A Study of Passenger Seat Parameters as a Basis for Active Safety Seat Control

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***Abstract*— During a front-end collision, injuries can be reduced by rapidly repositioning the passenger seat so as to resist the forward motion of the occupant. An occupant in a front-end collision will gain kinetic energy during a crash. This kinetic energy gives an approximate rating of the crash injury expectation. The two significant forces that retard the kinetic energy of the occupant are the frictional and normal forces, neglecting a possible seatbelt's or airbag's interference. In order to increase these significant retarding forces, the seat bottom angle can be increased which increases the normal force on the person, and in turn increases the frictional force. One means of increasing the seat bottom angle is to actively control the position of the seat. An actively controlled seat provides an excellent opportunity to increase these helpful forces during a crash. The purpose of this study is to determine how the seat bottom angle, sliding distance, and friction coefficient impact the relative velocity of the person with respect to the vehicle. Once these relationships are known, a solid foundation will exist for designing an active safety seat.**

***Index Terms*— Active Seat Control, Crash Pulse, Modeling, Safety Seat.**

I. Introduction

Active seat control has been used mainly to minimize vibrations that are felt by the occupants in order to improve ride quality [1]–[3]. Most active seats have one degree of freedom and control the vertical position of the seat. However, an active seat with two or more degrees of freedom would be able to react better to disturbances. For example, the three degree of freedom hyper-active seat sketched in Figure 1 is currently under development at the Georgia Institute of Technology [4]. If the seat could react quickly enough during a collision, then this active seat could perform as a safety seat. However, there are multiple configurations for safety seats, therefore the occupant response relative to the seat must be understood in order to properly reposition an active seat into a safety seat configuration.

In order to properly configure a safety seat, the purpose of a safety seat must be understood. A safety seat is designed to move in some way during a vehicle collision to decrease occupant injuries. One important motion of a safety seat is to increase the angle of the seat bottom, effectively increasing the normal and frictional forces on the occupant and preventing them from "submarining" under the steering wheel [5]–[7]. Another possible movement of a safety seat is to elevate the side of the seat during a side impact [8]. These two different configurations potentially decrease the chance that the occupant will be injured during a collision; however, information is lacking to determine the proper seat configurations to minimize injury.

Fig. 1. Sketch of Three Degree of Freedom Hyper-Active Seat

Safety seat configurations try to minimize the relative movement of an occupant during a collision. Front-end collisions cause a rapid deceleration of the vehicle which causes the occupant to slide forward relative to the seat. Increasing the angle of the seat bottom slows this relative movement. The relative velocity of the occupant is decreased due to the frictional force between the seat bottom and the occupant, as well as, the normal force.

The normal force between the seat bottom and the occupant depends on the seat bottom angle and the crash-pulse signature. A crash-pulse acceleration can be constructed from experimental data by crashing the vehicle into a barrier. The pulse for an average vehicle is on the order of 100 to 120 ms in duration, and reaches a maximum deceleration of 25 to 35 g's [9]–[11]. Figure 2 shows the crash-pulse signature for the 2000 Isuzu Rodeo [9].

