Fundamental Principles for Vehicle/Occupant Systems Analysis
Introduction to Restraints

- Automotive safety: reducing the relative velocity between the occupants and the vehicle interior to reduce the risk of injury to the occupant during a collision.
- Newton’s Laws: change in an occupant’s velocity requires a force to be applied to the occupant.
- Safety engineers analyze the maximum force applied to the driver or passenger without injury.
- Comply with certain Standards (ex. FMVSS 208 - Frontal, 214-side) for occupant protection.
Restraint systems

- The most familiar safety restraint features required by federal standard are safety belts and supplemental air bag restraint systems.
- Other non-regulated restraint systems include energy-absorbing E-A (or collapsible) steering column and E-A knee bolsters.
- Measured using Hybrid III or SID
- Potential injury indices includes peak pelvic acceleration and TTI (Thoracic Trauma Index)
Effective Restraint system

• Essential to know the required stopping distance
• Consider the tolerance level of 60 g’s in chest
  – Optimum or minimum stopping distance with a square wave (uniform) deceleration pulse, a.k.a. Equivalent Square Wave (ESW) is
    • 6-in from 30 mph and 24-in stopping distance from 60 mph
  – Half-sine deceleration pulse requires (more realistic)
    • 9.7 in for 30 mph and 37.7 for 60 mph
• Larger distances are required to stop from high velocities at sub-injury levels
• In a 30-mph barrier collision, a typical full-size car can have
  – up to 28 in of front-end crush
  – About 15 in between the occupant and the interior
  – 6 in deformation of the interior compartment
  – Total of about 49 in
Surviving high speed crashes

- Essential to use the frontend crush and available distance between the occupant and the interior.
- Accomplished when a restraint is used.
- The air bag, energy absorbing steering column and safety belts are all restraint systems that slow the occupant shortly after the vehicle starts to decelerate.
- Part of the distance is lost in a harness by slack and belt stretch.
- The distance between the driver and the steering wheel is lost in the case of the energy-absorbing column restraint, and the distance of the front-end crush and occupant space traversed during the sensing and deployment time for the air bag are lost.
- However, the remaining useful distance does increase the survival velocity appreciably.
Barrier Collision

• Studies of the vehicle response and the occupant response

• The primary impact:
  – Between the vehicle front-end structure and the fixed barrier.
  – Major portion of the crash energy is absorbed by structural deformation that produces a crash pulse transmitted to the occupant compartment.
  – The compartment intrusion is largely affected by the extent of the vehicle front-end deformation, influenced by vehicle design parameters such as the strength of the structural members, the available package space, the stack-up of non-crushable power-train components, the vehicle mass, and the test speed.

• The secondary impact
  – Between the occupant and the restraint system and/or the vehicle interior.
  – Occupant responses are measured by parameters such as the HIC, chest g’s, chest deflection, and femur loads.
  – Affected by the vehicle crash pulse, the extent of the intrusion and the intrusion rate into the occupant compartment, the restraint system, the vehicle interior profile/stiffness, and the dummy construction/instrumentation.
Integrated structural and occupant simulation

- Traditional design methodology: full vehicle crash testing to determine responses of an occupant, restrained or unrestrained contacting vehicle interiors with or without compartment intrusion.
- Integrated structural and occupant simulation modeling offers several potential advantages over the traditional full-vehicle crash testing.
- Advantages:
  - Early design guidance
  - Shorter vehicle design
  - Development time
  - Optimization of structural and package efficiency,
  - Evaluation of design alternatives and reduced prototype test requirements
FMVSS 208 – Frontal Collision

• Vehicles impacting a fixed barrier either perpendicular or at a 30 degree angle at a speed of 30 mph must provide protection for the front-seated Hybrid III dummy occupants as follows:
  – Head Injury Criterion (HIC) - The resultant acceleration at the center of gravity of the dummy head must be such that the expression:

\[
HIC = \left[ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} adt \right]^{2.5} (t_2 - t_1)
\]
FMVSS 208 – Frontal Collision

- Chest Injury (CLIP) - The resultant acceleration at the center of gravity of the dummy chest shall not exceed 60 g’s, except for the intervals whose cumulative duration is not more than 3 ms

