Summary of Current Knowledge from AHS Concept Studies

Steven E. Shladover

PATH

Knowledge Gained on AHS Throughput

- **AHS automation technology can increase throughput compared to manual driving**
- **AHS throughput is strongly influenced by:**
  - **knowledge and consistency of braking performance**
  - **percentage of heavy vehicles in traffic**
  - **merging protocols**
  - **conservatism of safety policies**
  - **whether or not platoons are supported**
- **Throughput is not very sensitive to communication, sensing and processing time lags** > what about degradation effects?
- **Substantial market penetration is needed to achieve noticeable throughput increases in mixed/manual traffic**

Knowledge Gained on AHS Safety

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Quantitative results for a wide variety of conditions, demonstrating that:

- Maneuver coordination improves both safety and throughput
- Alternate separation policies produce trade-offs between probability and severity of crashes when failures occur
- Increasing speed reduces both safety and throughput

Knowledge Gained on AHS Infrastructure Development

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- AHS civil infrastructure costs per two-way mile can range from near zero to:
  - $36 million in high-density urban areas
  - $6.5 million in intercity corridors
  - $3.1 million in rural areas
- Increased intelligence at merges reduces length of ramps needed
- In congested environments, impacts of AHS entering and exiting traffic on manual traffic can be substantial unless dedicated on/off ramps are used

Knowledge Gained on AHS Deployment Issues

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- AHS infrastructure deployment can be addressed in the same ways as conventional infrastructure deployment:
  - benefit/cost comparisons with alternatives
  - public costs and liabilities traded off against public benefits
  - civil infrastructure costs dependent on local conditions
- There is a large step from partial to full automation in:
  - driver roles
  - technology
  - liability
- That step must be taken before the level of automation is sufficient to detract significantly from driver attentiveness
- Comprehensive obstacle/hazard detection and avoidance is the primary technology impediment to full automation in mixed traffic

Unresolved Concept Issues

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- Absolute safety levels achievable and needed
- Enabling technology maturity and costs (especially for obstacle detection and avoidance)
- Absolute throughput levels achievable and compatible with rest of transportation network
- Relationship between public benefits (throughput) and individual benefits (travel times)
- Complete definition of driver roles (capabilities) in normal and abnormal conditions
- Infrastructure/vehicle deployment sequencing to avoid chicken/ egg problems
- Trade-offs between vehicle-vehicle and vehicle-roadside coordination of maneuvering and traffic flow
- Stakeholder priorities and willingness to pay

Unresolved Design Details

- Selection of lane sensing technology
- Selection of range sensor technology
- Selection of communication technology
- Definition of user interface
- Roadway geometry

Local Deployment Choices

Many aspects of AHS will be determined based on specific local circumstances:

- who owns/operates/maintains/regulates/pays
- roadway alignments (at grade, elevated, median or periphery, etc.)
- access and egress ramp configurations and locations
- policies for mixing heavy and light duty vehicles
- interactions with local streets and highways

NAHSC will identify a range of options for these, not a single solution

Throughput/Travel Time Analysis -- Summary

Datta Godbole, Mark Miller PATH

NAHSC Workshop #3

September 19, 1996

Objectives

- **Assess strengths and weaknesses of key AHS attributes**
  - Dedicated lane and mixed traffic analysis
  - Distribution of intelligence & communication links
  - Platoons or individual vehicles
- **Determine sensitivity to design parameters**
- **Application scenarios for performance evaluation**
  - Single lane urban AHS
  - Houston transit corridor (discussed in the breakout)

AHS Attribute Combinations for Throughput Analysis

- **Autonomous individual vehicles**
- **Cooperative individual vehicles**
  - **Low cooperation (emergency warning & maneuver coordination only)**
  - **High cooperation (continuous exchange of information)**
- **Cooperative platoons**
  - **Low cooperation between platoons (inter-platoon), and high cooperation within each platoon (intra-platoon)**
- **Non-uniform inter-vehicle spacing**
  - **Autonomous & cooperative individual vehicles**
    - Based upon knowledge of braking capabilities

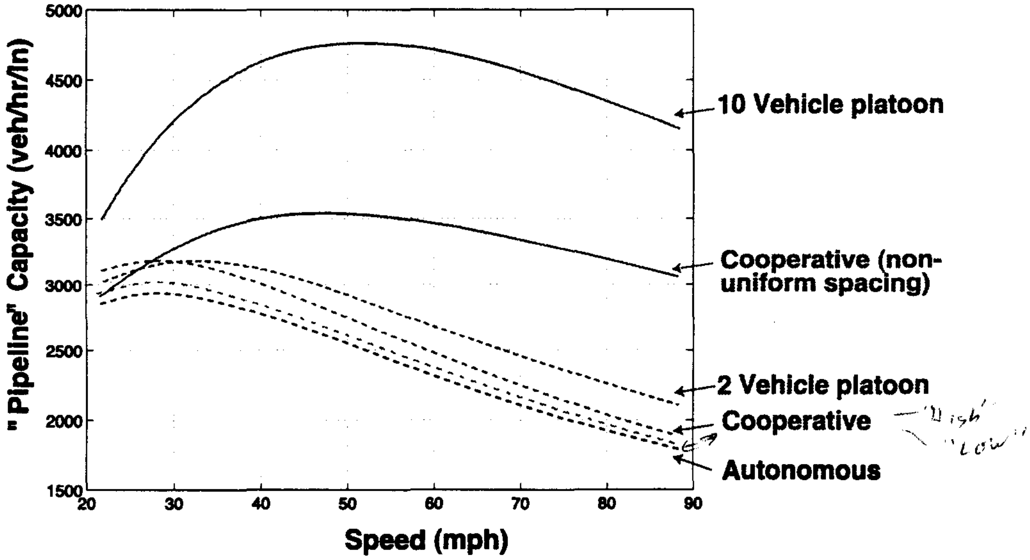
Pipeline Capacity Analysis

- **Assume single lane AHS pipe**
- **Calculate *safe* vehicle following distances for different AHS attribute combinations such that**
  - **No collisions in the absence of malfunctions**
  - **If front vehicle applies maximum braking (in response to a failure), then following vehicle should be able to stop**
    - Low relative velocity intra-platoon collisions can not be completely avoided in case of hard braking failure.
- **Spacings are sensitive to braking capability variations among vehicles**
  - **Non-uniform spacings, based on information of relative braking capability of front vehicle, can increase capacity**

Pipeline Capacity vs. Speed

NAHSC

93% Passenger Vehicles, 6% Trucks, 1% Buses



- Capacity increases with increasing level of cooperation
- Platooning results in highest pipeline capacity

