ASSOCIATION BETWEEN VEHICLE PANEL DAMAGE AND THORACIC INJURY IN ROLLOVER CRASHES

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ABSTRACT

Rollover crashes are infrequent and account for approximately 2% to 3% of all vehicle crashes in the US annually. However, when they do occur they are more likely to result in a serious injury or fatality than some other types of crashes. In rollovers, the thorax has been identified as one of the three most frequently seriously injured body regions. As such, research has been carried out over the last few decades to understand better environmental, vehicle and occupant variables in a rollover crash which contribute to an occupant sustaining a serious, i.e. of severity greater than or equal to three on the Abbreviated Injury Scale (AIS 3+), thoracic injury. The findings from the research described in this paper will provide information for the development of a dynamic rollover crash test protocol which includes assessment of thoracic injuries. The aim of this study is to determine if there is an association between vehicle panel damage and AIS3+ thoracic injuries. NASS CDS data from 2001 to 2012 was examined for single vehicle rollover crashes with occupants receiving serious thoracic injuries (cases) and those without thoracic injuries (controls). Vehicle panel damage for both cases and controls were coded and logistic regression performed to determine if there is an association between serious thoracic injury and vehicle panel damage.

The result of this study indicates that there is an association between thoracic injury and damage to the top-half of the left front door, top-half of the right front door and left side of the vehicle rearwards of the B-pillar.

INTRODUCTION

In 2012, rollovers constituted 2.4% of all vehicle crashes in the United States of America (USA) but they contributed to 34.6% of all motor vehicle crash fatalities equating to approximately 7,500 deaths (NHTSA, 2012b) . To date a widely accepted dynamic rollover crashworthiness crash test protocol has not been developed. In order to establish a valid protocol, the environmental, vehicle and occupant variables that are associated with serious injuries in a rollover need to be identified and a method of replicating these variables in a simulated rollover crash needs to be developed.

In a rollover crash, the head, spine and thorax are the three most commonly injured body regions for contained and restrained occupants (Mattos, Grzebieta, Bambach, & McIntosh, 2014; Parenteau, Gopal, & Viano, 2001) with the thorax being the second most commonly injured region (Bedewi, Godrick, Digges, & Bahouth, 2003; Moore, Vijayakumar, Steffey, Ramachandran, & Corrigan, 2005). Vital organs such as the heart and lungs are located within the thorax. Thus, protecting this region in a rollover crash is important and often under-researched in comparison to the head and spine. One of the more recent studies conducted to understand thoracic injuries in vehicle rollover crashes sustained by restrained and contained occupants was carried out by Bambach *et al.* (2013). Their study found that lung contusions are the most frequently reported thoracic injury followed by rib fractures. The main sources of these injuries were the door interior, seatbelt and seatback. The mechanisms of these injuries in rollover crashes is still being investigated through crash data, crash reconstruction, physical modelling and numerical modelling.

It was initially hypothesized that occupant injuries in rollovers are the result of intrusion into the occupant space (Conroy et al., 2006; Sharma & Singh, 2009). However, recent examination of NASS CDS rollover crash data by Bambach *et al.* (2013) found that only 7.4% of thoracic injuries are directly associated with any intrusion. As such, they proposed that thoracic injuries are likely to occur due to the occupant traversing laterally towards and impacting internal components of a vehicle. This finding shifts the focus to developing an understanding as to how vehicle roll kinematics results in an occupant traversing laterally into the vehicle's interior thus causing thoracic injury. Bambach *et al.* (2013) also noted that there was not an obvious correlation between vehicle damage and thoracic injury citing, "…typically the side of the vehicle displayed some damage, indicating ground contact. However, a wide variety of vehicle damage occurred, varying from no damage (indicating no ground contact) to significant damage (indicating significant ground contact)." Digges *et al.* (2013) examined this in more and sought to find an association between vehicle crash damage patterns and thoracic injury but their study was only based on eight rollover crashes. That is, there was insufficient data to establish a comprehensive relationship between vehicle crash damage patterns and thoracic injury.

This study extends the work carried out by Digges *et al.* (2013) and Bambach *et al.* (2013) by determining if there is an association between vehicle crash damage patterns and thoracic injuries quantitatively.

