LOGISTIC REGRESSION ANALYSIS OF LOWER LIMB INJURIES IN FRONTAL CRASHES

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ABSTRACT

The objective of our study is to evaluate lower limb injuries in frontal crashes, identify the parameters that have significant influence on such injuries, and quantify their effect using logistic regression technique.

This paper contains a review of lower limb injuries literature. Later the data subset used for our study is described. It is followed by an exploratory analysis consisting of: The evaluation of lower limb injuries and the analysis of effects of different parameters on such injuries. The logistic regression analysis is presented in the end to quantify the effects of some significant factors on lower limb and leg-foot complex injury risk.

Two response measures, injury risk and average injuries per occupant, were analyzed during the exploratory analysis phase. Both measures showed similar effects of all factors.

Based on our logistic regression model, we have also predicted the probability of lower limb and leg-foot complex injury under certain conditions of intrusion, crash severity, seating position and gender.

INTRODUCTION

With increased seat belt usage and the introduction of supplemental inflatable restraint systems, the risk of injuries to the head, neck, and chest have decreased substantially in frontal crashes. As a result, more people are surviving accidents and the relative importance of upper and lower extremity injuries in vehicular crashes has increased [1, 2].

New crash test methods that focus on maximizing lower extremity interaction with vehicle structures have been developed. Early tests focused on 40%-50% offset frontal tests against a rigid barrier [7]. The barrier design was further improved by installing a deformable barrier face on the rigid barrier. A deformable barrier test that engages 40% of the frontal width of a vehicle has been adopted by European Community (ECE) for testing vehicles by 1998 and beyond. This test at higher than regulated speed has been adopted by several public information programs (European New Car Assessment Program (Euro NCAP), Insurance Institute of Highway Safety (IIHS), Australia NCAP).

In addition to studying vehicle crash tests (Regulatory and Public Information), a substantial amount of research is being conducted in the biomechanics of lower limb injuries and in the development of advanced test devices that would lead to changes in the lower extremity design of current dummies.

Although the biomechanical testing is essential to determine the responses, mechanisms, and impact tolerances, it is believed that empirical study of field accident data is necessary to gain understanding of complex mechanisms that exist in the real world crashes. This paper reports on such an empirical study of the NASS database.

LITERATURE REVIEW

Huelke, et al. and Pilkey, et al., have presented an excellent review of literature and summarized the effects of crash severity, offset, intrusion, occupant position, pedal interference, belt usage, and left-right foot on injury [1, 8].

Our review of the literature is summarized as follows:

- The risk of lower limb injuries increases with an increase in crash severity [4, 8, 9, 10, 11].
- A significant number of lower limb injuries are produced in crashes that do not involve intrusion [9].
- The risk of lower limb injuries is higher with intrusion than without it [9, 11, 12]. Such injuries increase with an increase in the level of intrusion [10, 11]. Results from both car-to-car and car-to-barrier crash tests, with

instrumented Hybrid III dummies, show that some of the loads acting on lower extremities have strong correlation with occupant compartment deformations, even when crash severity is controlled, though other factors also influence occupant loads [13].

- Drivers receive more injuries than front seat passengers [11]. Drivers had twice as many foot fractures as front seat passengers [4].
- There are mixed data, reported in the literature, about the effect of position of the foot. Some studies report that the drivers left foot has more injuries than the right foot, specifically at higher level of intrusion [2, 14]. While other studies report that there is no significant difference between left and right foot injuries [4] or left and right leg injuries [2].
- Belt usage does not influence the injury frequency of the foot [4] or the lower extremity, however, there are higher number of pelvic injuries in unbelted cases [15].
- Thomas, et al., report that footwell intrusion increases the risk of leg injury to a greater extent than crash severity and that intrusion is not a surrogate variable for delta-V [9].

DATABASE

The National Automotive Sampling System (NASS)-formerly, the National Accident Sampling System-is the mechanism through which the National Highway Traffic Safety Administration (NHTSA) collects nationally representative data on motor vehicle and highway safety countermeasures [26]. The NASS was originally designed and implemented in 1979 to support highway and motor vehicle safety programs. The NASS program was reevaluated in the mid-1980s.

To enhance its applicability in addressing crashworthiness issues, the NASS was divided into two parts: (1) the General Estimates System (GES), which collects data on an annual sample of approximately 50,000 police-reported traffic crashes; and (2) the Crashworthiness Data System (CDS), which collects additional detailed information on an annual sample of approximately 5,000 police-reported traffic crashes involving passenger vehicles towed from the crash scene due to damage resulting from the crash.

Data Subset Used for the Analysis:

- NASS CDS Data for calendar years 1988-94
- Frontal impacts of 11-1 O'clock position
- Crash severity (Delta-V total) of 15-25 mph
- Front seat occupants of 1986-95 model year passenger cars

This is a case study. Data were not weighted for generalization over the population due to concerns related to the use of Primary Sampling Unit (PSU) weighting factors.

EXPLORATORY ANALYSIS

A preliminary analysis of all data was conducted to evaluate the type and severity of lower limb injuries and to explore the significance of different factors.

Responses Analyzed

Lower limb injuries, excluding the pelvic injuries, were categorized as:

- Foot-ankle
- Tibia-fibula (leg)
- Knee
- Thigh
- Unknown/ others

The Abbreviated injury scale (AIS) of two or greater (AIS2+) are considered as moderate to serious injuries [26]. Injuries mentioned in this paper refer to lower limb AIS2+ injuries.

We selected the following two response measures for evaluation:

- Injury Risk (Percent of occupants who received maximum AIS2+ (MAIS2+))
- Average Injuries (Number of injuries / number of occupants)

Injury Risk is the probability of injury to an occupant involved in such crash. Average Injuries accounts for multiple injuries. It is the probability of count of injuries to an occupant. Our analysis showed that both response measures yield similar trends.