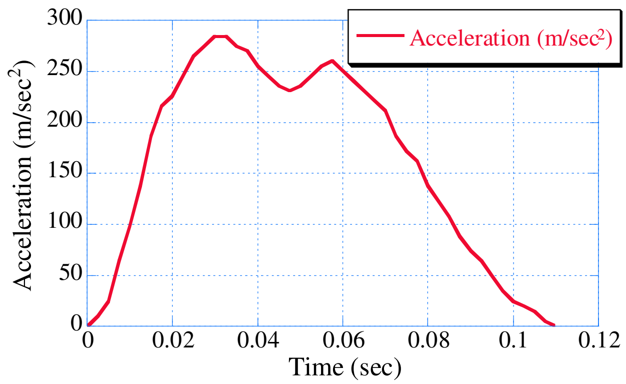

Fig. 2. Crash Pulse Signature - 2000 Isuzu Rodeo

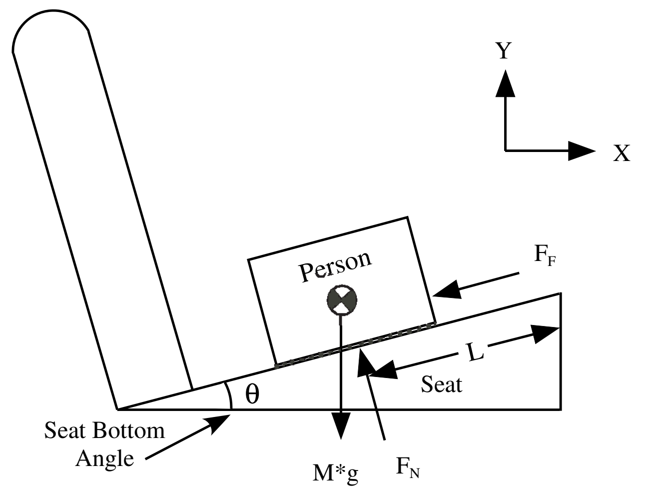

Fig. 3. Fixed-Seat Model of Occupant and Seat as a Block and Ramp

Some work has been done in order to reshape the crash pulse signature, however, the magnitude and duration of the crash pulse signature is similar for most vehicles and poses a threat to the occupant. Therefore, alternative means of improving safety are necessary. An increase in the seat bottom angle leads to a greater normal force between the occupant and seat. But an increase in the normal force will obviously increase the friction force, effectively decreasing the relative velocity of the person with respect to the seat bottom. A possible negative side effect of this approach is an increase in the relative velocity in the vertical direction, even though the overall relative velocity is decreased. This could result in the occupant's head impacting the vehicle ceiling. Another way to quantify the decrease in relative velocity is by measuring the decrease in relative kinetic energy of the person with respect to the vehicle. Here the effort is concentrated on how to slow the occupant by changing the angle of the seat bottom.

The ultimate goal for this research is to design an active seat having two or more degrees of freedom. This active seat would be used for two main purposes.

1) Reduce disturbances that affect ride quality.
2) Protect an occupant during a collision.

In order to design an active seat that has two or more degrees of freedom, the response of the occupant to certain seat parameters must be known. Such parameters include, but are not limited to: the seat bottom angle, the position of the occupant in the seat, and the coefficient of friction between the occupant and the seat bottom. The goal of this paper is to show how the response of the occupant varies with these parameters during a collision. The underlying hypothesis is that by changing these parameters, the relative kinetic energy of the occupant will be decreased, thereby lowering injuries. To this end, this paper will model the occupant and the seat, simulate the crash response of a occupant under different parameters, and use the results to discuss current safety seat designs.

II. Fixed-Seat Model

A fixed-seat model is used here to investigate the effect of increasing the seat bottom angle, changing the coefficient of friction, and changing the position of the occupant in the seat. Although the seat and occupant can be modeled in detail as in Liu and Wagner [12], a simple seat and block mass such as that of Stein will suffice for the purpose of this study [13]–[15]. Figure 3 shows the occupant and seat bottom modeled as a block on a ramp. Since this is a simple model, several dynamic effects are neglected, such as: compression of the seat, rotation of the occupant, and the effect of a seatbelt or airbag. These dynamics are neglected because the goal of this investigation is simple: determine the effect of the basic seat parameters. The crash event is simulated here by accelerating the seat (modeled as a ramp) in the negative horizontal, X, direction. The relative acceleration of the block is then calculated with respect to the ramp. The total acceleration, A_T, is a combination of the relative acceleration and the acceleration of the crash pulse:

$$A_T^X = A_R\cos(\theta) - A_P \tag{1}$$

$$A_T^Y = A_R\sin(\theta), \tag{2}$$

where A_P is the acceleration of the crash pulse, A_T^X is the total acceleration in the X direction, A_T^Y is the total acceleration in the Y direction, θ is the seat bottom angle, and A_R is the relative acceleration of the block with respect to the ramp. In order to solve (1) and (2), the forces on the block are summed in the X and Y directions:

$$MA_T^X = -F_F\cos(\theta) - F_N\sin(\theta) \tag{3}$$

$$MA_T^Y = -MF_G - F_F\sin(\theta) + F_N\cos(\theta), \tag{4}$$

where M is the mass of the block, F_F is the friction force, F_N is the normal force, and F_G is the force of gravity. Equations, (1) and (2) are substituted into (3) and (4) respectively to get:

