frames Let the inertial reference frame $\mathcal{F}$ have unit vectors $[\hat{e}_{\mathcal{F}1}, \hat{e}_{\mathcal{F}2}, \hat{e}_{\mathcal{F}3}]$ at origin F . Unit vector $\hat{e}_{\mathcal{F}1}$ points down the roadway in the vehicle's approximate direction of travel prior to the rollover event. Unit vector $\hat{e}_{\mathcal{F}2}$ points laterally to the left of the direction of travel, in the plane of travel. Unit vector $\hat{e}_{\mathcal{F}3}$ points up from and is perpendicular to the plane of travel. All unit vectors used in this paper are dextral, orthonormal, ordered triads.

Let the carrier frame $\mathcal{C}$ be attached to the vehicle's center of mass at point V . The carrier frame has unit vectors $[\hat{e}_{\mathcal{C}1}, \hat{e}_{\mathcal{C}2}, \hat{e}_{\mathcal{C}3}]$. Unit vector $\hat{e}_{\mathcal{C}1}$ points toward the front of the vehicle. Unit vector $\hat{e}_{\mathcal{C}2}$ points to the left of the vehicle, with the vehicle in a non-rolling configuration. Unit vector $\hat{e}_{\mathcal{C}3}$ points to the roof of the vehicle, with the vehicle in a non-rolling configuration. Note that the carrier frame is not attached to the vehicle and thus does not roll with the vehicle. The carrier frame rotates with the yaw of the vehicle

with respect to the inertial frame along the vertical axis.

Let the vehicle frame $\mathcal{V}$ be fixed to the vehicle's center of mass at point V . The vehicle's frame has unit vectors $[\hat{e}_{\mathcal{V}1}, \hat{e}_{\mathcal{V}2}, \hat{e}_{\mathcal{V}3}]$. Unit vector $\hat{e}_{\mathcal{V}1}$ points to the front of the vehicle. Unit vector $\hat{e}_{\mathcal{V}2}$ points to the left of the vehicle. Unit vector $\hat{e}_{\mathcal{V}3}$ points to the roof of the vehicle.

Fig. 1 illustrates these reference frames. Note that this convention differs from the SAE convention.

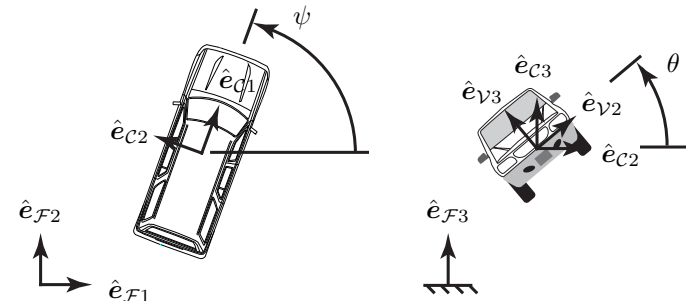


Figure 1: Illustration of inertial, carrier, and vehicle reference frames in a top view (left subfigure) and vehicle front view (right subfigure).

Degrees of Freedom The vehicle translates in the inertial frame as ${}^{\mathcal{F}}\mathbf{r}^{FV} = x \hat{e}_{\mathcal{F}1} + y \hat{e}_{\mathcal{F}2} + z \hat{e}_{\mathcal{F}3}$. The $\{x, y, z\}$ triad corresponds to the vehicle's longitude, latitude, and elevation at any time. Since we ignore elevation changes, z is constant for all time.

The carrier frame $\mathcal{C}$ rotates with respect to the inertial reference frame about the $\hat{e}_{\mathcal{C}3}$ axis, which is coincident with the $\hat{e}_{\mathcal{F}3}$ axis for all time. This rotation, ψ , represents the yaw angle of the vehicle. As viewed from above the vehicle, a positive ψ is a counterclockwise yaw; a negative ψ is a clockwise yaw.

The vehicle frame $\mathcal{V}$ rotates with respect to the carrier frame $\mathcal{C}$ about the $\hat{e}_{\mathcal{V}1}$ axis, which is coincident with the $\hat{e}_{\mathcal{C}1}$ axis for all time. This rotation, θ , represents the roll angle of the vehicle. A positive θ is a right-side-leading roll; a negative θ is a left-side-leading roll. For vehicles with the steering wheel on the left side of the vehicle, this convention extends to be a passenger-side-leading roll (positive roll angle) and a driver-side-leading roll (negative roll angle), respectively.

Initial Conditions We consider the point of trip to be the initial time $t = 0$. At the initial time, the vehicle's position and orientation are known from the accident reconstruction, written explicitly as $\{x_0, y_0, z_0, \psi_0, \theta_0\}$.

Determination of $\dot{x}_0$ and $\dot{y}_0$ requires consideration of the vehicle's path during the rollover. The vehicle translates from its point of trip to its point of rest along a path, defined as ${}^{\mathcal{F}}\mathbf{s}^V$. The path from trip to rest may not be linear.

and generally may have arcing or serpentine shapes. The length of the roll path, $\|\int ds\|$, is often referred to as the roll distance. We denote the roll distance as Δs , bearing in mind the roll distance is path-dependent. The roll distance is a known quantity, obtained from the accident reconstruction.