METHOD

Data

The US National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) collects data from approximately 5,000 police reported passenger car, light truck, van and utility vehicle crashes each year. In order to be selected in the sample, a crash must involve personal or property damage; be reported to the police; and the vehicle towed away. The CDS is a probability sample and each case is provided with a weighting factor to represent police reported crashes occurring in the US during that year thus allowing population estimates to be calculated (NHTSA, 2012a).

NASS CDS from 2001 to 2012, inclusive, was queried in SAS Enterprise Guide 5.1 (SAS Institute) with the following filters: single-vehicle tripped rollover crash with at least one quarter rollover where the front seat occupants were 16 years or older; were restrained and contained in the vehicle; the vehicle did not contact another object prior to, during or after rolling over; and no airbags were deployed. The vehicles included in this study were sedans, utilities, vans and light trucks with the steering wheel located on the left side. Multiple vehicle crashes with a vehicle undergoing a rollover prior to or subsequent to the impact with another vehicle produces different injury patterns thus were excluded (Digges, Eigen, & Dahdah, 2005). Additionally, it has been noted that 80% of all rollovers in the US are single vehicle rollovers (Eigen, 2003). From the filtered cases, two groups were created. Cases consisted of occupants with thoracic injuries of severity equal to or greater than three on the Abbreviated Injury Scale (AIS3+) (Champion, 2012) while controls consisted of occupants without thoracic injuries.

The query returned 43 cases and 761 controls. The weighting factor, $n_{weighted}$, was 4,573 and 325,067 for cases and controls respectively. From the 761 controls, 200 were randomly selected for vehicle panel damage coding. This was reduced to 181 ($n_{weighted}$ = 55,905) controls, thus achieving a ratio of cases to controls of 1:4 to 1:5, after filtering out vehicles deemed unsuitable for inclusion in this study. These included vehicles where vehicle panel damage was obscured by plastic sheets used to prevent ingress of water into the vehicle; vehicles which were cut open and it was unclear if the panels were bent by rescue workers or damaged during the crash; or when vehicles were undergoing repairs when the photos were taken.

Coding of Vehicle Panel Damage

The panels forming the exterior of each vehicle was divided into eleven segments for each vehicle class (sedans, utilities, vans and light trucks). The segments consisted of the front fender, front door upper half, front door lower half, vehicle side rearwards of the B-pillar for either side and the front hood, glasshouse roof and boot lid for the top. These segments were titled as Left/Right 1, Left/Right 2, Left/Right 3, Left/Right 4, Top 1, Top 2 and Top 3 respectively for entry into SAS (See Figure 1).

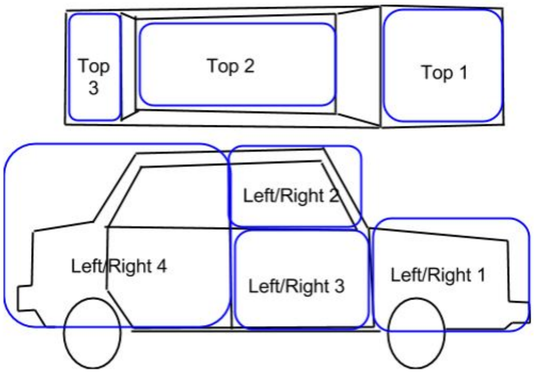
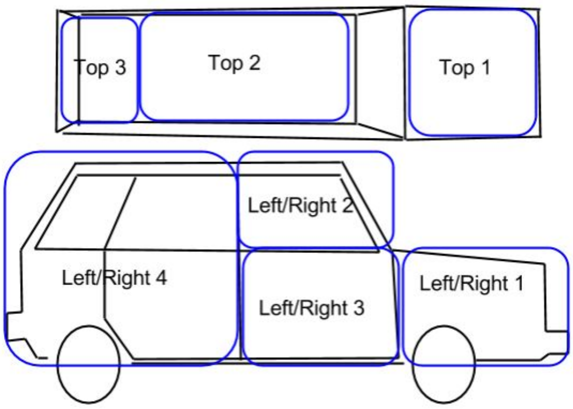
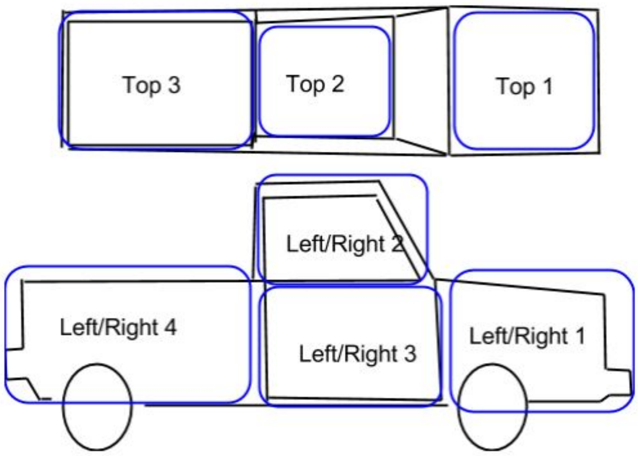
<table>
<tr><th>Vehicle Class</th><th>Vehicle Segments</th></tr>
<tr><td>Sedans</td><td>
</td></tr>
<tr><td>Utilities and Vans</td><td>
</td></tr>
<tr><td>Light Trucks</td><td>
</td></tr>
</table>