$$M(A_R\cos(\theta) - A_P) = -F_F\cos(\theta) - F_N\sin(\theta) \tag{5}$$

$$MA_R\sin(\theta) = -MF_G - F_F\sin(\theta) + F_N\cos(\theta). \tag{6}$$

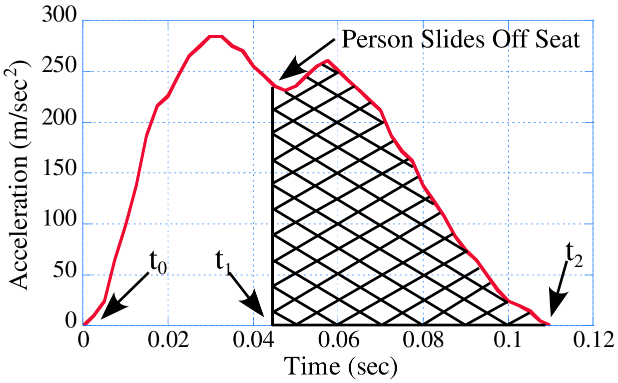

Fig. 4. Two Segments of the Dynamic Model

Another relevant equation is the law of coulomb friction:

$$F_F \leq \mu_K F_N, \tag{7}$$

where μ_K is the coefficient of kinetic friction. Because the acceleration of the ramp caused by the crash pulse is large, the effect of the static friction is ignored and it is assumed that the block will begin sliding from the start of the crash pulse. Therefore, it is assumed:

$$F_F = \mu_K F_N. \tag{8}$$

Equations (5), (6), and (8) are solved to obtain the relative acceleration of the block with respect to the ramp, and the normal force:

$$\begin{aligned} A_R = &-\mu_K F_G \cos(\theta) - \mu_K A_P \sin(\theta) \\ &- F_G \sin(\theta) + A_P \cos(\theta) \end{aligned} \tag{9}$$

$$F_N = M(F_G \cos(\theta) + A_P \sin(\theta)). \tag{10}$$

Equation (9), which describes the relative acceleration of the block with respect to the ramp, is dependent on the seat bottom angle, gravity, the crash pulse signature, and the coefficient of kinetic friction. Equation (10), which describes the normal force, is dependent on the seat bottom angle, the mass of occupant, gravity, and the crash pulse signature. The position where the occupant is sitting on the seat, L, as shown in Figure 3, is not taken into account in the above equations, but is accounted for later in the process.

This dynamic model only applies when the occupant is in contact with the seat. However, the occupant is going to slide to the end of the seat at some point and the forces from the seat are no longer going to affect the person. This is not accounted for in (9), therefore the relative velocity must be divided into two parts: the time when the block is in contact with the ramp, and the time after. Figure 4 illustrates the two parts of the dynamic model. During the first part of the simulation, from t_0 to t_1, the block is sliding on the ramp. For this portion, the relative velocity is found by integrating (9) and the X and Y relative velocity components are recorded, as well as, the time. The second part of the simulation accounts for the remainder of the crash pulse from t_1 to t_2. The second part of the crash