From conservation of energy, we find the vehicle's initial speed, $\dot{s}_0$, as

$$\dot{s}_0 = \sqrt{2\mu g \Delta s}, \quad (1)$$

where μ is the drag factor, assumed to be a constant, and g is the gravitational constant. The initial speed is also called the trip speed. The present formulation assumes a flat roll plane, and thus potential energy contributions due to changes in elevation have been ignored.

The path angle, α , along which the vehicle translates in the plane can be found from the accident reconstruction. The path angle is measured from the global reference frame axis $\hat{e}_{\mathcal{F}1}$ to the tangent of the path at any point along the path. A positive value of α makes a positive rotation along the $\hat{e}_{\mathcal{F}3}$ axis; a negative value of α makes a negative rotation along the $\hat{e}_{\mathcal{F}3}$ axis. To construct a continuous function for α , we interpolate piecewise linear functions of path lines connecting vehicle positions between templates on the accident reconstruction diagram.

With the path speed $\dot{s}$ and path angle α known for all time, the component speeds $\dot{x}$ and $\dot{y}$ can be expressed as $\dot{x} = \dot{s} \cos(\alpha)$ and $\dot{y} = \dot{s} \sin(\alpha)$. The initial conditions, $\dot{x}_0$ and $\dot{y}_0$, are then expressed at $t = 0$ with $\dot{s}_0$ and α_0 . Since z is assumed constant for all time, $\dot{z} = 0$ for all time and thus $\dot{z}_0 = 0$.

The initial conditions for $\dot{\psi}_0$ and $\dot{\theta}_0$ can be estimated from the accident reconstruction. Some accident reconstructionists define the trip point at $\theta_0 = 0$, for which taking $\dot{\theta}_0 = 0$ is reasonable. Other accident reconstructionists define the trip point at $\theta_0 = \pm\pi/8$, for which a non-zero input for $\dot{\theta}_0$ may be appropriate.

Equations of Motion The governing equation of motion along the vehicle's path is given by

$$\ddot{s} = -\mu g, \quad (2)$$

where $\ddot{s}$ is the vehicle's acceleration along the path.

Integrating the governing equation of motion from the time when the vehicle trips, t_0 , to the time when the vehicle comes to rest, t_f , gives the roll time, Δt_{roll} , where

$$\Delta t_{\text{roll}} = \frac{\dot{s}_0}{\mu g}. \quad (3)$$

The vehicle's speed along the path at any time is given by

$$\dot{s}_t = \dot{s}_0 - \mu g t, \quad \forall t \in [t_0, t_f]. \quad (4)$$

The vehicle's distance along the path at any time is given by

$$s_t = \dot{s}_0 t - \frac{1}{2} \mu g t^2, \quad \forall t \in [t_0, t_f]. \quad (5)$$

The vehicle's component speeds are then given by

$$\dot{x}_t = \dot{s}_t \cos \alpha_t, \quad (6)$$

$$\dot{y}_t = \dot{s}_t \sin \alpha_t. \quad (7)$$

The vehicle's x and y positions must be integrated along the path

$$x_t = \int_{t_0}^t \dot{x}_{\mathcal{F}1} \cdot d\dot{s}, \quad (8)$$

$$y_t = \int_{t_0}^t \dot{y}_{\mathcal{F}2} \cdot d\dot{s}. \quad (9)$$

The vehicle's yaw angle ψ and roll angle θ are interpolated similarly to the vehicle's path angle α . From the accident reconstruction, the roll and yaw angles are extracted for every vehicle template between and including the point of trip and point of rest. Piecewise linear functions are interpolated between known yaw and roll angles at each of the vehicle template locations.

Yaw rates and roll rates are constructed in a similar manner. For a given template, the yaw angle at the current template, minus the yaw angle from the previous template, divided by the time elapsed between the current and previous template, is calculated to give the yaw rate at the current template. The discrete yaw rates at each template are then used to construct piecewise linear functions, providing an interpolation for the yaw rate $\dot{\psi}$.

Roll rates are constructed in an exactly analogous manner and may include the following modification. To satisfy the constraint that the roll rate, integrated over time, must be equal to the number of rolls, n_{rolls} , we introduce a roll rate scaling κ such that

$$360^\circ \cdot n_{\text{rolls}} = \int_{t_0}^{t_f} \kappa \dot{\theta} dt, \quad (10)$$

to calculate a consistent roll rate.

OCCUPANT MODEL The occupant model includes three phases: (1) the occupant moving within the vehicle, (2) the occupant being ejected and moving through the air, and (3) the occupant landing on the ground and coming to rest. The occupant is modeled as a point mass with three translational degrees of freedom.

Occupant in Vehicle Let an occupant be located at point O , moving in the vehicle frame $\mathcal{V}$. The occupant is located with respect to the vehicle as

$$\mathbf{r}^{VO} = \chi \hat{e}_{\mathcal{V}1} + \rho \cos \phi \hat{e}_{\mathcal{V}2} + \rho \sin \phi \hat{e}_{\mathcal{V}3}, \quad (11)$$