- Femur Loads - The compressive force transmitted axially through each dummy upper leg shall not exceed 2,250 lbs

- Chest Deflection - The chest deflection shall not exceed 76.2 mm
Barrier Test - Output

- Instruments provide vehicle acceleration/deceleration data experienced in the passenger compartment.
- Two, tri-axial accelerometers are mounted to the rocker panels at the base of the B-pillar for such measurements.
- For frontal barrier or rear impacts, longitudinal component of acceleration from underneath the B-pillar, located in an undeformed area of the vehicle occupant compartment.
- The deceleration-time history is a superposition of a spectrum of frequencies representing the instrumentation noises, elastic-plastic vibrations, structural collapse, and engine/accessories interactions as they impact one another.
- An unfiltered or raw deceleration-time history provides little information of value.
- Equivalent Square Wave (ESW) is a specific type of characterization
Barrier Test

- Against a rigid concrete barrier
- HIII 50\(^{th}\) percentile male driver (unbelted)
- Steering assembly airbag
- Dummies instrumented with triaxial accelerometers at the centers of gravities of the head and chest, and load cells at the femur
- Recorded data processed according to SAE J211 specification
- The filtered data are then analyzed for calculating injury performance numbers assessing dummy performance in compliance with FMVSS 208

Figure from Priya prasad, 2005
Application of Concepts to Vehicle/Occupant Analysis

- Force required to change a velocity is proportional to acceleration.
- Complicating factors such as relative motion for whiplash injury are not considered.
- The parameter that causes injury, “force”, is measured with a force transducer.
- Assuming that rigid body dynamics apply, understanding that the human body is not a rigid body.
Application of Concepts to Vehicle/Occupant Analysis

- A “g” as generally used by biomechanics engineers and automotive researchers is the acceleration of gravity.
  - If the human head can stand about 80 g’s for several milliseconds without injury, then multiplying the 80 g’s by the weight of the head (15 lbs) arrives at a force of about 1200 lbs
  - The force be distributed over the head so there is no localized deformation at the point of impact.
  - The chest can stand about 60 g’s if the force is distributed.

- Tolerance in “g” units is that the stopping distance required without exceeding the tolerance can be calculated by the basic laws
Vehicle Response

- In the case where a vehicle crashes into a rigid fixed barrier, less stopping distance is required than in braking.
- The vehicle loses all of its kinetic energy in a fraction of a second through front-end structural deformations.
- The amount of deformation is equal to the stopping distance of the vehicle.
- Since the stopping distance of a vehicle in the barrier crash is normally short, a much higher force is generated at the barrier interface
Vehicle Response

• The vehicle stopping distance (or dynamic crush) in barrier tests largely depends on crash pulses

• The dynamic crush can be determined by double integration of the vehicle crash pulse with known initial impact velocity
Vehicle Response

Vehicle deceleration versus displacement

Assuming the frictional forces are negligible, the area under the deceleration vs. displacement curve (or \(G_v\) vs. \(D_v\)) is equal to the initial kinetic energy of the vehicle.

Longitudinal vehicle displacement (2nd integration of longitudinal deceleration)

The vehicle stopping distance occurred at the maximum displacement (23.2 in) – max crush length \(X_v\).

Figure from Priya Prasad, 2005
Equivalent Waveform

Pulse Waveform Efficiency

- The efficient utilization of the vehicle available package space in front-end structure, which depends on the pulse waveform efficiency, is of vital importance.

$$\eta = \frac{1}{2} \frac{mv^2}{mX_v A_p}$$

Equivalent Square Wave (ESW):

- Square wave is an idealized pulse that is used in many crash-related analyses

$$F_{avg} = \frac{1}{2} \left( \frac{mv^2}{X_v} \right)$$

$$ESW = \frac{F_{avg}}{mg} = \frac{1}{2g} \left( \frac{v^2}{X_v} \right)$$
Velocity-time histories/ vehicle and occupant

- Acceleration of the vehicle and/or the occupant is directly related to the slope of the velocity-time curve at any time $t$;
- The difference, at any time $t$, between the occupant and the vehicle velocity time curves represents the relative velocity ($Dv$) between them; and
- The displacement of the vehicle and occupant over the ground is represented by the area under their respective velocity-time curves with respect to the time axis, and the relative displacement of the occupant with respect to the vehicle is the area between their respective velocity-time curves.