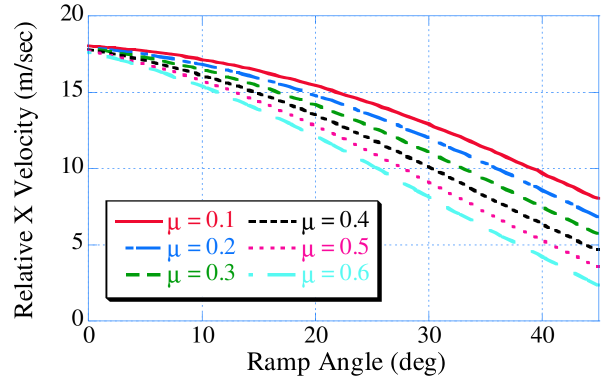

Fig. 5. Relative X, Horizontal Velocity of the Block vs. Ramp Angle

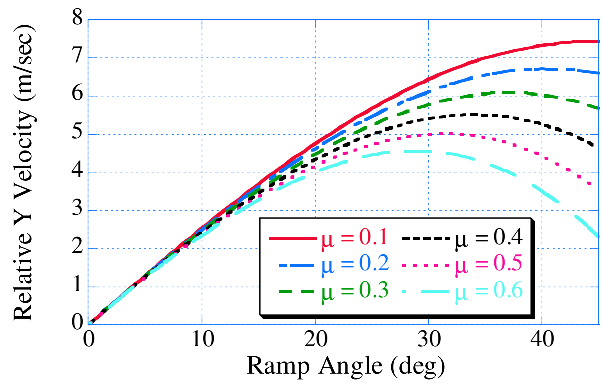

Fig. 6. Relative Y, Vertical Velocity of the Block vs. Ramp Angle

pulse is integrated to get the remaining relative velocity, which is independent of seat frictional forces.

III. Fixed-Seat Simulation Results

In order to determine the response of the block to a crash, data was collected over a large range of parameters. The ramp angle was varied from 0 to 45 degrees. At each degree, the kinetic friction coefficient was varied from 0.1 to 0.6. On the low end, a value of 0.1 would represent silk pants on a leather seat and, on the high end, a value of 0.6 would represent heavy jeans on a cloth seat. The ramp length was set to 0.464 m, which was taken from the average seat bottom length of 41 different vehicles [9]. This length assumes that the occupant is sitting all the way back in the seat when the collision occurs. The mass of the occupant was assumed to be 81.6 kg (180 lbs).

The relative velocity is broken into components to understand their individual contribution to the total relative velocity. Figures 5 and 6 show the X and Y relative velocity components of the block with respect to the ramp at the end of the crash pulse as a function of ramp angle and friction. As expected, the relative X, horizontal velocity component decreases as the ramp angle increases. Unfortunately, the relative Y, vertical velocity component increases up to a point as the ramp angle

