Lecture 5.39

5.1 Road Accidents

Physics of Vehicle Collisions

Vehicle crashes obey classic Newtonian mechanics. The severity of a collision is governed by the rapid dissipation of kinetic energy ($E_k = \frac{1}{2}mv^2$) during impact.

Because kinetic energy increases with the square of velocity, doubling vehicle speed quadruples the impact energy that must be absorbed by vehicle crumple zones and human bodies during a crash.

- Kinetic Energy Formula: $E_k = \frac{1}{2}mv^2$; velocity has a quadratic impact on crash energy
- Law of Conservation of Linear Momentum: $m_1 u_1 + m_2 u_2 = m_1 v_1 + m_2 v_2$
- Work-Energy Theorem: Work done by braking friction equals loss in kinetic energy ($F \cdot S = \Delta E_k$)
- Deceleration Forces: Rapid deceleration (g-forces) experienced by occupants during impact

Vehicle Skid Marks and Drag Factor

When a driver applies emergency braking, locked tires slide along the pavement, generating intense friction that melts rubber and deposits dark tire skid marks on the road surface. Skid marks provide undeniable physical evidence of the braking distance. The drag factor (f) represents the average coefficient of friction between sliding tires and pavement.

Surface Type	**Dry Condition (f)**	**Wet Condition (f)**
Asphalt (Bituminous)	0.6 – 0.8	0.3 – 0.5
Concrete (Portland)	0.7 – 0.9	0.5 – 0.7
Gravel / Dirt	0.4 – 0.6	0.4 – 0.5

- **Types of Marks:** Skid marks (locked braking), Scuff marks (yaw/cornering), Yaw marks
- **Measuring Skid Length (S):** Averaging measured skid marks across all four wheels

Mathematical Derivation of Pre-Impact Speed

Using the Work-Energy principle, traffic engineers calculate the minimum initial speed (V) of a vehicle prior to emergency braking based on skid mark length.

Equating kinetic energy loss to friction work ($F \cdot S = f \cdot W \cdot S = \frac{1}{2}mv^2$) yields the fundamental metric formula: $V = \sqrt{254 \cdot f \cdot S}$, where V is speed in km/h, f is drag factor, and S is skid length in meters.

- Derivation: $\frac{1}{2}mv^2 = mgfS \implies v = \sqrt{2gfS}$
- Metric Highway Formula: $V = \sqrt{254 \cdot f \cdot S}$ (Speed V in km/h, distance S in meters)
- Grade Adjustment: $V = \sqrt{254 \cdot (f \pm n) \cdot S}$, where n is percent grade/slope
- Minimum Speed Concept: Calculated speed is the minimum speed because residual impact energy is excluded

Human Factors: PIEV Theory of Reaction Time

Driver Perception-Reaction Time (PRT) is the total time elapsed between the appearance of an unexpected hazard and the physical application of brakes.

The PIEV theory divides total reaction time into four consecutive psychological phases:

Perception (Sensory) → **Intellection** (Processing) → **Emotion** (Evaluation) → **Volition** (Action)

- **Perception:** Driver's eye visually registers hazard on carriageway
- **Intellection:** Brain recognizes and processes nature of hazard
- **Emotion:** Emotional response (fear, judgment) determining course of action
- **Volition:** Brain sends motor signal to foot to apply brake pedal
- **IRC Standard:** Total PIEV time taken as 2.5 seconds for Stopping Sight Distance design

Pedestrian Crash Kinematics and Trajectories

Pedestrian-vehicle impacts exhibit distinct physical collision trajectories depending on vehicle front-end geometry (bumper height, hood slope) and impact velocity.

Key pedestrian kinematics trajectories include Wrap Trajectory (pedestrian strikes bumper, wraps onto hood/windshield), Forward Projection (pedestrian struck by flat bus/truck front and thrown forward), Roof Vault, and Fender Vault.

- Wrap Trajectory: Common with sedan cars; lower legs struck first, head impacts windshield
- Forward Projection: Common with high-bumper commercial vehicles; victim pushed and run over
- Throw Distance Formulas: Empirical relations linking pedestrian throw distance to impact speed
- Injury Mechanisms: Secondary impact with pavement often causes severe head trauma

Commercial Heavy Vehicle Crash Dynamics

Commercial trucks and multi-axle trailers present unique stability hazards due to high center of gravity, heavy gross mass, and long stopping distances.

Key crash phenomena include Rollover (instability on sharp horizontal curves due to high center of gravity), Jack-knifing (trailer skidding laterally relative to tractor during hard braking), and Underride Crashes (passenger cars sliding underneath elevated truck rear/sides).