Factors Considered

The following exploratory factors were analyzed:

- Intrusion
- Location of intrusion
- Crash severity (Delta-V total)
- Seating position
- Gender
- Impacting object
- Belt usage
- Occupant's age

At this stage of the analysis, one factor was analyzed at a time ignoring the effects of all other factors. All factors were analyzed for the two conditions: With intrusion, and without intrusion. Subsequently, four factors (Intrusion, crash severity, gender, and seating position) were selected for logistic regression analysis to quantify the contribution of each factor and their interactions.

Results of the Analysis

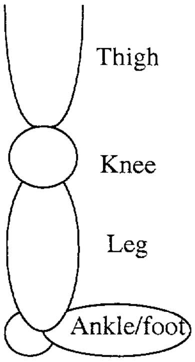
The data indicated that 11% of all front seat occupant involved in a 15-25 mph accident incurred MAIS2+ lower limb injuries. The occupants and the injuries considered in the study are summarized in Appendix (A).

Intrusion - Intrusion was defined as one inch or more of intrusion on the same side as the occupant.

Figure (1) shows the distribution of injuries by body region with intrusion and without intrusion. Table (1) compares injuries with and without intrusion.

Not controlling for any other factors, Injury Risk was found to be about three times higher with intrusion than without intrusion. Average Injuries were about four times with intrusion, compared to that without intrusion. Also, the severe injuries (AIS3) were slightly higher with intrusion (Table 1).

The frequency of the occupants involved in accidents with intrusion was relatively low, resulting in 30% less injured occupants with intrusion. Because of more multiple injuries with intrusion, however, total number of injuries were 8% more with intrusion.



Body Region	Intrusion Injuries N(%)	No-Intrusion Injuries N(%)
Thigh	39 (16)	23 (10)
Knee	47 (19)	59 (26)
Leg	62 (25)	74 (33)
Ankle/foot	74 (30)	66 (29)
Unknown	23 (9)	4 (2)
All	245 (100)	226 (100)

Fig. (1): Distribution of AIS2+ Injuries by body regions

TABLE 1. Comparisons of Injuries with and without Intrusion

	Intrusion	No-Intrusion
Frequency (N)	456	2056
Injury Risk (% of occupants considered)	27	8
Total Occupants Injured	122	158
Average Injuries/ Occupant	0.49	0.11
Total Injuries	245	226
AIS 3 Injuries (% of injured occupant)	35	29

Location of Intrusion - The occupants and injuries considered in this study are categorized by location of intrusion as follows (Appendix B):

- Floor and/or toe-pan (FLOOR) intrusion
- Instrument panel (IP) intrusion
- FLOOR and IP (COMPLEX) intrusion

FLOOR intrusion is more frequent than IP intrusion or COMPLEX intrusion, however, Injury Risk for FLOOR intrusion is far less (Table 2). The increased risk for IP intrusion is due to frequent leg and knee injuries compared to only frequent leg injuries with FLOOR intrusion. Also, the increased injury risk of COMPLEX intrusion may be due to knee entrapment. Occupants with IP intrusion had fewer multiple injuries than occupants with other categories of intrusion. There was no significant difference in the severity of injuries for any type of intrusion (Table 3 & 4).

Leg and foot/ankle injuries were more frequent with FLOOR intrusion while knee injuries were more frequent with IP intrusion.There was no significant difference in the frequency of thigh injuries in all three cases (Table 5).

Not controlling for other factors, it was found that:
Crash Severity - Injury Risk increased with the crash severity for both cases of intrusion and non-intrusion (Figure 2) when compared correspondingly.

Seating Position - Injury Risk for driver was 72% higher with intrusion and 30% higher without intrusion than that for front seat passenger.

Gender - Injury Risk for female occupant was 55% higher with intrusion and 110% higher without intrusion than that for male occupant.

Other Factors - Injury Risk was least in impacts with wide stationary objects than in impacts with vehicle-in-transport or with narrow objects for both cases of intrusion and no-intrusion (Figure 3).

TABLE 5. AIS2+ Injuries by Body Regions for Different Categories of Intrusion

Body Regions	FLOOR N (%)	IP N (%)	COM-PLEX N (%)
Thigh	16 (14)	3 (18)	20 (17)
Knee	17 (16)	8 (47)	22 (18)
Leg	32 (30)	3 (18)	27 (23)
Ankle/foot	36 (33)	1 (6)	37 (31)
Unknown	7 (6)	2 (12)	14 (12)
All	108 (100)	17 (100)	120 (100)

TABLE 2. Comparisons of Injury Risk for Different Categories of Intrusion

Intrusion	Frequency N	Injury Risk %
FLOOR	266	21
IP	34	32
COMPLEX	155	35

TABLE 3. Comparisons of Injury Severity (MAIS) for Different Categories of Intrusion

Intrusion	Occupants Injured (%)		
	MAIS 2	MAIS 3	Total
FLOOR	29 (52)	27 (48)	56 (100)
IP	7 (64)	4 (36)	11 (100)
COMPLEX	27 (49)	28 (51)	55 (100)

TABLE 4. Comparisons of Injury Severity (AIS) for Different Categories of Intrusion

Intrusion	Total Injuries (%)		
	MAIS 2	MAIS 3	Total
FLOOR	72 (67)	36 (33)	108 (100)
IP	11 (65)	6 (35)	17 (100)
COMPLEX	76 (63)	44 (37)	120 (100)

Note: In some tables percentages do not add to 100 because of rounding.