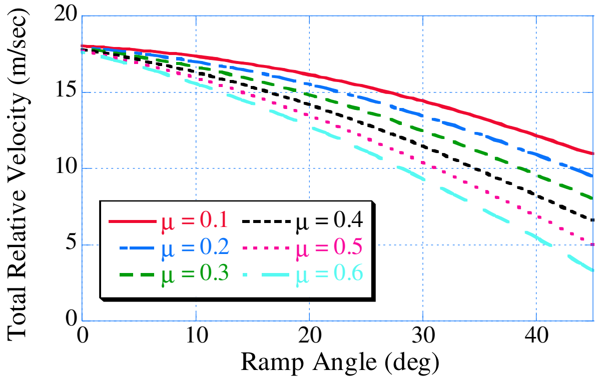

Fig. 7. Total Relative Velocity of the Block vs. Ramp Angle

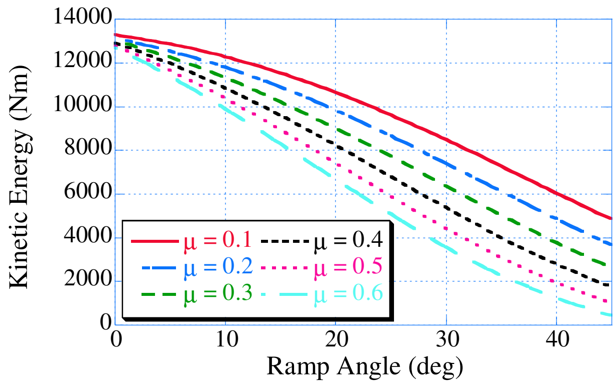

Fig. 8. Relative Kinetic Energy of the Block vs. Ramp Angle

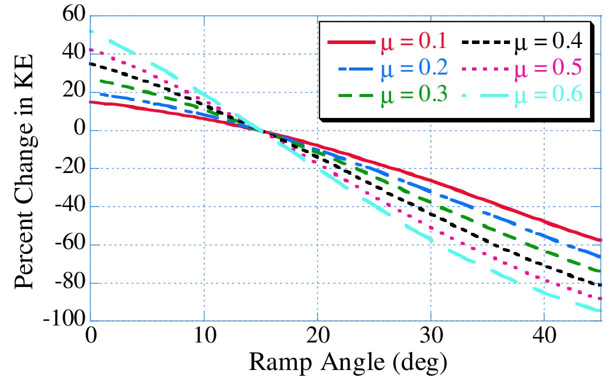

Fig. 9. Percent Change in Relative Kinetic Energy of the Block vs. Ramp Angle

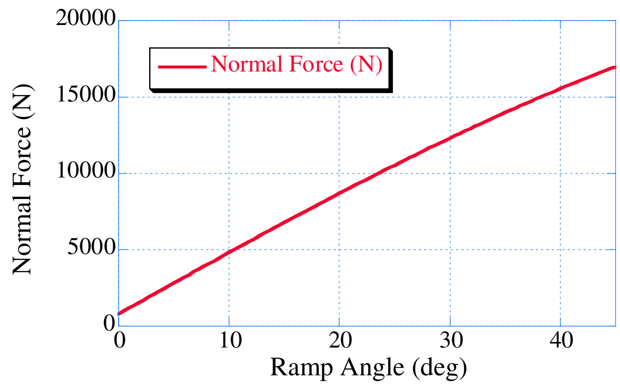

Fig. 10. Normal Force between the Block and the Ramp vs. Ramp Angle

increases. Without the effect of friction, the maximum relative Y velocity would occur at a ramp angle of 45 degrees as shown in Figure 6. As the friction coefficient is increased, the maximum possible Y, relative velocity component decreases and so does the angle at which it occurs. When changing the configuration of a safety seat, it must be clear how much the relative velocity increases in the vertical direction to prevent the occupant from being driven into the roof. Both Figures 5 and 6 portray the significant effect of changing the coefficient of kinetic friction and the ramp angle.

The total relative velocity, however, is dependent on both the X and Y relative velocity components. Figure 7 shows that as the ramp angle increases, the total relative velocity decreases, even though the relative velocity in the Y direction increases. Figure 8 shows that, correspondingly, the kinetic energy decreases as the ramp angle increases. These results verify that increasing the seat angle will decrease the relative kinetic energy of the occupant and possibly lower the chances of injury in a front-end collision. Figures 7 and 8 show that an extremely large seat bottom angle will be the safest. However, current seats are far from this angle [9].

Figure 9 shows the percent change in kinetic energy as the ramp angle is changed from the industry average seat bottom angle of 15 degrees [9]. Singer, et al. designed a passive safety seat that would follow an optimal trajectory during a crash. Their safety seat increased the seat bottom to an angle of 25 degrees [16]. Comparing a 15 degree seat to a 25 degree seat, our results would predict a decrease in the kinetic energy of the block anywhere from 24 to 40 percent, based on coefficients of kinetic friction between 0.3 and 0.6. Beauvais and Meade designed a safety seat that increased the angle from 15 degrees under normal conditions to 45 degrees in the time of an accident [17]. That corresponds to a 58 to 95 percent decrease in kinetic energy.

However, there are negative effects of increasing the ramp angle, like the increase in the vertical velocity shown in Figure 6. Furthermore, another adverse effect is an increase in normal force. Figure 10 shows the normal force increases as the ramp angle increases. The normal force has a nearly linear response to an increase in the ramp angle. By increasing the ramp angle from 15 to 25 degrees, the normal force increases 55 percent. Some, such as Bullerdieck and Hasstedt, have proposed to increase the seat to 90 degrees, in which case the relative kinetic energy will be decreased to zero [18], [19]. However, by increasing the ramp angle from 15 to 90 degrees, the normal force increases from 6,800 to 23,200 N.