- High Center of Gravity: Increases rollover susceptibility on un-banked horizontal curves
- Jack-Knifing: Loss of directional control causing trailer to swing out at right angles
- Rear/Side Underride Protection: Mandatory RUP/SUP steel bumpers preventing car wedging
- Braking Distance Disparity: Fully loaded trucks require 40% longer stopping distance than cars

Two-Wheeler and Motorized Cycle Collision Mechanics

Motorcycles and scooters exhibit high instability and zero occupant structural enclosure, making two-wheeler riders exceptionally vulnerable during impact events.

Collision dynamics involve rapid rider ejection, side sliding (capsizing), and direct impact with fixed roadside obstacles. Proper helmet usage absorbs impact energy, reducing fatal head trauma by over 40%.

- Capsizing / Side Sliding: Rider laying bike down to avoid direct broadside impact
- Rider Ejection: Kinetic launch of rider over handlebars during sudden front-wheel stop
- Helmet Mechanics: Outer shell dissipates point impact; inner EPS foam absorbs deceleration force
- Lane Filtering Risks: Collisions occurring when motorcycles weave between slow-moving trucks

Statistical Modeling of Crash Frequencies

Because road crashes are random, discrete, and relatively rare events, traffic engineers utilize advanced statistical distributions to model crash frequencies across road networks.

Standard statistical models include the Poisson Distribution (assuming crash mean equals variance) and Negative Binomial Regression models (accounting for over-dispersion in real-world crash data across diverse highway corridors).

- Discrete Event Modeling: Treating crashes as non-negative integer counts
- Poisson Model: $P(Y = y) = \frac{e^{-\lambda}\lambda^{y}}{y!}$; basic crash frequency model
- Negative Binomial (NB) Model: Preferred model handling over-dispersed crash data ($Var > Mean$)
- Empirical Bayes (EB) Method: Combining historical site crash counts with safety performance functions

Modern Crash Reconstruction Technologies

Accident reconstruction has evolved from manual tape-measure surveys to digital forensic techniques that capture highly accurate spatial crash evidence.

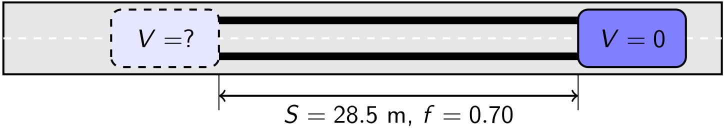
Advanced tools include 3D Terrestrial Laser Scanners (LiDAR mapping of crash scenes), Event Data Recorders (EDR / vehicle 'black boxes' recording pre-crash speed, throttle, and brake inputs), and specialized crash simulation software (PC-Crash, HVE).

- 3D Laser Scanning: Capturing millions of spatial point clouds to reconstruct crash scenes digitally
- Event Data Recorder (EDR): Extracting vehicle sensor data (speed, steering angle, ABS trigger)
- Drone Photogrammetry: Rapid aerial mapping of crash debris fields to clear traffic quickly
- Computer Simulation: Physics-based trajectory modeling using software like PC-Crash

Case Study: Speed Estimation from Skid Marks

To solidify concepts, consider a real-world engineering problem: A vehicle involved in a collision left four locked-wheel skid marks averaging 28.5 m on a level asphalt road.

Given a measured pavement drag factor $f = 0.70$, calculate the minimum vehicle speed prior to braking. Using $V = \sqrt{254 \cdot f \cdot S} = \sqrt{254 \times 0.70 \times 28.5} = \sqrt{5067.3} \approx 71.18$ km/h.



- **Engineering Interpretation:** The vehicle was traveling at a minimum speed of 71.2 km/h before braking.

Summary of Advanced Road Accident Dynamics

This lecture examined collision physics, mathematical speed estimation from skid marks, PIEV reaction time theory, pedestrian/heavy vehicle kinematics, and forensic reconstruction tools.

Mastering collision mechanics enables traffic engineers to scientifically reconstruct crashes, verify witness statements, estimate pre-impact speeds, and design safer roadway infrastructure.

- Kinetic energy quadruples as speed doubles, dramatically inflating crash severity
- Pre-impact speed is estimated using the skid formula $V = \sqrt{254 \cdot f \cdot S}$
- PIEV theory accounts for the 2.5-second perception-reaction time in Stopping Sight Distance
- Pedestrian, two-wheeler, and commercial truck crashes follow distinct physical trajectories
- 3D laser scanning, EDRs, and computer simulation represent modern reconstruction tools