Effect of Entry on AHS Pipeline Capacity

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- Merging assumptions
  - Cooperative vehicles and platoons can communicate the location of gaps to the entering vehicles
  - Pre-platoons can be formed at the on-ramp
  - Traffic on the mainline can yield to the entering traffic
- Effects of different AHS modes of operation are evaluated by
  - Maximum achievable throughput
  - Required entry-section lengths
  - Delays at ramp metering
  - Increased travel time for mainline traffic due to entry
- Need to investigate mainline flow control strategies

1) manual drivers cooperate
2) manual drivers take risks

Throughput vs. Speed

NAHSC

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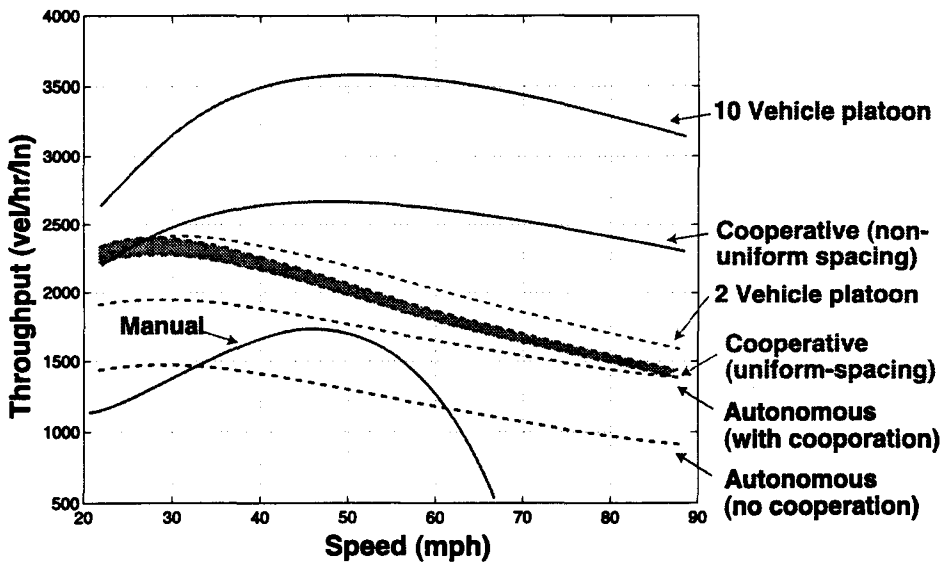

– **Example: The above throughput plot is obtained for representative values of ramp metering delays, increase in travel time & entry section length.**

Travel Time Analysis

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- **Assumptions**
  - **10 mile segment of 3 lane highway**
  - **1 lane converted to automated traffic**
  - **Manual lane capacity 2000 v/hr (at 35 mph)**
  - **Free flow speed 60 mph**
  - **AHS volumes do not exceed capacity**
- **Conclusions**
  - **As AHS throughput increases**
    - Number of vehicles traveling under free flow conditions increases
    - Level of aggregate demand at onset of unstable traffic conditions increases

Travel Time Analysis

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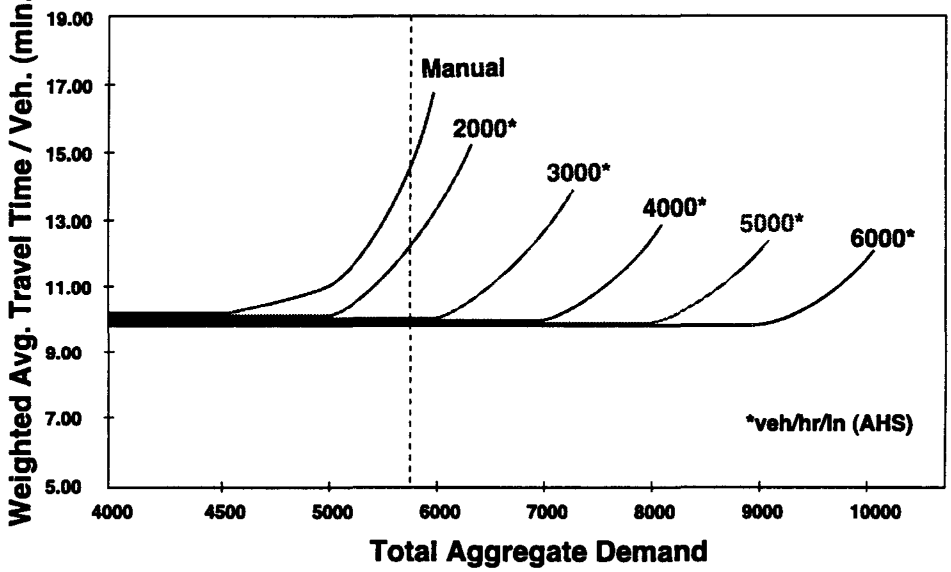
Vehicle Travel Time



– For a given level of aggregate demand, higher levels of AHS throughput corresponds to lower travel time

Mixed Traffic Throughput Analysis

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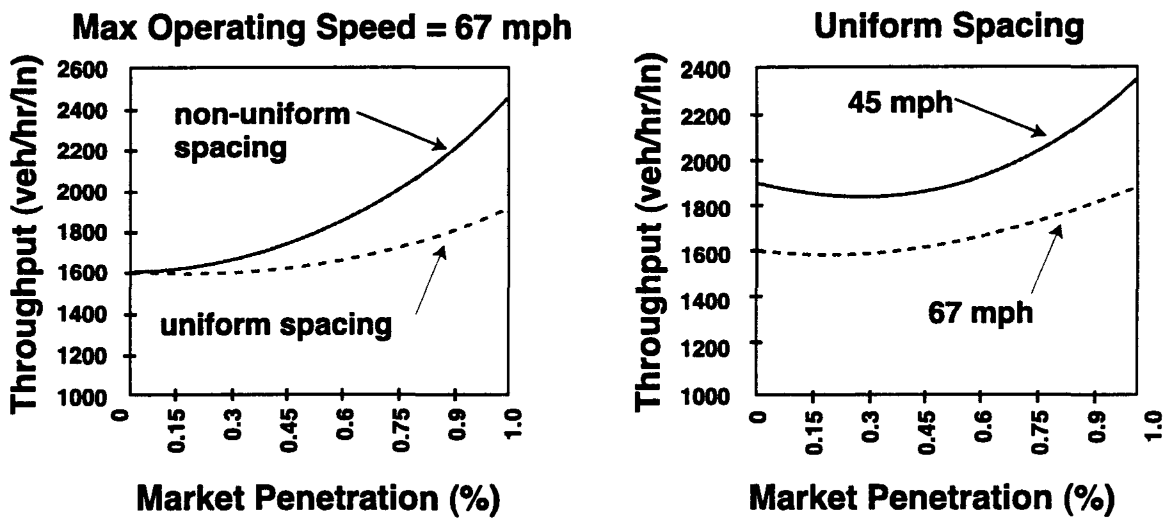
- **Assumptions**
  - **Driver behavior unchanged from today**
  - **All light-duty vehicles**
  - **Random sequencing of automated and manual vehicles**
  - **Manual throughput data from UMTRI ACC study**
    - Average speed 67 mph, headway 2.3 sec, 1600 veh/hr/ln
- **Results**
  - **Throughput is sensitive to**
    - Operating Speed
    - Separation between two automated vehicles
    - Merge derating factor
  - **Throughput might decrease initially at low market penetration**

does travel time ↑ for AHS vehicle?