Figure1. Each class of vehicle (sedans, utilities, vans and light trucks) was divided into 11 segments.

Coding of vehicle segment damage was then performed. Segment damage was dichotomously coded with segments receiving either no to minor damage, coded as zero, or segments receiving major damage, coded as one, from vehicle-to-ground contact. No or minor damage is defined as segments which have sustained scratches or small dents from the vehicle-to-ground impact and is unlikely to have substantially affected the vehicle's rollover kinematics. Major damage is defined as segments which have sustained substantial damage to the vehicle's panel and/or structure upon vehicle-to-ground impact sufficient to alter the vehicle's rollover kinematics. An example of minor and major damage is provided in Figure 2. Where it is unclear as to whether a segment has moderate or major damage, a conservative approach was taken and the segment damage was coded as zero.

Figure2. Examples of vehicle panels with minor damage (left) versus major damage (right).

In the event that two adjacent segments received major damaged directly from the vehicle-to-ground impact, both segments would be coded as receiving major damage. However, if one segment received major damaged from the vehicle-to-ground impact and subsequently affected an adjacent segment thus causing major damage, then only the segment damaged from the vehicle-to-ground contact was coded as receiving major damage and the adjacent segment was coded as receiving minor damage.

The weighting of each NASS CDS case was not applied to vehicle segment damage as it is applicable to the type of vehicle crash and not to segment damage.

Statistical Method

A multiple variable logistic regression model was developed in SAS Enterprise Guide 5.1 (SAS Institute) to assess the association between predictor variables and the response variable. The predictor variables for the model consisted of variables from the vehicle, occupant and the crash environment. They were evaluated for inclusion in the model based on the possibility that they may be associated with serious thoracic injury and guided by previous reports (Bambach et al., 2013; NHTSA, 2002). The variables considered for inclusion in the model were: vehicle quarter rollover, occupant age, occupant gender, roll direction relative to the occupant, vehicle class (sedan, utility, van and light truck), roadway alignment (straight road, left curve or right curve), rollover initiation location (roadway, paved shoulder, unpaved shoulder or roadside/median), surface condition (dry, wet, snow, slush, ice or sand/dirt/oil/gravel) and roadway profile (level, uphill, hill crest, downhill or sag). Other variables such as occupant height, weight and BMI were considered. However, due to missing observations for several cases, these variables were not included as this would have reduced the number of already limited cases in this study.

The aforementioned variables were classified as either continuous (vehicle quarter rollover, speed limit and occupant age), dichotomous (occupant gender and roll direction relative to the occupant) or polytomous (vehicle body type, rollover location, roadway alignment, surface condition and roadway profile). Due to the small sample size in this study, polytomous variables were classified as dichotomous in the following manner: vehicle body type was either a utility/van/light truck or sedan; rollover location was either on the roadway or otherwise; roadway alignment was either straight or curved; surface condition was either dry or otherwise; and roadway profile was either level or otherwise.

The response variable was the presence, coded as one, or its absence, coded as zero, of a serious (AIS 3+) thoracic injury.