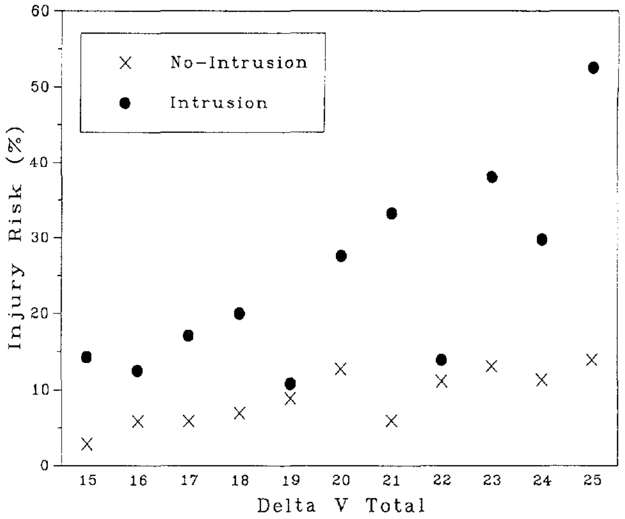


Fig. (2): Injury risk by Crash Severity

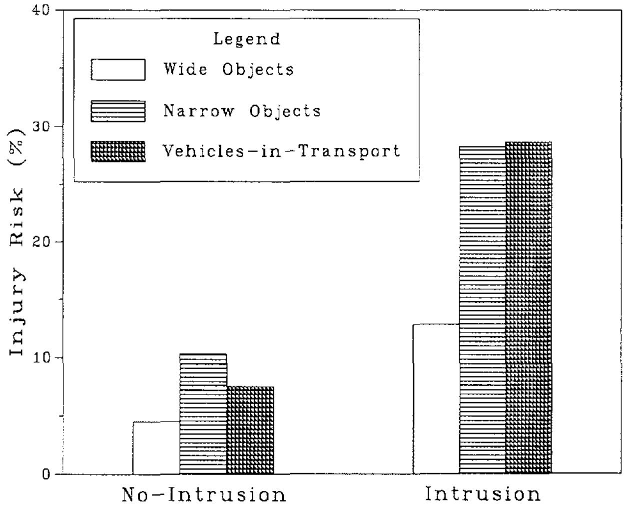


Fig. (3): Injury Risk by Impacting Object

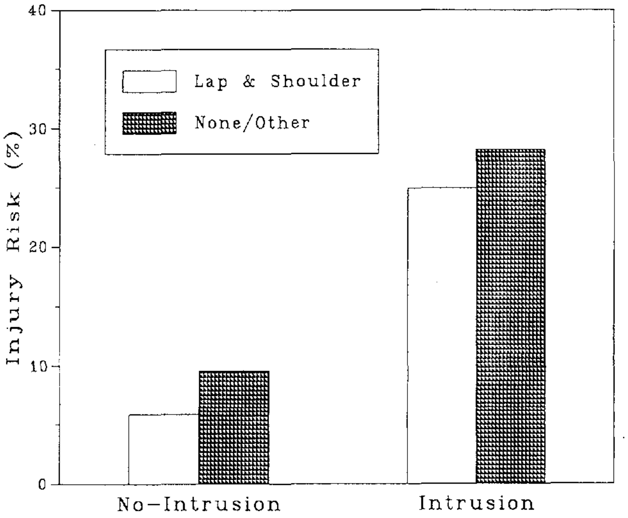


Fig. (4): Injury Risk by Belt Usage

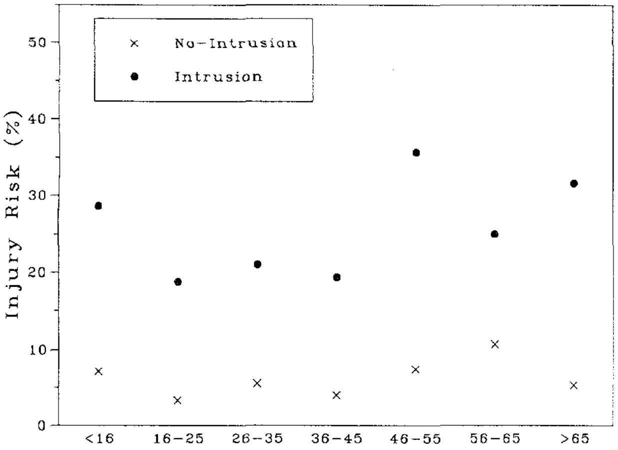


Fig. (5): Injury Risk by Age for Male

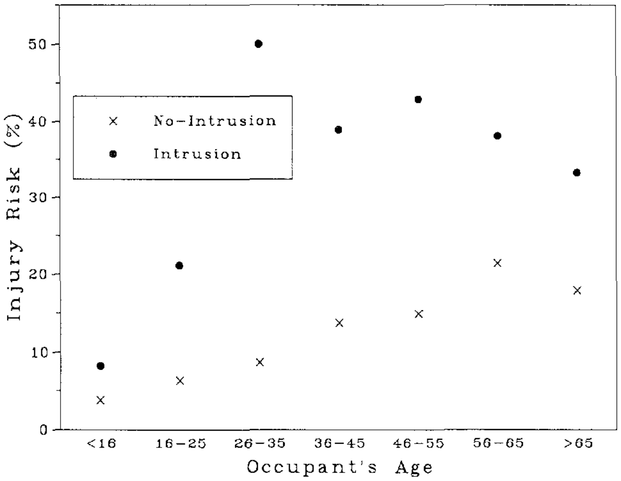


Fig. (6): Injury Risk by Age for Female

Injury Risk was reduced by (53%) when three point belt system was properly used in cases with no intrusion. There was no significant difference in injury risk for belted occupants with intrusion (Figure 4).

Figures (5) and (6) show the Injury Risk to males and females as it varies with their age. There was an increase in the risk with age of females with no-intrusion. There was no trend of injury risk with age of females with intrusion and with age of males with or without intrusion.