Mixed Traffic Analysis:
Sensitivity to Speed and Spacing

Merge Derating Factor - 25%



– Throughput benefits increase with market penetration

Throughput Analysis Summary

- Summary
  - Most AHS attribute combinations result in increased throughput and reduced travel time than current highway systems
  - Increases in inter-vehicle coordination result in increased throughput
  - Increase in AHS operating speed will ultimately reduce throughput
  - Platooning provides highest throughput
- Future work
  - Analyze the effects of flow control strategies on multilane AHS networks
  - Determine impact of AHS on the entire transportation system

Throughput/Travel Time Analyses -- Breakout

Mark Miller and Datta Godbole
NAHSC Workshop #3
September 19, 1996

Objectives & Outline

- Objectives
  - Assess strengths and weaknesses of different AHS attribute combinations
  - Determine sensitivity to design parameters
  - Assess impact of mixed (automated+manual) traffic on throughput
- Outline
  - Pipeline capacity analysis based on safe spacing
  - Capacity degradation due to entering traffic
  - Travel time analysis
  - Mixed traffic throughput evaluation
  - Throughput evaluation for case studies: Houston

AHS Attribute Combinations

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- **Autonomous individual vehicles**
- **Cooperative individual vehicles**
  - **Low cooperation (emergency warning & maneuver coordination only)**
  - **High cooperation (continuous exchange of information)**
- **Cooperative platoons**
  - **Low cooperation inter-platoon, and high cooperation intra-platoon**
- **Non-uniform inter-vehicle spacing**
  - **Autonomous & cooperative individual vehicles**
    - Based on information about braking capabilities

Safe Spacing Design for Pipeline Capacity Analysis

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- **Calculate *safe* vehicle following distance**
  - **If front vehicle applies maximum braking (in response to a failure) then following vehicle should be able to stop**
  - **Used to calculate inter-platoon separation and minimum safe spacing between individual vehicles**
    - Low impact intra-platoon collisions can not be avoided in case of hard braking
  - **No intra-platoon collisions in the absence of malfunctions**
- **Minimum safe spacing depends on**
  - **Braking capabilities of the two vehicles**
  - **Type of information available for control**
  - **Sensing, actuation & communication delays**
  - **Operating speed, speed-tracking accuracy**

Pipeline Capacity Analysis

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- **Scenario: Single lane AHS pipe**
  - **Using spacing design tools calculate minimum *safe* inter-vehicle , intra-platoon & inter-platoon spacing**
  - **Use above spacing with the corresponding speed to calculate pipeline capacity**
- **Results**
  - **Capacity vs. speed for each AHS attribute combination**
  - **Effect of mixed classes of vehicles on capacity**
  - **Sensitivity to design parameters**
    - Sensitive to braking capability and speed-tracking accuracy
    - Less sensitive to delays

Pipeline Capacity vs. Speed

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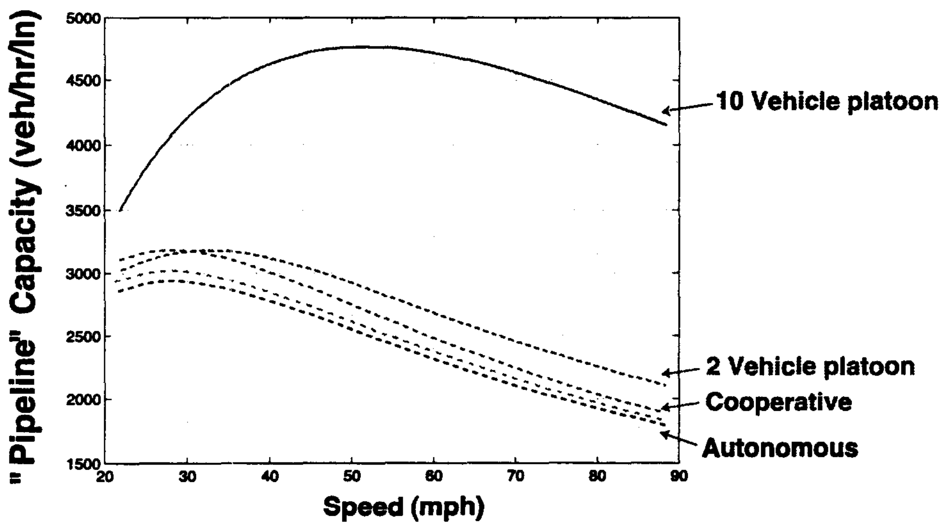
93% Passenger Vehicles, 6% Trucks, 1% Buses



- **Capacity increases with increasing level of cooperation**
- **Platooning results in highest pipeline capacity**

Pipeline Capacity vs. Percent of Trucks

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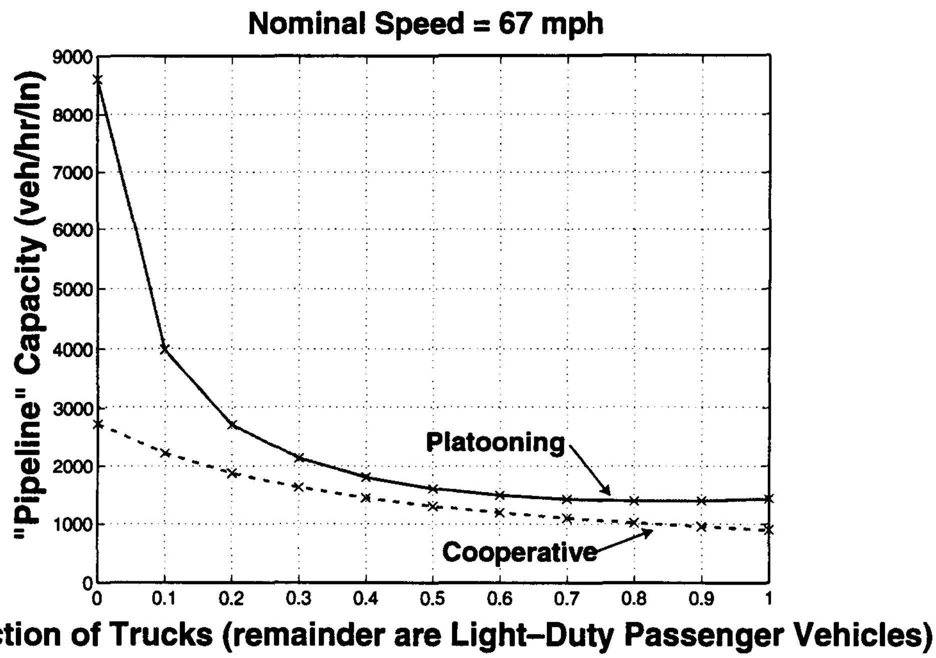