Purposeful selection was used to determine significant variables, evaluated to a significance level of 0.20 for the initial stage and 0.05 for subsequent stages of the model, associated with serious thoracic injuries that were to be included in the base model (Hosmer, Lemeshow, & Sturdivant, 2013). The dichotomously coded segment damage variables were then added to the base model and were evaluated to a significance level of 0.05. Non-significant segment damage variables were then removed to create the final model. Additionally, checks for linearity between each continuous variable and the logit was also performed (Friendly, 2012; Hosmer, Lemeshow, & May, 2008).

RESULTS

The base model from the logistic regression analysis includes the following variables: vehicle quarter rollover, dichotomously coded rollover location (off roadway versus on road way), dichotomously coded vehicle class (utility/van/light truck versus sedans), and dichotomously coded surface condition (dry or otherwise) (See Table 1). The dichotomously coded segment damage variables were then added to this model and all non-significant segment damage variables removed thus resulting in the final model (See Table 2). It is noted that the dichotomously coded surface condition was removed from the final model as it became insignificant (p=0.41, OR= and 1.67). Additionally, the Left 2 segment damage was kept in the final model even though its p-value of 0.058 is higher than the statistical significance level of 0.05. However, its odd ratio point estimate of 2.46 is high and thus an important factor (Olivier & Bell, 2013). The final model consists of the following variables: vehicle quarter rollover; dichotomously coded rollover location (off roadway versus on road way); dichotomously coded vehicle class (utility/van/light truck versus sedans); Left 4; Right 2; and Left 2 segment damage.

Table1.

Multiple variable logistic regression results for thoracic injury (AIS 3+) and base model covariates.

Variable	MLE Ratio Estimate	Standard Error	Odds Ratio Point Estimate	95% Confidence Interval	p-Value
Increase in One Quarter Roll	0.82	1.40	2.26	1.73, 2.95	<0.001
Rollover off Roadway	1.22	0.61	3.40	1.04, 11.13	0.043
Utility/Van/Light Truck	1.59	0.59	4.90	1.55, 15.52	0.007
Dry Surface	1.13	0.56	3.10	1.04, 9.24	0.042

Table2.

Final logistic regression model.

Variable	MLE Ratio Estimate	Standard Error	Odds Ratio Point Estimate	95% Confidence Interval	p-value
Increase in One Quarter Roll	0.74	0.15	2.09	1.57, 2.79	<0.001
Rollover off Roadway	1.36	0.64	3.90	1.11, 13.72	0.034
Utility/Van/Light Truck	1.31	0.64	3.71	1.06, 12.93	0.039
Left 4 Segment	1.21	0.48	3.35	1.30, 8.62	0.012
Right 2 Segment	1.30	0.50	3.68	1.37, 9.85	0.009
Left 2 Segment	0.90	0.47	2.46	0.97, 6.22	0.058

DISCUSSION

The results from the multiple variable logistic regression model indicate that the number of vehicle quarter rollovers; the vehicle is a utility, van or light truck; the rollover occurred off the roadway and there is major damage to the Left 4, Right 2 and Left 2 segments are associated with a front seat occupant sustaining a serious thoracic injury. An increase in one quarter rollover is associated with a 2.1 times increase in the odds of receiving a serious thoracic injury, a finding similar to that from previous studies (Bambach et al., 2013; Moore et al., 2005; Viano & Parenteau, 2007). This increase in odds is likely due the higher velocity or crash energy and greater opportunity for occupants to impact the vehicle's interior. This study also shows that being an occupant in a utility, van or light truck, as opposed to those in a sedan, is associated with a four fold increased in the odds of sustaining serious thoracic injury and confirms the findings of a previous study by Bambach *et al.* (2013). It is possible that this is due to the higher aspect ratios of utilities, vans and light trucks compared to sedans resulting in a higher deceleration rate as the vehicle rolls. Rollovers that are initiated on the shoulder or the median are 3.7 times more likely to result in a front seat occupant sustaining a serious thoracic injury than if the initiation occurred on the roadway. This is possibly due to the higher friction forces that occur when a vehicle furrows into the soft surface (Allen, Rosenthal, & Chrstos, 1997; Warner, Smith, James, & Germane, 1983) resulting in a higher deceleration than if the vehicle tripped on a paved surface.

Intuitively, an increase in occupant age would be associated with an increased probability of sustaining an injury in a rollover crash. However, this was found not to be a significant variable in this study and is likely to be due to the small sample size and that age was treated as a continuous variable. It is noted that age was also entered into the model as an interval variable. However, this did not affect the outcome of the model.