LOGISTIC REGRESSION ANALYSIS

Logistic regression is a form of statistical modeling that is appropriate for categorical outcome variables. It describes the relationship between a categorical outcome(response) variable and a set of explanatory variables. The response variable is usually dichotomous, but it may be polytomous, that is, have more than two response levels. The explanatory variables in logistic regression can be categorical or continuous.

For the present study, the following two dichotomous response variables were modeled:

1) leg-foot complex injury (yes, no), and
2) lower limb injury (yes, no) [excludes pelvic injuries]

A relationship of the response variables was described with a set of four categorical explanatory variables: intrusion, delta V total, seating position, and gender. The explanatory variables were categorized as follows:

- Intrusion (< 1 in, 1-6 in, >= 6 in)
- Delta V total (15-17 mph, 18-22 mph, 23-25 mph)
- Seating position (driver, right front passenger)
- Gender (male, female)

Two separate analyses were performed for leg injury and lower limb injury. The relationship between each response variable and the four explanatory variables was estimated by fitting a model of main effects only, because the interaction effects between explanatory variables were negligible. The main effect logit model has the form:

$$Logit(p) = \ln\left(\frac{p}{1-p}\right) = \alpha + (\sum \beta i Xi)$$

where

p = the probability of the event that an injury occurred (response measure)

α = Intercept parameter (overall effect)

βi = Slope parameters (coefficients of Xi)

Xi = Explanatory variables (intrusion (X_1), delta V total (X_2), seating position (X_3), and gender (X_4))

The upper and lower 95% confidence limits for the predicted risks were calculated by using the following formulae:

$$UL = \frac{1}{1 + \exp(-(\hat{\eta} + 1.96\hat{\sigma}(\hat{\eta})))}$$

$$LL = \frac{1}{1 + \exp(-(\hat{\eta} - 1.96\hat{\sigma}(\hat{\eta})))}$$

where

$\hat{\eta} i = \hat{\alpha} + (\sum \hat{\beta} i Xi)$ (Estimated logit)

$\hat{\alpha}$ = Estimate of α

$\hat{\beta} i$ = Estimate of βi

$\hat{\sigma}(\hat{\eta} i)$ = The standard errors of the parameter estimates derived from the logit analysis

The calculated values of Parameter Coefficients along with corresponding standard error are given in Table 7.

The figures 7-14 show the confidence limits along with the predicted values. Table 6 shows the values of all parameter coefficients and standard error.

The statistical software "PROC LOGISTIC" from SAS System was used for modeling logistic regression.

TABLE 6. Parameter Coefficients of Logistic Model

Variable	Instance	Parameter Coefficient Value($\beta_i X_i$)	Standard Error
Overall effect (α)	**	-4.4311	0.2792
Seating Position	Passenger*	0.	
	Driver	0.6356	0.2133
Gender	Male*	0.	
	Female	1.0171	0.1730
Intrusion	< 6 inch*	0.	
	6-18 inch	1.7671	0.2427
Velocity	15-17mph*	0.	
	18-22mph	0.6516	0.2044
	23-25mph	1.4321	0.2792

* Represents lowest level (risk) instance
** At the lowest level of all variables

Results of the Analysis

The effects of each of the four explanatory variables on the injury risks, as calculated from the main effects model are summarized below. The effects of each variable shown was calculated after adjusting for the effects of the remaining variables at some fixed levels. The effects of all levels of each variable and their 95% confidence limits were calculated from the parameter estimates and their corresponding standard error estimates, derived from the main effects model.

All four factors analyzed using logistic regression were found to be statistically independent and significant. Interactions of these factors were found to be insignificant.

The predicted values of both response measures derived from the main effect model for various conditions of occupant involvement are shown in appendices C and D.

Lower Limb Injury Risk

- As intrusion increases there is a significant increase in risk. Occupants with six inches or more of intrusion were nearly five times as likely to receive at least one moderate to serious leg injury than occupants with less than one inch of intrusion (Figure 7).

- As Delta V increases, there is a significant increase in risk. Occupants with higher Delta V (23-25 mph) were about three times as likely to receive at least one moderate to serious leg injury than occupants with lower (15-17 mph) Delta V (Figure 8).

- Females were twice as likely to receive at least one moderate to serious leg injury than males (Figure 9).

- Drivers were one and half times as likely to receive at least one moderate to serious leg injury than right front passengers (Figure 10).

Leg-Foot-Complex Injury Risk - The "Leg-foot-complex" response produced similar results as the "Lower Limb" response (Figures 11-14).

CONCLUSIONS

1. A significant number of lower limb injuries are produced without any residual intrusion.
2. Indications are that lower limb injury risk is higher with IP intrusion than floor/ toe-pan intrusion.
3. The crash severity, intrusion, seating position and gender are independent significant factors of lower limb injury risk. Statistically, interactions could not be extracted.
4. The injury risk is higher for higher crash severity and increased level of intrusion. Drivers have higher risk than front seat passengers and females have higher risk than males.