Braking Capability Distribution

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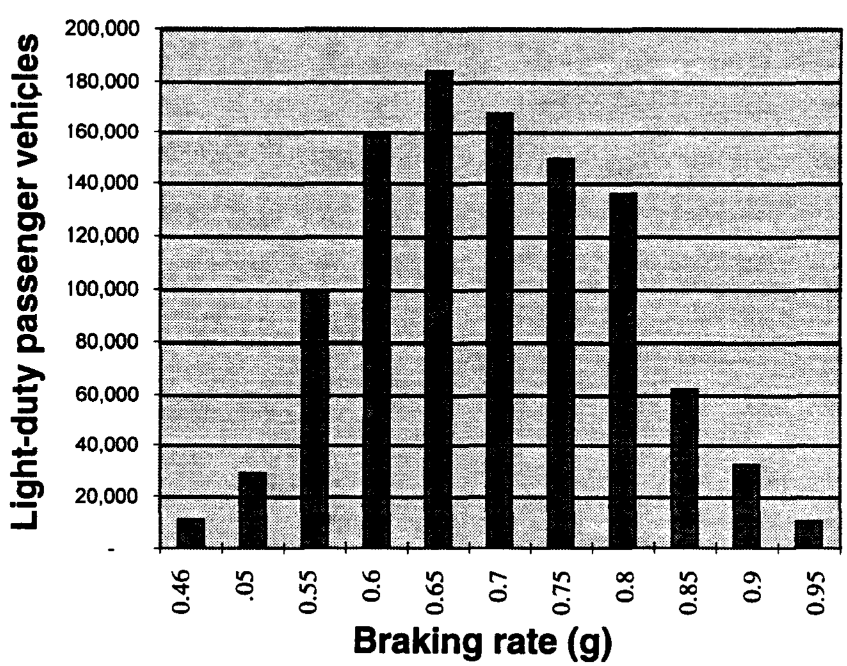
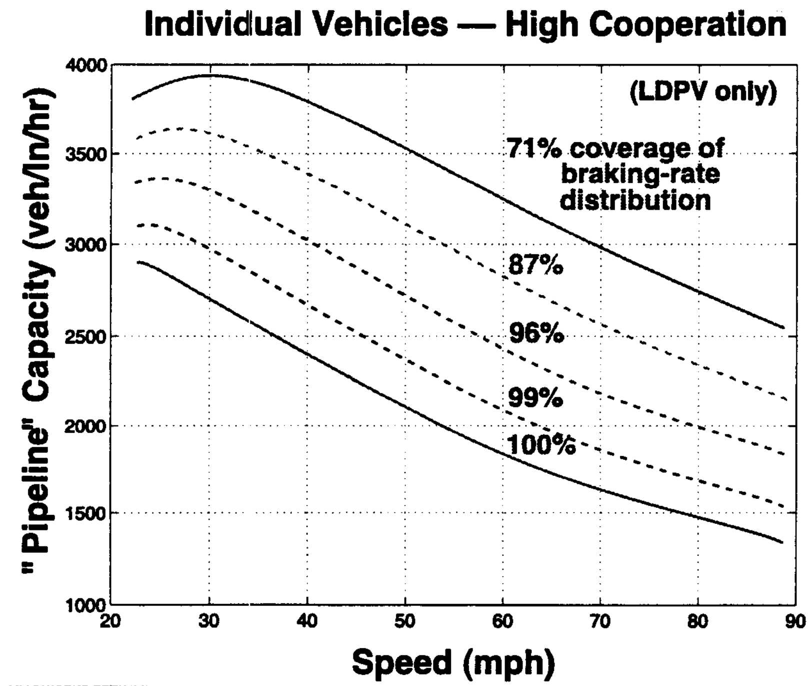


Sensitivity to Braking Capability



- Spacing highly sensitive to braking capability
- Capacity can be improved by
  - Restricted access to the highway facility
  - Non-uniform inter-vehicle spacing

Capacity Improvement Using Non-Uniform Spacings

- Spacings & capacity are highly sensitive to differences in braking capability
- Braking capabilities are distributed over a wide range resulting in conservative inter-vehicle following distances for uniform spacing design
- Capacity improvement using non-uniform spacing design
  - Inter-vehicle spacing is based on the information about relative braking capability of vehicles
  - Requires vehicles to estimate their own braking capability and communicate it to the following vehicle

Pipeline Capacity vs. Speed Non-Uniform Spacings

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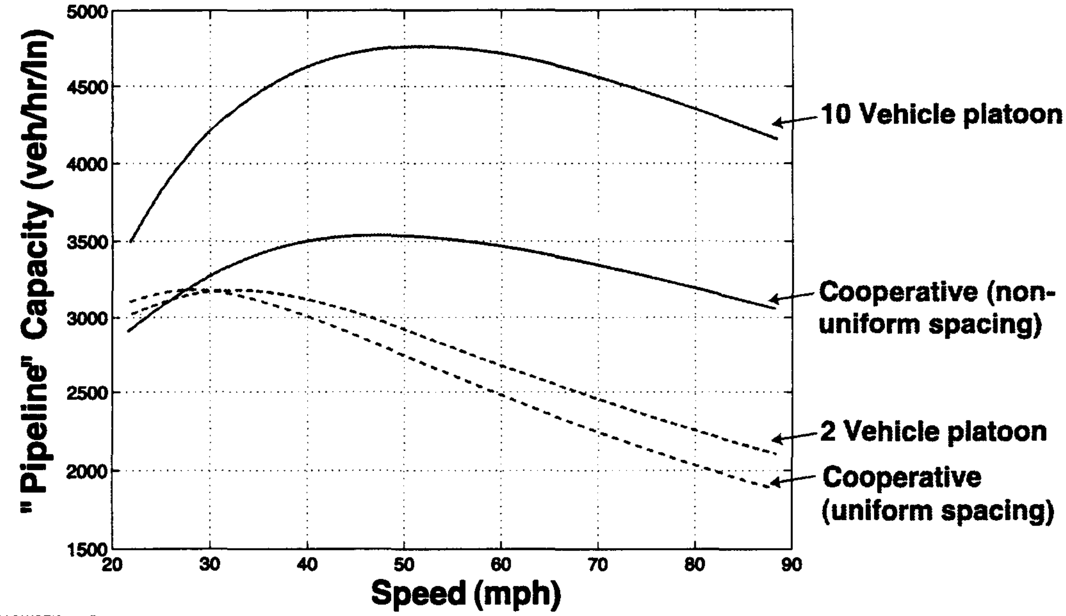
93% Passenger Vehicles, 6% Trucks, 1% Buses