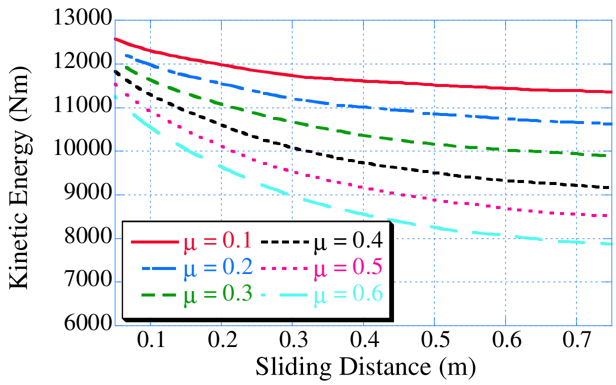

Fig. 11. Relative Kinetic Energy of the Block vs. Sliding Distance

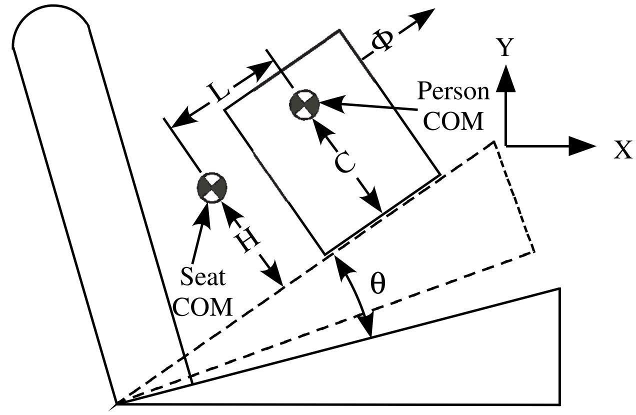

Fig. 12. Moving-Seat Model of Person and Seat

This trade-off between decreasing the total relative velocity and increasing the normal force is clear. Both results must be understood to properly configure a safety seat. Although decreasing the relative kinetic energy of the occupant will decrease the occupant's chances of being injured, increasing the normal force too much might inadvertently injure the person.

The previous data was presented with a constant seat bottom length. During a collision, one cannot guarantee that the occupant is going to be sitting against the seat back. Some people sit closer to the steering wheel than others, and seats can vary in lengths [9]. In the fixed-seat simulation, this effectively changes the sliding distance of the block with respect to the ramp. Figure 11 shows what effect changing the sliding distance would have on the relative kinetic energy of the block. The longer the block slides on the ramp, the less kinetic energy it has at the end of the crash pulse. Figure 11 shows that sitting back in the seat and thus increasing the sliding distance required to reach the end of the seat has a large effect on decreasing the relative velocity of the occupant with respect to the seat.

IV. Moving-Seat Model

A more complex model of the occupant and seat was derived to analyze the effect of the seat moving. Instead of having the seat fixed, the moving-seat model simulates the seat moving from a beginning position to a final position. Figure 12 shows the model that was used to derive the equations of motion. The equations of motion were derived in a similar way to the simple seat model. The relative acceleration of the occupant with respect to the seat is:

$$\begin{aligned} A_R = {} & A_P\cos(\theta) - \ddot{X}\cos(\theta) - \ddot{Y}\sin(\theta) + \ddot{\theta}HL + \ddot{\theta}C + \dot{\theta}^2\Phi \\ & + \dot{\theta}^2 L + \mu_K \mathrm{sgn}(\dot{\Phi})\ddot{X}\sin(\theta) - \mu_K \mathrm{sgn}(\dot{\Phi})\ddot{Y}\cos(\theta) \\ & - \mu_K \mathrm{sgn}(\dot{\Phi})A_P\sin(\theta) - \mu_K \mathrm{sgn}(\dot{\Phi})\ddot{\theta}\Phi \\ & - 2\mu_K \mathrm{sgn}(\dot{\Phi})\dot{\theta}\dot{\Phi} - \mu_K \mathrm{sgn}(\dot{\Phi})\ddot{\theta}L + \mu_K \mathrm{sgn}(\dot{\Phi})\dot{\theta}^2 C \\ & - \mu_K \mathrm{sgn}(\dot{\Phi})F_G\cos(\theta) + \mu_K \mathrm{sgn}(\dot{\Phi})\dot{\theta}^2 HL \\ & + F_G\sin(\theta), \end{aligned} \tag{11}$$

where X is the movement of the center of mass (COM) of the seat in the horizontal direction, Y is the movement of the COM of the seat in the vertical direction, L is the starting distance from the COM of the seat to the COM of the person, H is the negative distance from the COM of the seat to the seat bottom, C is the distance from the COM of the occupant to the seat bottom, and Φ is the distance the person travels relative to the seat. The relative velocity, $\dot{\Phi}$, is calculated when the relative distance, Φ, equals the seat distance. The normal force on the person is:

$$\begin{aligned} F_N = {} & M(\ddot{\theta}\Phi + 2\dot{\theta}\dot{\Phi} + \ddot{\theta}L + \ddot{Y}\cos(\theta) + A_P\sin(\theta) \\ & - \ddot{X}\sin(\theta) + F_G\cos(\theta) - \dot{\theta}^2 HL - \dot{\theta}^2 C). \end{aligned} \tag{12}$$

The other variables in (11) and (12) are the same as in the simple seat model.