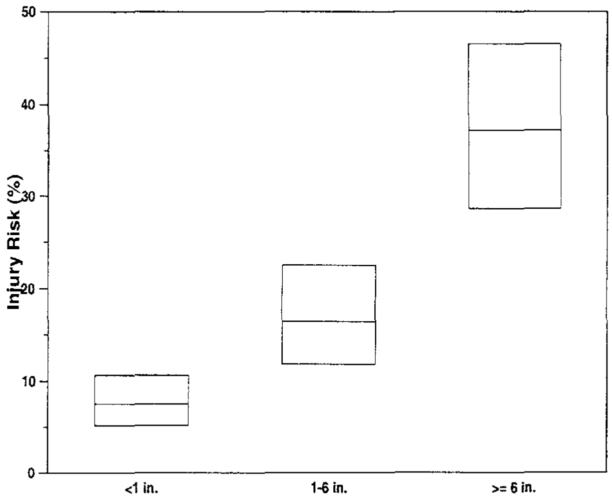


Fig. (7): Effect of Intrusion on leg-foot complex with 95% confidence intervals

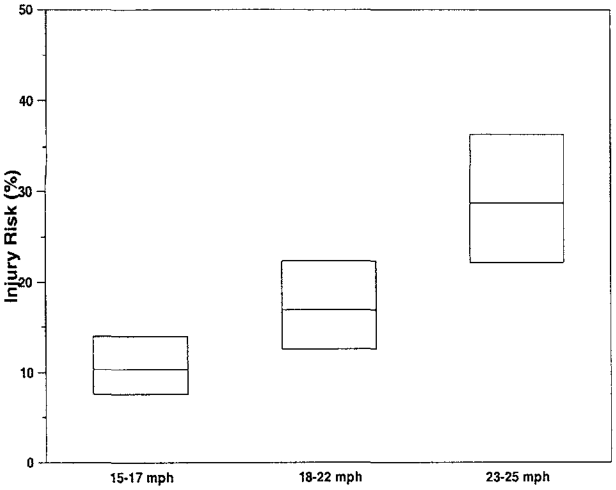


Fig. (8): Effect of impact severity on leg-foot complex with 95% confidence intervals

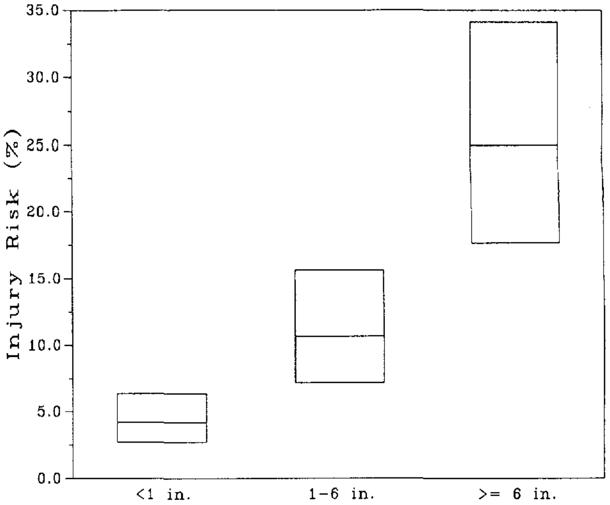


Fig. (11): Effect of Intrusion on leg-foot complex with 95% confidence intervals

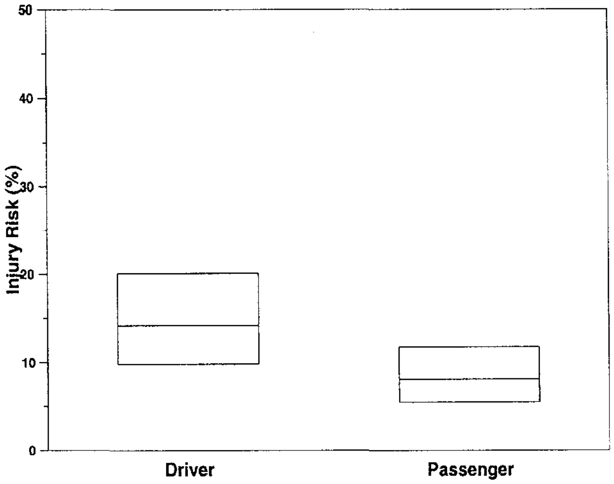


Fig. (9): Effect of seating position on leg-foot complex with 95% confidence intervals

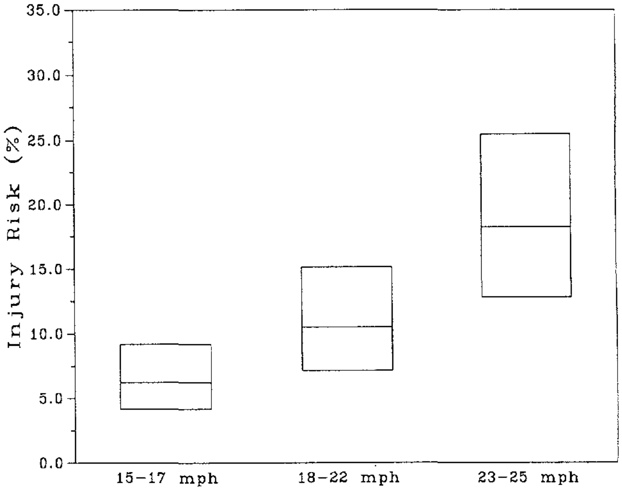


Fig. (12): Effect of impact severity on leg-foot complex with 95% confidence intervals