AHS Entry: Effect on Pipeline Capacity

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- **Merging disciplines**
  - Autonomous vehicles merging into AHS traffic with and without yielding by the mainline traffic
  - Cooperative vehicles merging into AHS traffic with knowledge of gap locations
  - Pre-platoons entering a platooned AHS, with the entering platoon tagging behind an AHS platoon
- **Effect of merging disciplines evaluated by**
  - Reduction in pipeline capacity
  - Required ramp lengths (*capped at 1.0 mile*)
  - Delays at ramp metering (*capped at 2 minutes*)
  - Mainline traffic delays due to entering traffic

AHS Entry Analysis (worst case)

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- **Autonomous individual vehicles (no cooperation)**
  - **Lack of cooperation results in long entry sections and lower throughput:** ***For 1.0 mile merging section, pipeline capacity reduction = 50%***
- **Autonomous individual vehicles (w/ cooperation)**
  - **By incorporating yielding to entering traffic, the throughput can be improved at the cost of travel time on AHS:** ***1% increase in travel time per entry ramp corresponds to a pipeline capacity reduction of 25% with 0.5 mile merging section***
- **Cooperative individual vehicles & Platoons**
  - **Throughput increase achieved by**
    - Knowledge of gap locations
    - Entering vehicles tagged behind existing platoon
    - A 2 min entry ramp delay results in 25% capacity reduction

Throughput vs. Speed

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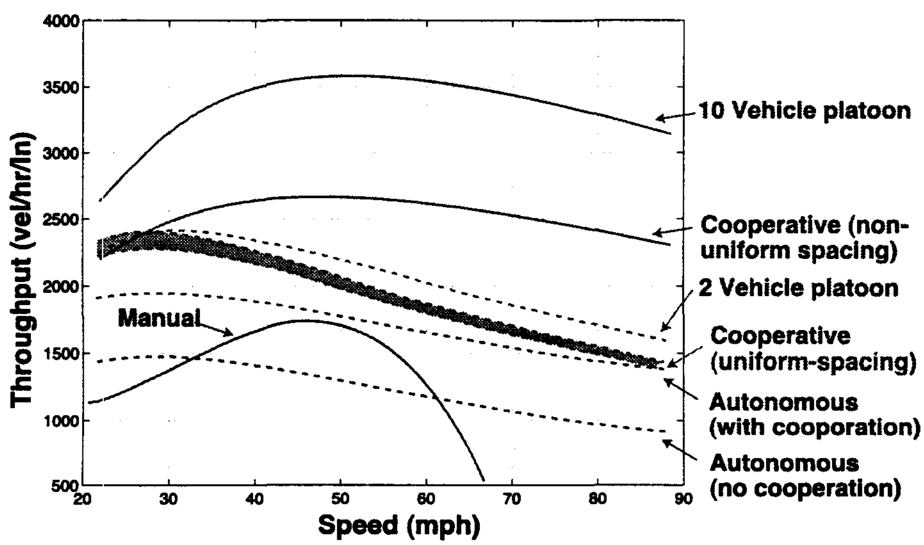
93% Passenger Vehicles, 6% Trucks, 1% Buses



- **Inter-vehicle coordination improves throughput**
- **Need to investigate gap management strategies**
- **Platooning provides maximum throughput**

Travel Time Analysis

NAHSC

- **Assumptions**
  - 10 mile segment of 3 lane highway
  - 1 lane converted to automated traffic
  - Manual lane capacity 2000 veh/hr at 35 mph
  - Manual lane free-flow speed 60 mph
  - Automated lane free-flow speed -- 60 & 80 mph
  - AHS volumes do not exceed capacity