V. Moving-Seat Simulation Results

The dynamic equations of motion were simulated and compared to the fixed-seat model. For the case considered here the seat started at an angle of 15 degrees and transitioned to an angle of 25 degrees using an S curve. In order to be more realistic, the simulation includes a delay to simulate the crash sensor response, as well as, the duration to move the seat into the final configuration. The sensor time delay was set to 10

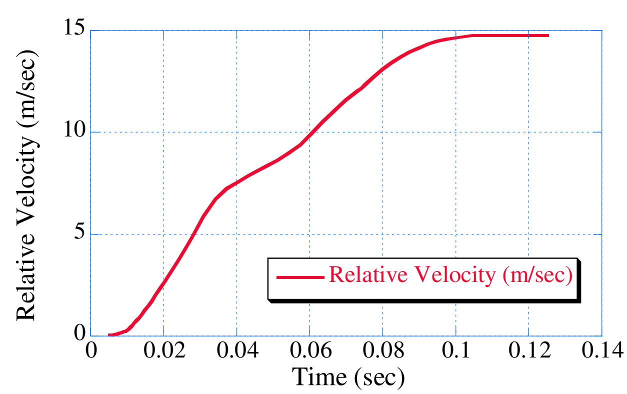

Fig. 13. Relative Velocity of the Block to the Ramp

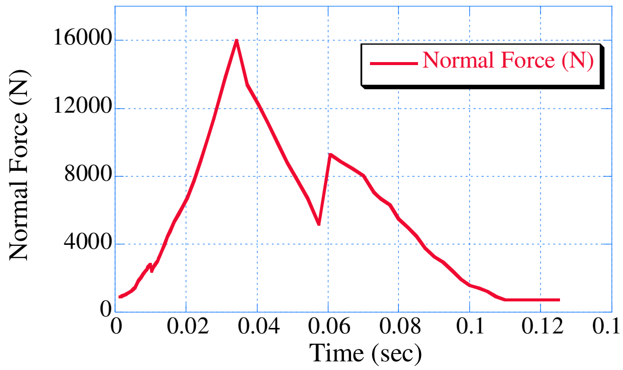

Fig. 14. Normal Force on the Block with respect to Time

ms and the transition time between 15 and 25 degrees was set to 50 ms. This simulation was then compared to the fixed-seat model with a ramp angle of 25 degrees. Both simulations used a μ_K of 0.3. The moving-seat simulation calculated a relative velocity of the block at the end of the ramp of 14.8 m/sec as shown in Figure 13, while the fixed-seat simulation calculated it to be 13.8 m/sec as shown in Figure 7 . However, the fixed-seat model also calculated that the relative velocity would be 15.9 m/sec with a ramp angle of 15 degrees. Therefore, the relative velocity of the moving-seat model was 1.1 m/sec less compared to the fixed-seat model with an angle of 15 degrees.

This result shows that having the seat fixed at a 25 degree angle decreases the relative velocity the most, but this is not a realistic solution because of comfort issues for the occupant. Increasing the seat angle from 15 to 25 degrees in the time of a crash will decrease the relative velocity of the occupant more than the current industry standard seat bottom angle of 15 degrees [9].

The negative results of rapidly increasing the seat bottom angle in the time of a crash is an increase in the normal force on the occupant, as well as, an increase in the person's vertical velocity. Figure 14 shows the normal force on the occupant with respect to time. The normal force reaches a maximum of about 16,000 N, which is considered the safe upper limit of the human spine. Studies show that accelerations of the human body above 20 g's, or approximately 16,000 N for the 81.6 kg person, may fracture the lumbar vertebrae [20]. Therefore, increasing the seat bottom angle from 15 to 25 degrees any faster than 50 ms may result in injuries of that nature.