Previous studies (Bambach et al., 2013; Cuerden, Cookson, & Richards, 2009; Parenteau et al., 2001) have found that rollover direction was associated with an increased probability of sustaining an injury. However, this study has not come to that same conclusion with findings similar to the studies by Bedewi *et al.* (2003), Conroy *et al.* (2006) and Viano & Parenteau (2007).

Damage to the Right 2 and Left 2 segment is associated with a 3.1 and 2.5 increase in the odds of sustaining a thoracic injury respectively. An explanation of the vehicle kinematics resulting in damage to these segments is provided below followed by a discussion on the possible relationship between damage to these segments and thoracic injury.

A vehicle in a clockwise rollover (right side leading), as viewed from the rear, may receive damage to the Right 2 segment as it impacts the ground on entering the 2nd, 6th and 10th quarter rollover, noting that most rollovers do not exceed 12 quarter rollovers (Bambach et al., 2013). The vehicle may also receive damage to the Left 2 segment as it impacts the ground on entering the 3rd, 7th and 11th quarter rollover. Similarly, a vehicle in a counter clockwise rollover (left side leading), as viewed from the rear, may receive damage to the Left 2 segment as it impacts the ground when it enters the 2nd, 6th and 10th quarter rollover and damage to the Right 2 segment as it impacts the ground when it enters the 3rd, 7th and 11th quarter rollover.

In a clockwise rollover, thoracic injury may be occurring at the 2nd quarter rollover as the driver and passenger's thorax might be oriented approximately horizontally (Heller et al., 2010), relative to the ground, with gravitational force acting on both occupants so that the driver and passenger is accelerated into the centre console and the right door interior respectively resulting in a thoracic injury (See Figure 3). In a counter-clockwise rollovers the driver and passenger are accelerated into the left door interior and centre console respectively. The occupant's thorax position is less clear once the vehicle rotates past the 2nd quarter rollover thus making it difficult to form a plausible cause of thoracic injury.