Figure from Priya prasad, 2005
Velocity profiles

The shaded area under the velocity curve represents the 24 in of vehicle crush, which is equal to the distance the vehicle travels over the ground.

Figure from Priya prasad, 2005
Velocity profiles

Velocity-time diagram of crashing vehicle and unrestrained occupant

Velocity-time diagram of crashing vehicle and restrained driver

The speed at which the occupant hits the interior components may be different from the speed change of the vehicle if the occupant is restrained with various restraint systems.

Figure from Priya prasad, 2005
Eppinger and Patrick Guidelines

1. Maximize the time over which restraint forces are applied to minimize the magnitude of the forces applied to an occupant. This, in turn, will minimize the “g”-level, which should be below human tolerance levels. The total time is very difficult to control or design. However, the effectiveness of the belt can be a parameter in a restraint system design.

2. Maximize the distance of the occupant’s travel over the ground by utilizing the vehicle crush and the available space within the occupant compartment. Therefore, a restraint system should be designed to provide sufficient cushioning (or the necessary distance) for decelerating the occupant.

3. Minimize the effectiveness time of a restraint system by applying as great a restraint force as soon as possible during the impact event. This force should not exceed the established tolerance level in terms of dummy performance numbers as specified in FMVSS requirements.

4. Minimize body articulations, local deformations and rate of deformations, and local inertial accelerations during the restraint event. Minimize excessive relative motion between body segments and body-to-vehicle interiors.
Eppinger and Patrick Guidelines

5. Minimize concentrated forces on sharp edges and hard surfaces. Distribute forces over the greatest possible area. Distributed forces are preferable to concentrated forces in design of occupant protection systems. Structures generally deform less with distributed loads and therefore, deformation-based injuries are reduced. This reduces local surface pressures applied to a body region that have also been related to structural failure.

6. Use energy-absorbing materials designed to crush at forces below human tolerance levels and extract energy from the occupant by maximizing the energy absorption during crush or deformation. Force-distributing padding is preferred over major energy-absorbing structures such as steering hub, knee contact area, instrument panel and interior components.

7. Maximize the efficiency of a restraint system by designing as closely as possible to a square waveform. This is most effective in terms of utilizing a minimum package space requirement.

8. Maintain compartment integrity and minimize structural intrusions in both magnitudes and relative velocities.
Frontal Impact Analysis

• A frontal crash is a two-impact event

• Primary Impact
  – Vehicle strikes a barrier, causing the front-end to crush.
  – Kinetic energy of the vehicle is expended in deforming the vehicle’s front structure.
  – The design of the front-end, rear, or side to crumple in a collision and absorb crash energy is called crash energy management or crashworthiness.
Frontal Impact Analysis

• Secondary Impact
  – The second (secondary) impact occurs when the occupant continues to move forward as a free-flight mass and strikes the vehicle interior or interacts with or loads the restraint system.
  – Some of the kinetic energy is expended in deforming the vehicle interior or the restraint system, and in compressing the occupant’s torso.
  – Remaining kinetic energy is dissipated as the occupant decelerates with the vehicle.
  – The kinetic energy dissipated during the second impact is a function of the occupant’s mass and of the differential velocity of the occupant to the interior.
Energy Absorbing Materials

- Energy-absorbing (EA) materials on the interior, and devices such as EA steering columns, belts and air bags provide two important synergistic benefits.
  - First, these enhance “ride-down” for the occupant within the vehicle compartment.
  - Second, these absorb some of the energy of the second impact
EA material properties

• EA materials can be designed through selection of appropriate characteristics to crush at forces below human tolerance levels.

• EA materials absorb energy while being crushed, and because of this crush, the occupant’s differential velocity with the interior in the second impact is reduced over a longer period of time than that from impacting with a rigid surface.