VI. Conclusions

This paper shows that the seat bottom angle, coefficient of kinetic friction, and slide distance all have a significant impact on the relative kinetic energy of an occupant during a front-end collision. Increasing any of those variables will decrease the kinetic energy of the occupant relative to the vehicle. However, these parameters can only be increased until the normal force on the occupant, or the vertical velocity becomes too large.

The data presented here clarifies that trade-off and provides guidelines for designing an active safety seat that changes position during a crash.

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References

[1] X. Liu and J. Wagner, "Design of a vibration isolation actuator for automotive seating systems - part ii: Controller design and actuator performance," *Intl. J. of Vehicle Design*, vol. 29, no. 4, pp. 357–375, 2002.

[2] N. G. Pantelelis and A. E. Kanarachos, "A simple and effective active seat suspension for agricultural vehicles," in *Proceedings of Control Applications and Ergonomics in Agriculture*, Athens, Greece, 1998, pp. 301–306.

[3] K. C. Cheok, X. H. Hong, and N. K. Loh, "Discrete-time frequency-shaping parametric lq control with application to active seat suspension control," *IEEE Transactions on Industrial Electronics*, vol. 36, no. 3, pp. 383–390, 1989.

[4] S. Klooster, K. Kozak, J. Vaughan, P. Sanders, and W. Singhose, "Fluid power control of a hyper-active seat for low-frequency vibration suppression," in *2003 ASME IMECE*, Washington, D.C., USA, 2003.

[5] K. Bohmler, "Restraining system for vehicle occupants," U.S. Patent 5,908,219, May 27, 1997.

[6] T. Mikami, "Seat with user protecting means," U.S. Patent 5,556,160, October 4, 1994.

[7] L. B. Simon, "Automatic vehicle occupant restraint," U.S. Patent 3,591,232, April 1, 1969.

[8] R. L. Wooley, "Structures for lifting outboard side of seat of motor vehicle during side impact collision," U.S. Patent 5,149,165, May 6, 1991.

[9] W. Glass, "Technical report on the fmvss 213 crash pulse and test bench analysis," Department of the Navy Naval Air Warfare Center Aircraft Division, Tech. Rep., April 2002.

[10] L. K. Sullivan and D. T. Willke, "Dynamic evaluation of child restraints using various frontal crash pulses," National Highway Traffic Safety Administration Vehicle Research and Test Center," Technical Report, December 2001.

[11] A. Kullgren, M. Krafft, A. Nygren, and C. Tingvall, "Neck injuries in frontal impacts: Influence of crash pulse characteristics on injury risk," *Accident Analysis and Prevention*, vol. 32, pp. 197–205, 2000.

[12] X. Liu and J. Wagner, "Design of a vibration isolation actuator for automotive seating systems - part i: Modeling and passive isolator performance," *Intl. J. of Vehicle Design*, vol. 29, no. 4, pp. 335–356, 2002.

[13] G. J. Stein, "Results of investigation of an electropneumatic active vibration control system for a driver's seat," *Proceedings of the Institution of Mechanical Engineers, Part D (Journal of Automotive Engineering)*, vol. 209, no. D3, pp. 227–234, 1995.

[14] ——, "An electro-pneumatic active vibration control system for the driver's seat of agricultural tractors," *Archives of Acoustics*, vol. 21, no. 3, pp. 345–353, 1996.

[15] ——, "New results on an electropneumatic active seat suspension system," *Proceedings of the Institution of Mechanical Engineers, Part D (Journal of Automotive Engineering)*, vol. 214, no. Part D, pp. 533–544, 2000.

[16] N. C. Singer, S. J. Gordon, C. T. Zirps, and M. A. Russo, "Safety seat," U.S. Patent 5,636,424, January 13, 1994.

[17] R. Beauvais and A. J. Meade, "Vehicle safety device," U.S. Patent 5,022,707, October 6, 1988.

[18] K. L. Hasstedt, "Vehicle seat," U.S. Patent 4,634,169, May 28, 1985.

[19] H. H. Bullerdieck, "Safety seat for vehicles," U.S. Patent 4,085,963, November 6, 1975.

[20] T. U. I. f. A. E. Psychology, *Handbook of Human Engineering Data*, 2nd ed. Medford: Tufts University, 1952.