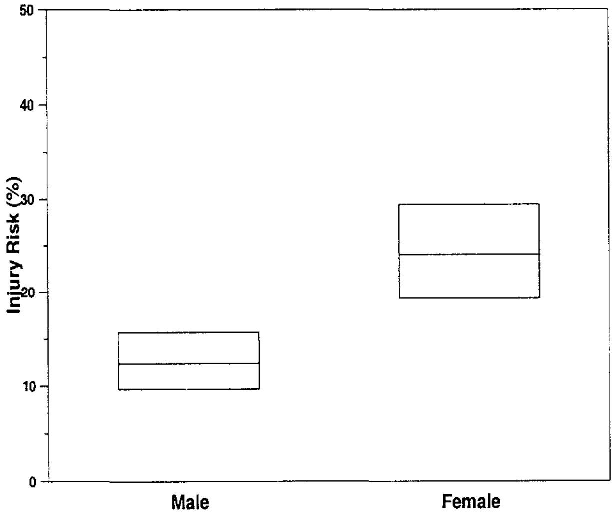


Fig. (10): Effect of gender on leg-foot complex with 95% confidence intervals

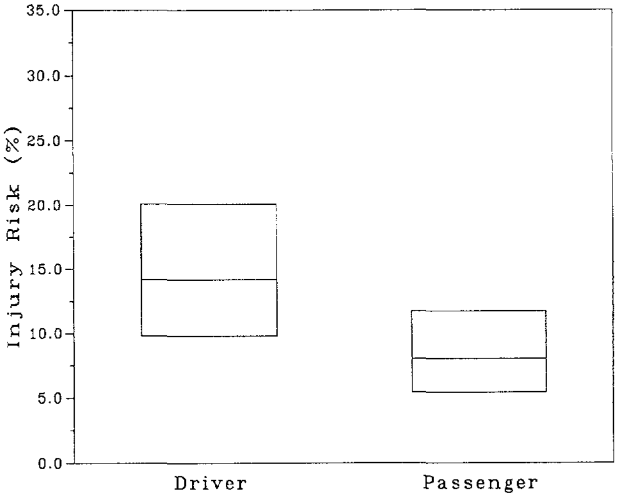


Fig. (13): Effect of seating position on leg-foot complex with 95% confidence intervals