• This produces lower deceleration forces on the occupant
Side Impact Analysis

- Velocity profiles obtained by the numerical integration of accelerometer data taken from the following locations:
  - Center of gravity (CG) of the moving deformable barrier (MDB)
  - Non-impacted left-hand rocker of the target vehicle
  - Door inner panel at the armrest
  - Side Impact Dummy (SID) pelvis

Figure from Priya prasad, 2005
Momentum exchanges-Side Impact

• The primary momentum exchange taking place between the MDB and the target vehicle. During this event, the rigid body motion of the target vehicle increases while the MDB velocity decreases until at some point in time, both the MDB and the target vehicle achieve a common velocity.

• The momentum exchange taking place between the MDB and the door. The door quickly attains the high velocity of the MDB.

• Finally, the momentum exchange taking place as the intruding door comes into contact with the stationary SID. The dummy pelvis, hit by a fast-intruding door, is quickly accelerated in the lateral direction.
Side Impact - FBD

- The forces acting on the door are:
  - $F_{MDB}$ is the punch-through force of the MDB acting on the door
  - $F_{structure}$ is the body side structural resistance of the target vehicle that resists door intrusion.
    - structural resistance is provided by door support frame.
    - Force is the integral of the door support frame reaction pressures acting on the door peripheral areas and is shown as one-half of its concentrated load in two parts
  - $F_{dummy}$ is the door-to-dummy interaction force, also is the reaction force acting on the dummy

Figure from Priya prasad, 2005
Side Impact - observations

• From Newton’s Second law, following observations were made
  – Decreasing the MDB punch-through force \( (F_{MDB}) \) would decrease the force acting on the dummy \( (F_{dummy}) \)
  – decreasing the rate of change in the linear momentum of the door by making the door lighter or decreasing the door intrusion velocity would decrease the force acting on the dummy.
  
  ─ increasing the struck vehicle body side structural resistance \( (F_{structure}) \) would also decrease the force acting on the dummy
Countermeasures for limiting the force on the dummy during side impact

- Reducing the door intrusion velocity (and hence, its rate of change in linear momentum)
  - via structural upgrading of the body side.
  - Reduces the severity of subsequent momentum exchange between the door and the dummy.

- Limiting the peak forces acting on the dummy ($F_{\text{dummy}}$)
  - *Use a foam cushion* with a nearly constant force-crush characteristic or
  - a deployable side airbag.
  - Reduces the MDB punch-through force ($F_{\text{MDB}}$) *while also making* the door inner sheet metal and trim more compliant for occupant cushioning, thereby further reducing $F_{\text{dummy}}$.

- Optimizing the specific stiffness by
  - maximizing the structural stiffness/unit material usage of the vehicle body side structure
  - via efficient structural design and
  - use of an airbag or foam cushion.
  - an optimum combination of the first two strategies.
Structural Upgrading

- The crash event between the MDB and the target vehicle is shortened.
- MDB slows at a faster rate while the struck vehicle rigid body motion speeds up at a higher rate.
- The door intrusion and intrusion velocity are reduced.
- The dummy pelvis, hit by a slower intruding door, is subjected to a milder acceleration as evident by the slope the dummy pelvis velocity curve.
- The structural upgrade weight penalty to achieve this effect is enormous.
- The weight penalty is estimated at more than 18 kg (40 lbs) for a 2-door compact vehicle.
- TRL has shown that certain structural upgrading of the vehicle body side structure could lead to an undesirable intrusion profile of B-pillar/door by tilting inboard at the “waistline” and concentrating the impact load on the occupant in the thorax region.
- A more desirable crush pattern for the B-pillar/door is to remain upright during side impact for a more evenly distributed impact loading on the occupant.