Travel Time vs. Demand Sensitivity to AHS Throughput

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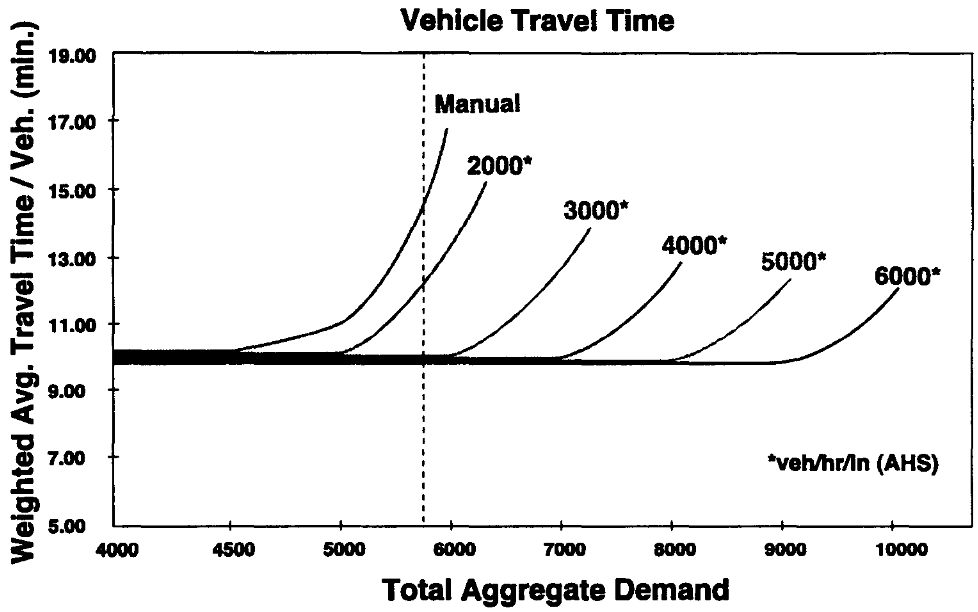
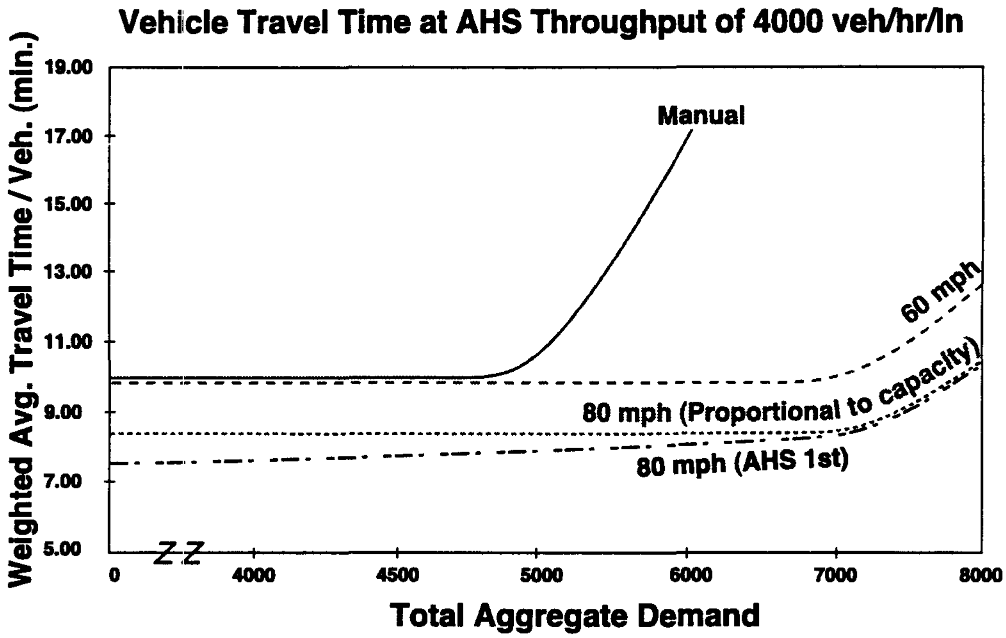


- For a given level of aggregate demand, higher levels of AHS throughput correspond to lower travel time

Travel Time vs. Demand Sensitivity to AHS Speed



– Higher AHS speed results in lower travel time

Travel Time Analysis Observations

- As AHS throughput increases
  - Level of aggregate demand at which onset of unstable traffic conditions begin increases
  - Number of vehicles traveling under free-flow conditions increase
- For a given level of aggregate demand
  - Higher levels of AHS throughput correspond to lower travel time
- If free-flow speed on AHS is greater than manual free-flow speed
  - Travel time benefits are even greater than previous case

Houston Case Study (Ongoing Work)

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- Approximately 10 mile stretch of I-10 (Katy Freeway), 1-lane reversible HOV facility west of Houston CBD
- Park & ride facility and slip ramps used for access and egress in addition to primary western & eastern terminii
- Three demand scenarios projected for year 2020:
  - 1750 vph, 3000 vph, 4000 vph (at peak demand points along corridor) with 4%bus, 96% light-duty vehicles
- Throughput in vehicles per hour
  - Autonomous:
    - 900-1650 (uniform), 1200-2200 (non-uniform)
  - Cooperative:
    - 1750-2350 (uniform), 2600-3400 (non-uniform)
- Low-level demand: cooperative, autonomous (non-uniform)
- Mid-level demand: cooperative (non-uniform)
- Platooning can satisfy all three demand levels

Mixed Traffic Throughput Analysis

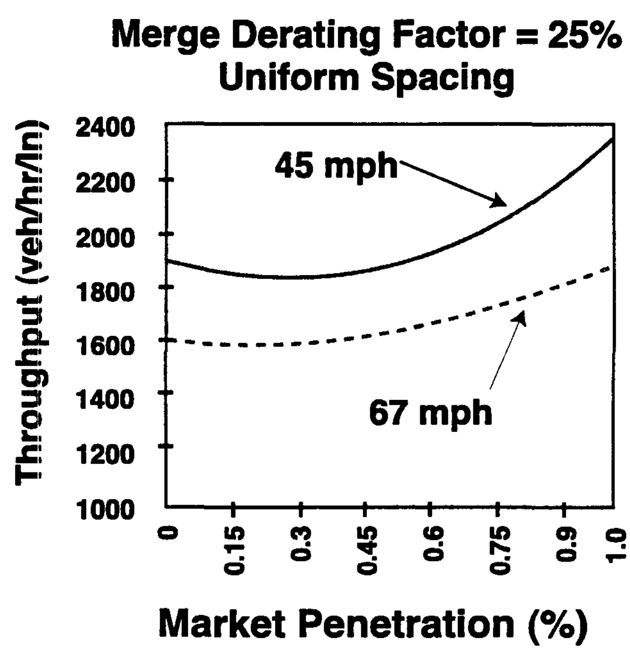
NAHSC

- Assumptions
  - Driver behavior unchanged from today
  - All light-duty vehicles
  - Random sequencing of automated and manual vehicles
  - All manual throughput (UMTRI ACC study)
    - Average speed 67mph, headway 2.3 sec, 1600 veh/hr
  - Automated vehicle operate in autonomous mode
  - Manual vehicle follows automated vehicle at the same distance as another manual vehicle
  - Automated vehicle follows manual vehicle no closer than it would follow another automated vehicle

Mixed Traffic Throughput Analysis (Cont...)

- **Results**
  - **Throughput vs market penetration of automated vehicles as a function of**
    - Operating speed
    - Degree of merging disturbances
    - Inter-vehicle spacing
- **Conclusions**
  - **Benefits increase with market penetration**
  - **Future work: Extend work to multiple vehicle classes**