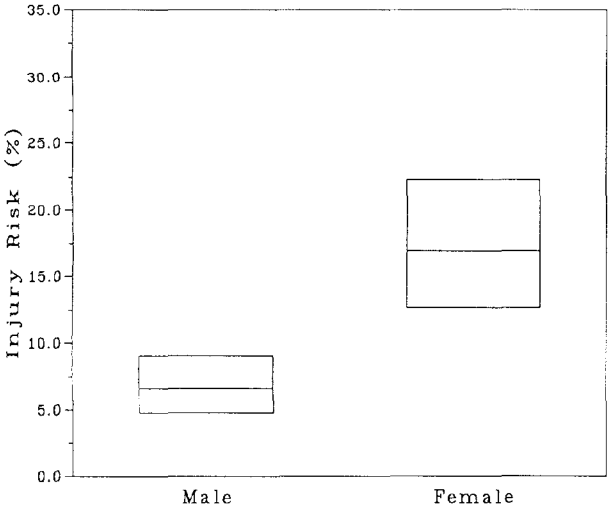


Fig. (14): Effect of gender on leg-foot complex with 95% confidence intervals

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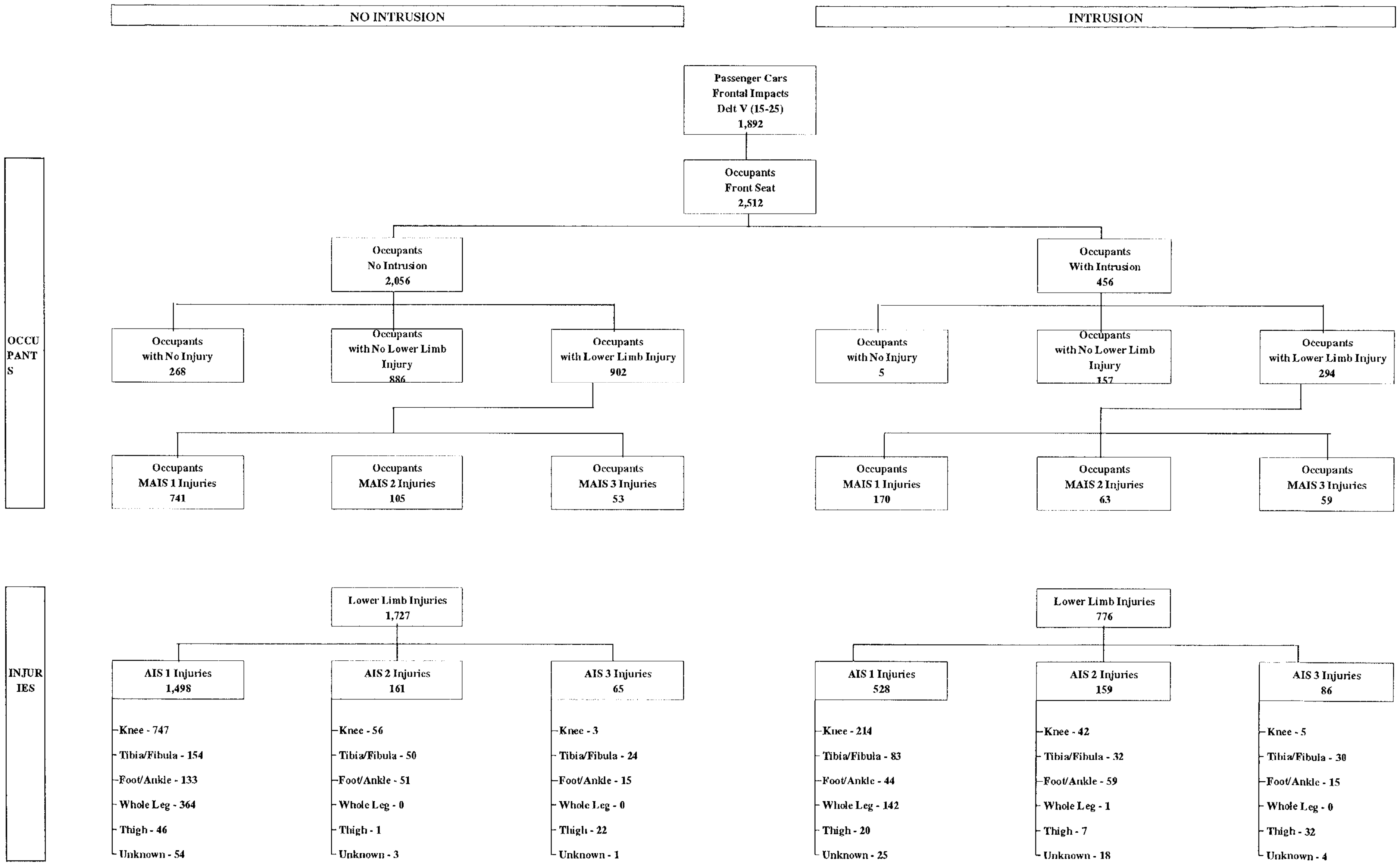
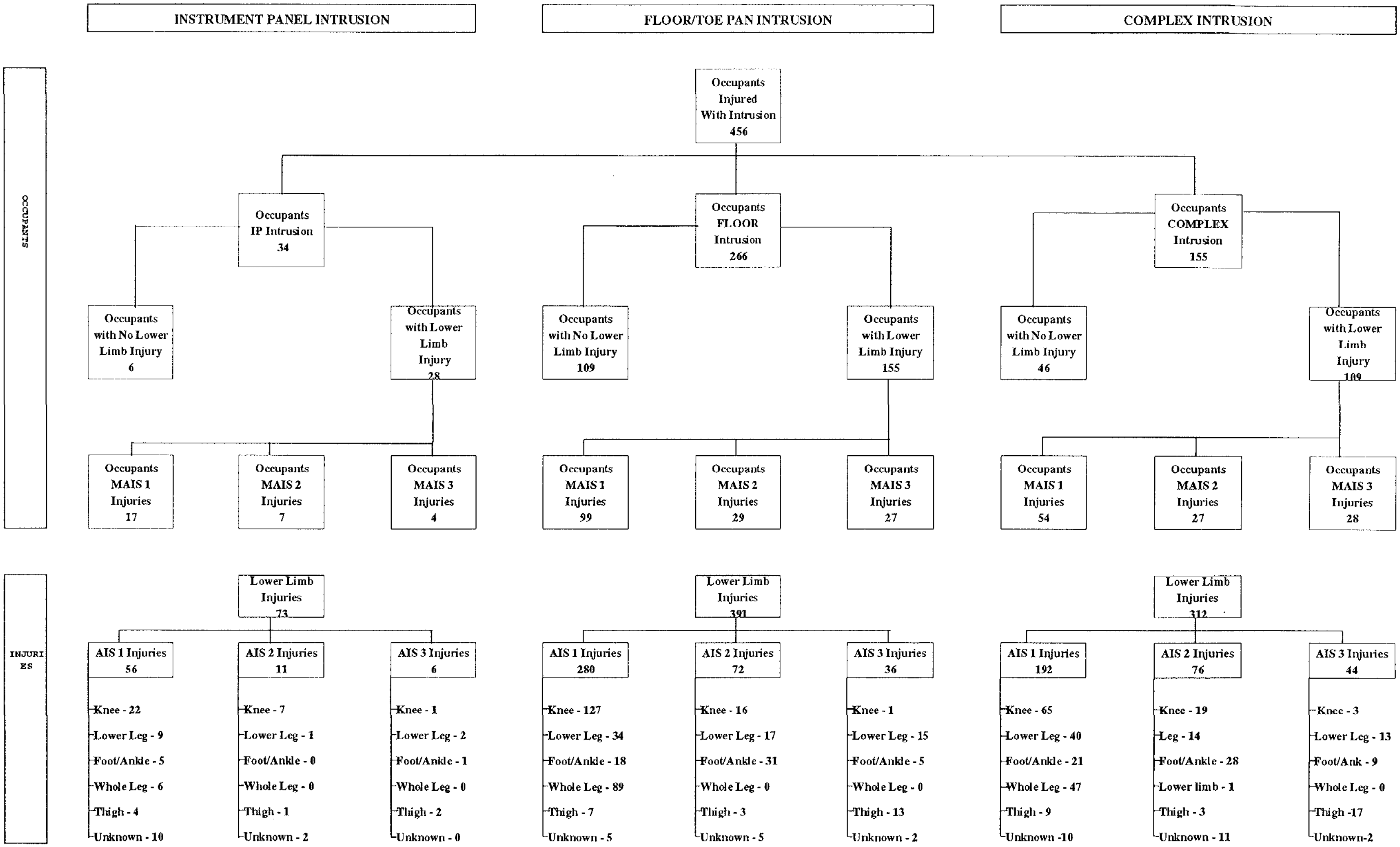
APPENDIX A. OCCUPANTS AND INJURIES CATEGORIZED BY INTRUSION



* 1988-94 NASS, 1986-95 Model Year Passenger Cars, Delta V Total 15-25 MPH, Frontal Impacts (clock position 11-1 O'Clock)
* Intrusion = Floor/Toe and/or I.P. Intrusion

APPENDIX B. OCCUPANTS AND INJURIES CATEGORIZED BY INTRUSION LOCATION



* 1988-94 NASS, 1986-95 Model Year Pass. Cars, Delta V Total 15-25 MPH, Frontal Impacts (clock position 11-1 O'Clock)