Effects of a hypothetical structural upgrade

Figure from Priya prasad, 2005
Effects of cushioning

- A stiff linear spring constant ($K_1$), increases in direct proportion to the panel deflection ($\delta$) as the dummy leans heavily against the door during side impact.
- The force ($F_{\text{dummy}}$) acting on the dummy pelvis, which is equal to $K_1 \delta$ causes the pelvis acceleration (in the $M_{\text{pelvis}} a_{\text{pelvis}}$ term) to exceed the limits.
- Initially, when the dummy is hit by the intruding door and as the reaction force ($F_{\text{dummy}}$) begins to rise but is less than $F_{\text{constant}}$, the stiff spring $K_1$ will deflect up to $\delta_1$ until $F_{\text{dummy}} = F_{\text{constant}}$.
- At this point onward, the load-limiting spring will begin to crush ($\delta$) at a constant force ($F_{\text{constant}}$).
- The dummy pelvis, subjected to an appropriate level of this constant reaction force from the door, will accelerate at a constant level without exceeding the requirement as long as the cushion does not bottom out.
Deployable Door trim

- The crush duration between the MDB and the target vehicle will remain unchanged from the baseline
- Door velocity profile will remain unchanged
- Deploying load-limiting foam cushion contacts the dummy pelvis early in the crash event and accelerates it away from the intruding door sooner than that of the baseline
- Consequently, the dummy pelvis will experience a milder acceleration as evident from the slope of its velocity history
- Strategy is to use a deploying door trim with the load-limiting foam cushion behind it to quickly push the stationary SID away from the intruding door steel at a controlled rate.
Compatibility Between Restraint System and Vehicle Front Structure

- Vehicle front needs to be designed for compatible crush characteristics with restraints.
- $\delta_1$ – dummy moves at constant speed
- $\delta_2$ – increasing deceleration
- $\delta_3$ – constant deceleration
- $\delta_v + \delta_{p/v} > \delta_p$
  $\delta_{p/v}$ is the occupant displacement with respect to the compartment

Idealized model
Restrained Occupant Models

• Two models of chest deceleration to study simulation of a restrained occupant and vehicle front-end dynamics
  – A trilinear segment approximation to the chest deceleration
  – A sine-wave approximation
• The models are used to calculate the required stopping distance
• Knowing the available vehicle interior space, the required vehicle crush distance and the average vehicle deceleration can then be calculated
Tri-linear approximation (1/3)

- $(0 < t < t_e)$, the occupant velocity is assumed to be constant, occupant is in a free flight since “belt slack”.
- The occupant continues to move at the initial velocity of the vehicle until time $t_e$.
- At $t = t_e$, the restraint system becomes effective, and therefore, it is referred to as the effectiveness time of the belt (or restraint system).

Figure from Priya prasad, 2005
Tri-linear approximation (2/3)

- \((t_e < t < t_2)\), the restraint slack has been taken up.
- The occupant starts interacting with the restraint at a certain relative velocity, and then begins to decelerate due to the induced belt loads until a maximum chest deceleration is reached.
- The occupant motion during this period is assumed to be at a constant deceleration rate (onset rate).

Figure from Priya prasad, 2005
Tri-linear approximation (3/3)

- In the third period, \( (t_2 < t < t_3) \), the occupant velocity continues to reduce until it vanishes.
- The maximum chest displacement is reached at time \( t_p \).

Figure from Priya prasad, 2005
Parameters for vehicle – occupant system analysis

<table>
<thead>
<tr>
<th>Case</th>
<th>Item</th>
<th>$t_e$ (ms)</th>
<th>$a$ (g’s/s)</th>
<th>$A_p$ (g’s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>3-point belt(13 - 18% elongation webbing)</td>
<td>34</td>
<td>1000</td>
<td>40</td>
</tr>
<tr>
<td>Case 2</td>
<td>3-point belt(3 -6% elongation webbing)</td>
<td>30</td>
<td>1200</td>
<td>40</td>
</tr>
<tr>
<td>Case 3</td>
<td>3-point belt(3-6% webbing with preloader)</td>
<td>20</td>
<td>1200</td>
<td>40</td>
</tr>
</tbody>
</table>
Sine-Wave Chest Deceleration Model

- The belted occupant is simulated by one mass-linear spring system subjected to a constant deceleration of magnitude equal to the vehicle ESW
- This model simulates only the belted right front passenger, and precludes the passenger from contact with the vehicle interior surfaces such as the glove compartment, front crash pad and windshield

Figure from Priya prasad, 2005
Compatibility Between Restraint System and Vehicle Front Structure

• The area under a velocity-time history curve represents the occupant travel distance relative to ground and the slope of the velocity curve equals the acceleration levels of the occupant.