Mixed Flow Analysis Sensitivity to Speed



Mixed Traffic Analysis
Sensitivity to Merge Derating Factor

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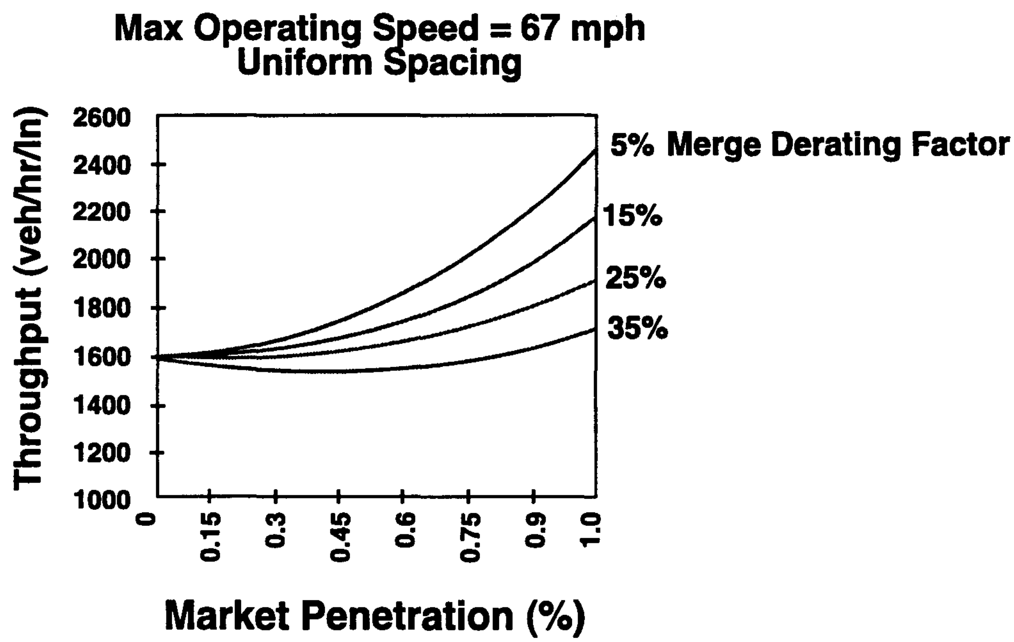

Mixed Traffic Analysis
Sensitivity to Spacing

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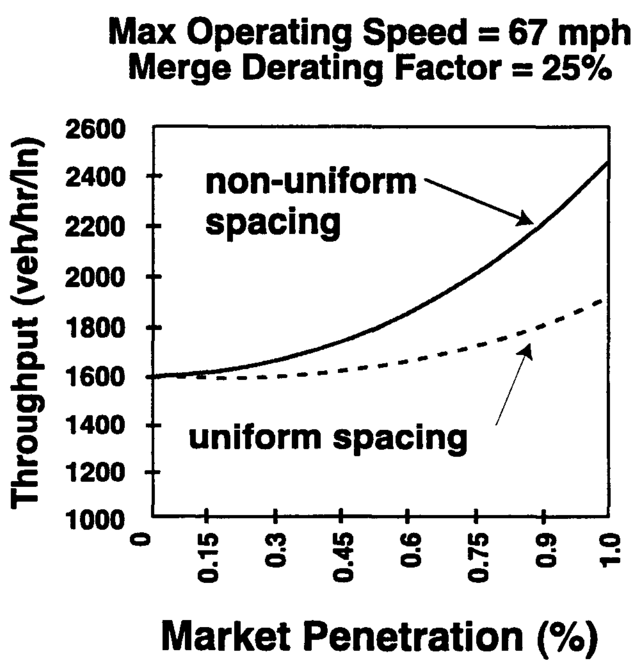

Throughput/Travel Time Analysis -- Summary

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- **Most AHS attribute combinations result in higher throughput and reduced travel times over manual highways**
- **Increased inter-vehicle maneuver cooperation results in increased AHS capacity & throughput**
- **Increase in speed reduces throughput**
- **Platooning provides highest throughput**
- **Future work**
  - Analyze the effects of flow control
  - Impact of AHS on the entire transportation network

AHS Safety Analysis
Plenary Briefing

Raja Sengupta PATH

Overview

- **Safety Objective:** No accidents
  - Design AHS for ~~no collision~~ in the absence of malfunctions and improved safety in case of malfunctions or environmental hazards
- **MOEs are used to quantify the design objective**
  - number of collisions per VMT, severity of each collision, number of vehicles in each collision, etc.
- **To determine system MOE values we need to know**
  - number of environmental hazards per VMT
  - number of component failures per VMT
  - AHS emergency response strategies
    - requires detailed design, extensive data collection
- **At this stage, we need to understand how the key attributes influence the safety properties of future AHS designs**

Analysis Approach

NAHSC

- Assume the malfunction has occurred, i.e., define emergency scenarios
  - Hard Braking Emergency
    - On a single dedicated lane AHS at full capacity, a vehicle brakes hard in response to a malfunction, until it stops
  - Obstacle Avoidance
    - A stationary obstacle appears suddenly on one lane of a dedicated two lane AHS at full capacity
- Model emergency response strategies for relevant combinations of key attributes
  - Distribution of Intelligence, Separation Policy
    - Autonomous, Low or High Cooperative Individual Vehicles, Co-operative Platooned Vehicles
- Compare attribute combinations with each other

Response Strategies: Differentiating Attribute Combinations

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- Autonomous Individual Vehicles
  - No warning to follower during emergency braking
  - No cooperation for emergency lane change
- Low Cooperative Individual Vehicles
  - Slower warning to follower during emergency braking
  - Cooperation for emergency lane change
- High Cooperative Individual Vehicles
  - Faster warning during emergency braking
  - Cooperation and global coordination for emergency lane change
- Cooperative Platooned Vehicles
  - High Cooperative for intra-platoon following and Low Cooperative for inter-platoon following

Analysis Method

NAHSC

- **Inputs: AHS vehicle and system parameters**
  - Automated vehicle parameters
    - probabilistic model of braking capability
    - emergency detection delays, brake actuation delays
  - operating speed, inter-vehicle spacing
  - emergency response strategies
- **Outputs: safety metrics**
  - collision velocity distribution for the first collision
  - total collision probability (frequency)
  - mean square collision velocity (severity)
- **To obtain system MOE's multiply by malfunctions per VMT**

Obstacle Avoidance Example

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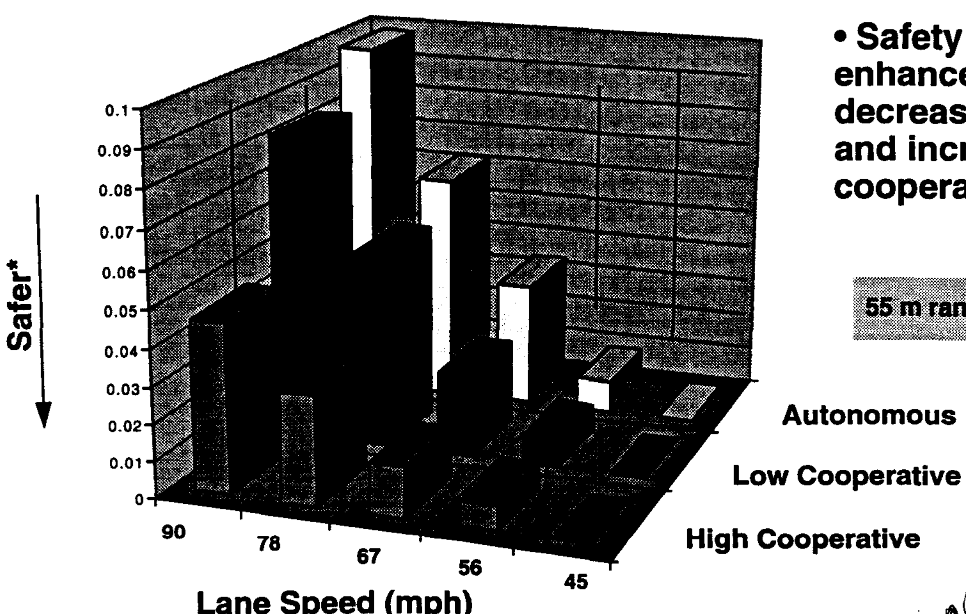