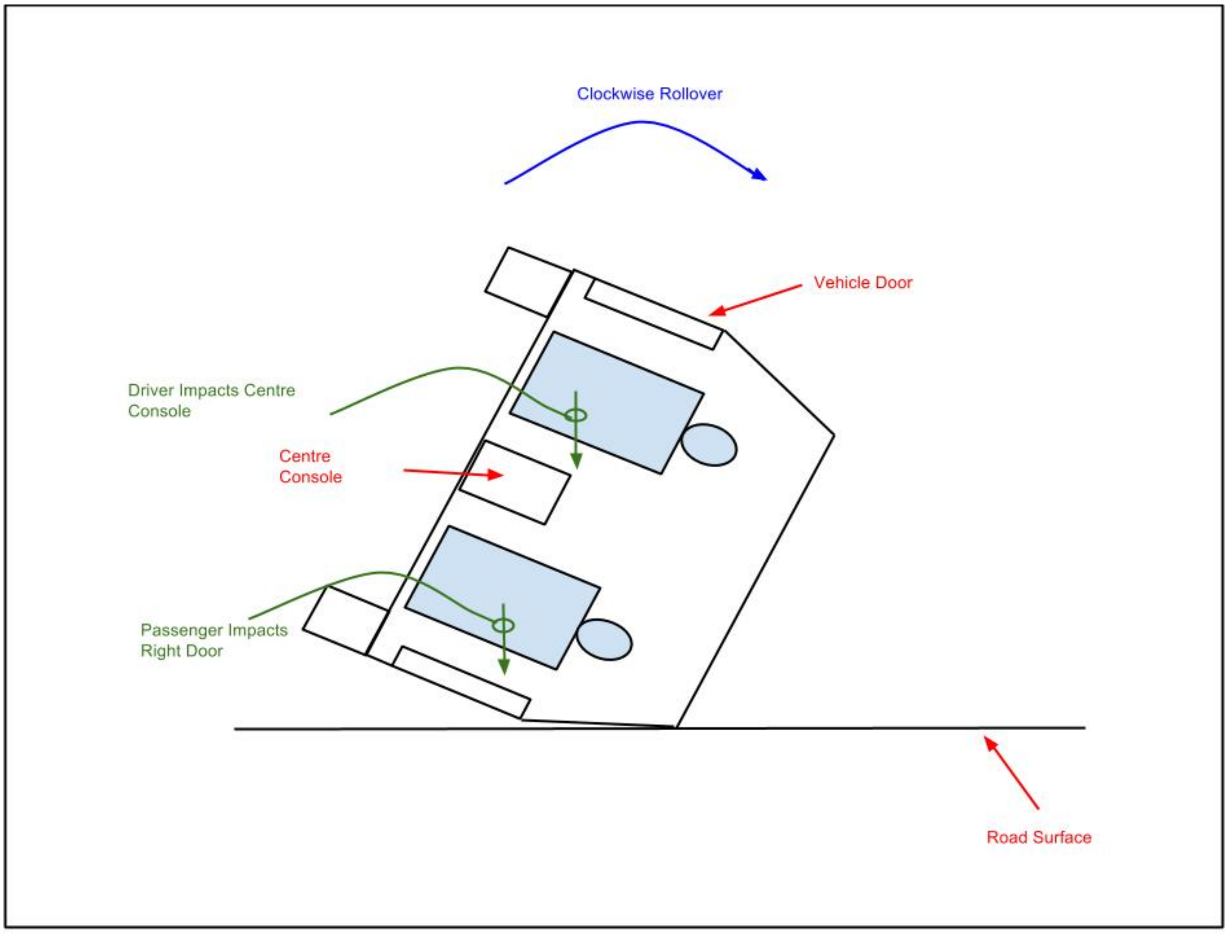


Figure3. Vehicle right rollover, as viewed from the rear of the vehicle, impacting the ground at the Right 2 segment with the driver impacting the center console and passenger impacting the right door interior.

Damage to the Left 4 segment was found to be associated with serious thoracic (OR=3.9). The vehicle kinematics and damage mechanism is similar to that which results in Left 2 damage. However, it is likely a negative vehicle pitch, as defined by the SAE sign convention for vehicles, would be present thus allowing the rear of the vehicle to contact the ground as it enters the 2nd, 6th and 10th quarter rollover, for counter clockwise rotations, and as the vehicle enters the 3rd, 7th and 11th quarter rollover for clockwise rotations.

It is interesting to note that damage to the rear right of the vehicle rearwards of the B-pillar, Right 4 segment, is not associated with thoracic injury and is likely to be due to the small number of cases and, to a lesser extent, controls.

Limitations

The limitations of this study should be noted. The NASS CDS data is a probability sample rather than a census and the data is dependent on the investigation and data entry accuracy of the NASS investigator. Logistic regression models can be biased towards a particular sample. Occupant height and weight were not included as variables in the analysis. The coding of vehicle panel damage is subjective and is based on residual deformation only. Sheet metal strength varies from vehicle model to model thus two different vehicle models subjected to the same impact force will deform to different extents. Certain parts of a vehicle, such as the A-pillar, are significantly stronger than the panels forming the exterior of the vehicle thus if the vehicle in a rollover impacted the ground with a structural component first, this may result in the panels receiving minor damage. The regression model establishes associations between the predictor variables and response variable but it does not imply causality.

CONCLUSION

In this study, coding of vehicle panel damage was carried out for a total of 224 vehicles involved in pure rollover crashes. The association between vehicle panel damage; vehicle class; occupant variables; and the crash environment variables and serious, AIS 3+, thoracic injury was assessed. Vehicle quarter rollover, rollovers involving Utilities/Van/Light trucks, rollovers occurring off the roadway, damage to the vehicle rearwards of the left B-pillar (Left 4 segment), damage to the top-half of the right front door (Right 2 segment) and damage to the top-half of the left front door (Left 2 segment) were associated with serious thoracic injury in rollover crashes.

Although this study has identified damage to the left rear of the vehicle rearwards of the B-pillar and top-half of the right and left front door are associated with serous thoracic injury and may need to be taken into account in rollover reconstructions, future studies are still needed to verify this finding and to develop a better understanding as to how damage to these areas of the vehicle is associated with thoracic injuries. Future studies could also include vehicle roof strength to weight ratio and roof shape as variables in the logistic regression model as well as increasing the number of cases and controls.

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