Figure from Priya Prasad, 2005
Compatibility Between Restraint System and Vehicle Front Structure

Parametric study conducted for speeds 30, 35, 40 mph

- **Effectiveness time** $t_e = 0.034 \text{ s}$
- **Onset rate** $\alpha = 1000 \text{ g/s}$
- **Constant Decel.** $A_p = 40 \text{ g}$

**Table:**

<table>
<thead>
<tr>
<th>Case</th>
<th>Barrier Impact Velocity (mph)</th>
<th>Chest Onset (G/sec.)</th>
<th>MAX. Const. Decel. (G)</th>
<th>Effectiveness Time (msec)</th>
<th>Total Chest Travel (inches)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
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<td>1000</td>
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<td>40</td>
<td>1000</td>
<td>40</td>
<td>34</td>
<td>53.0</td>
</tr>
</tbody>
</table>

Note: Area of 240 mm² equals 1.0 in. of travel

Figure from Priya prasad, 2005
Belt Restraint System

- The minimum required vehicle crush decreases as the effectiveness time (response time) decreases.
  - A certain amount of reduction in vehicle length can then be realized and benefit from application of a pre-crash sensor in early triggering restraint system.
- Using early triggering restraint system, the 35 mph impact could also be achieved with no increase in vehicle length using the 30 mph baseline structure.
Supplemental Airbag Restraint System (SARS)

- The SARS is automatically deployed after a certain crash severity is reached.
- The sensing times may vary from 8 ms to 13 ms with a threshold velocity of approximately 10 to 15 mph, at which the actuators trigger.
- The entire sequence of operations is completed in approx. 40 to 50ms.
- Higher onset rates and constant deceleration are used since the bag would act as a non-linear “hard” spring.
- Minimum required crush distance based on the supplemental airbag restraint system performance is larger than that determined for the belt restraint systems.

Figure from Priya Prasad, 2005
Constant Deceleration Model for Vehicle Response (ESW)

- This model assumes that the vehicle deceleration remains constant during vehicle crush, namely,
  \[ A_v = \text{constant} = \text{ESW} \]
- The vehicle velocity-time and crush-time histories are:
  \[ V(t) = V_o - A_v t \]
  \[ X_v = V_o t - 0.5 * A_v t^2 \]
- Time at which the vehicle stops is given by
  \[ T_v = V_o / A_v \]
  \[ \Delta_v = 0.5 * V_o T_v \]
Ride Down

• Is a mechanism whereby the occupant is in contact with the vehicle interior before the vehicle velocity approaches zero.

• Helps in possible reduction of occupant loads
  – Since the second collision occurs at a lesser relative velocity than that would have occurred when the vehicle is completely stationary
Ride-Down Concept and Application

• Using the ESW concept, the mechanism of ride-down can be illustrated as follows:

• Let
  – $A_v$ be an ESW vehicle deceleration
  – $V_o$ be the vehicle impact velocity
  – $\delta_v$ be the vehicle dynamic crush or stopping distance;
  – $V_r$ be the relative velocity between the occupant and vehicle interior or the ride-down velocity;
  – $\delta_{occ}$ be the initial spatial distance between the occupant and vehicle interior
Ride-Down Concept and Application

- Time for vehicle to stop
  \[ t_v = \frac{V_o}{A_v} \]
- Time for occupant contacting interior
  \[ t_c = (2 \frac{\delta_{occ}}{A_v})^{0.5} \]
- **For ride down**, \( t_v > t_c \)
- Final relationship are
  \[ V_r = V_o \left( \frac{\delta_{occ}}{\delta_v} \right)^{0.5} \]

Some interesting remarks
- If \( d\delta_{occ} > d\delta_v \), the occupant impacts the vehicle interior when the vehicle is stopped or is in rebound.
- It is then possible that the second collision velocity may be equal to or greater than the initial impact velocity.
- The second collision velocity varies as the square root of the ratio of \( d\delta_{occ}/d\delta_v \).
  - If ESW deceleration assumed for the vehicle
  - A more detailed ride-down analysis possible for other vehicle deceleration profiles