APPENDIX C. PREDICTED INJURY RISK OF LEG-FOOT COMPLEX

					Observed Values		Predicted Values	
S. No.	Crash Severity	Position	Gender	Intrusion	Events	N	Injury Risk	95% Confidence Interval
1	Low	Driver	Male	No	5	346	1.9	1.3 - 2.9
2	Low	Driver	Male	Low	2	31	5.1	3.1 - 8.2
3	Low	Driver	Male	High	3	14	13.0	7.8 - 20.8
4	Low	Driver	Female	No	20	350	5.3	3.8 - 7.4
5	Low	Driver	Female	Low	1	20	13.3	8.7 - 20.0
6	Low	Driver	Female	High	0	3	30.0	19.3 - 43.4
7	Low	Passenger	Male	No	0	105	1.0	0.6 - 1.8
8	Low	Passenger	Male	Low	0	4	2.8	1.5 - 5.0
9	Low	Passenger	Male	High	0	1	7.3	3.9 - 13.3
10	Low	Passenger	Female	No	7	137	2.9	1.8 - 4.6
11	Low	Passenger	Female	Low	0	14	7.5	4.4 - 12.7
12	Low	Passenger	Female	High	1	3	18.5	10.5 - 30.4
13	Mid	Driver	Male	No	13	336	3.3	2.3 - 4.7
14	Mid	Driver	Male	Low	4	61	8.6	5.7 - 12.8
15	Mid	Driver	Male	High	5	24	20.8	13.7 - 30.4
16	Mid	Driver	Female	No	31	327	9.0	6.9 - 11.7
17	Mid	Driver	Female	Low	7	46	21.4	15.3 - 29.0
18	Mid	Driver	Female	High	3	10	43.1	31.0 - 56.1
19	Mid	Passenger	Male	No	1	76	1.8	1.1 - 3.0
20	Mid	Passenger	Male	Low	0	12	4.8	2.7 - 8.1
21	Mid	Passenger	Male	High	0	5	12.2	7.0 - 20.5
22	Mid	Passenger	Female	No	7	127	5.0	3.3 - 7.6
23	Mid	Passenger	Female	Low	4	17	12.6	7.9 - 19.6
24	Mid	Passenger	Female	High	2	3	28.6	17.9 - 42.4
25	High	Driver	Male	No	8	107	6.2	4.2 - 9.0
26	High	Driver	Male	Low	8	42	15.3	10.5 - 21.8
27	High	Driver	Male	High	7	22	33.4	23.6 - 45.0
28	High	Driver	Female	No	10	97	15.9	11.7 - 21.3
29	High	Driver	Female	Low	18	38	34.2	25.7 - 43.8
30	High	Driver	Female	High	10	15	59.1	46.5 - 70.6
31	High	Passenger	Male	No	0	32	3.4	2.0 - 5.7
32	High	Passenger	Male	Low	1	14	8.7	5.2 - 14.4
33	High	Passenger	Male	High	2	5	21.0	12.8 - 32.6
34	High	Passenger	Female	No	3	35	9.1	5.8 - 14.0
35	High	Passenger	Female	Low	1	10	21.6	14.1 - 31.6
36	High	Passenger	Female	High	1	6	43.4	29.7 - 58.1

APPENDIX D. PREDICTED INJURY RISK OF LOWER LIMB

					Observed Values		Predicted Values	
S. No.	Crash Severity	Position	Gender	Intrusion	Events	N	Injury Risk	95% Confidence Interval
1	Low	Driver	Male	No	10	345	3.7	2.7 - 5.0
2	Low	Driver	Male	Low	3	31	8.5	5.7 - 12.4
3	Low	Driver	Male	High	5	14	21.7	14.5 - 31.2
4	Low	Driver	Female	No	27	350	7.8	6.0 - 10.2
5	Low	Driver	Female	Low	2	20	17.1	12.1 - 23.8
6	Low	Driver	Female	High	1	3	38.3	27.2 - 50.8
7	Low	Passenger	Male	No	1	104	2.2	1.5 - 3.4
8	Low	Passenger	Male	Low	0	4	5.3	3.2 - 8.5
9	Low	Passenger	Male	High	0	1	14.3	8.7 - 22.6
10	Low	Passenger	Female	No	12	137	4.9	3.4 - 7.0
11	Low	Passenger	Female	Low	0	14	11.1	7.1 - 16.8
12	Low	Passenger	Female	High	1	3	27.2	17.6 - 39.6
13	Mid	Driver	Male	No	24	336	6.3	4.8 - 8.2
14	Mid	Driver	Male	Low	6	61	14.1	10.2 - 19.1
15	Mid	Driver	Male	High	7	24	33.0	23.9 - 43.5
16	Mid	Driver	Female	No	44	326	13.1	10.6 - 16.1
17	Mid	Driver	Female	Low	12	46	26.8	20.5 - 34.3
18	Mid	Driver	Female	High	3	10	52.4	40.8 - 63.8
19	Mid	Passenger	Male	No	2	76	3.9	2.6 - 5.8
20	Mid	Passenger	Male	Low	0	12	9.0	5.8 - 13.6
21	Mid	Passenger	Male	High	0	5	22.8	14.9 - 33.4
22	Mid	Passenger	Female	No	12	127	8.3	6.0 - 11.5
23	Mid	Passenger	Female	Low	5	17	18.1	12.5 - 25.5
24	Mid	Passenger	Female	High	3	3	39.9	28.1 - 53.0
25	High	Driver	Male	No	15	107	11.7	8.7 - 15.6
26	High	Driver	Male	Low	14	42	24.4	18.3 - 31.8
27	High	Driver	Male	High	10	22	49.3	38.5 - 60.2
28	High	Driver	Female	No	15	97	22.9	18.0 - 28.7
29	High	Driver	Female	Low	19	37	42.0	33.5 - 51.0
30	High	Driver	Female	High	13	15	68.5	57.6 - 77.7
31	High	Passenger	Male	No	3	32	7.4	4.9 - 11.0
32	High	Passenger	Male	Low	1	14	16.3	11.0 - 23.6
33	High	Passenger	Male	High	3	5	36.9	25.9 - 49.5
34	High	Passenger	Female	No	4	35	15.2	10.8 - 21.0
35	High	Passenger	Female	Low	2	10	30.4	22.0 - 40.3
36	High	Passenger	Female	High	1	6	56.7	43.7 - 68.9