- **Safety is enhanced with decreased speed and increased cooperation**

55 m range to obstacle

*Mean Square Collision Velocity (m/s)^2

individual vehicle

Relationship Between Safety & Capacity (Light Duty Vehicles)

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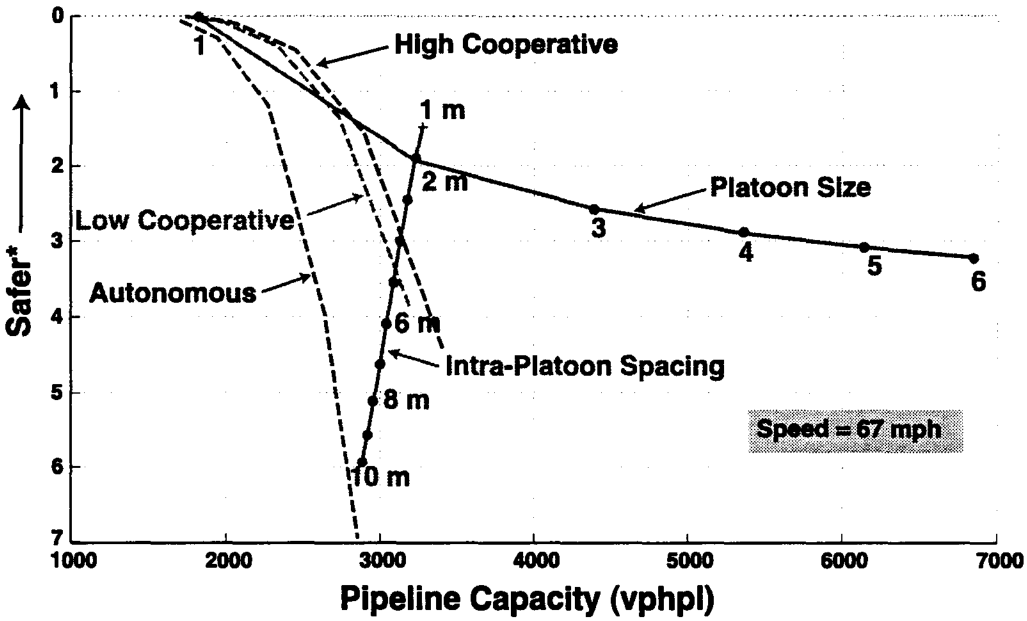
- Safety increases with cooperation



*Mean square collision velocity (m/s)2

Hard Braking Emergency: Individual Vehicles & Platoons

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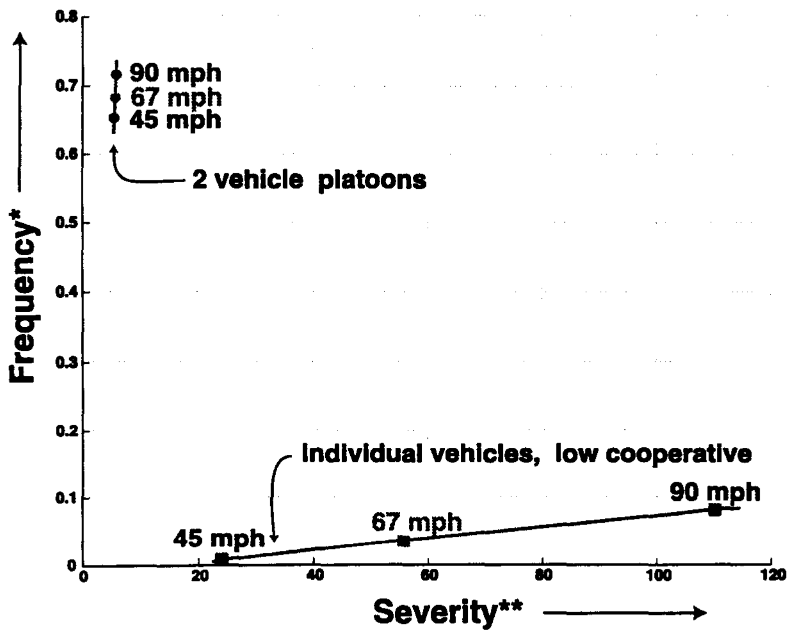


- One must choose between frequency and severity at medium capacities (3000 vphpl)

*Collision probability during hard braking emergency

**Mean square collision velocity (m/s)2

Summary of Results

NAHSC

* correct

- Inter-vehicle cooperation improves safety
- For medium pipeline capacity (3000 vphpl)
  - collision frequency more important : Individual vehicle AHS
  - collision severity more important: Platooned AHS
- For high pipeline capacity (5000 vphpl +)
  - Platooning much safer in first forward collision
- In all cases safety decreases with increasing speed
- Future
  - New alternative: Individual vehicles with non-uniform spacing (4500 vphpl)
  - Multiple collisions
  - Other safety scenarios

RSPLEN.PPT(9/96)

issues:

- interplay between small spacing ↓ & probability of loss of control (= collision) ↑
- Report from CALSPAN SRL says 1st collision isn't the worst - may change conclusions (Phil Reynolds CALSPAN/SRL)
- False alarm rates & human comfort (e.g. hard braking for no reason) → Discomfort
- System may require different expectations - but that's hard to do incrementally (maybe)
- Injuries to people from unexpected radical maneuvers
- correctness of cooperative maneuvers with differing implementations

- what about message delay in high-cooperative case?

20 msec high co-op.
50 msec low co-op
200 msec independent

} detection delays modelled.

(ve) - "bridge-out" failure mode →
how do you shut off vehicle flow?

- "cooperation is good" → but what if cooperation fails.

- single-lane AHS - can't avoid close obstacle - must look at platoon crunch.

→ Try driving into a brick wall @ 9 mph while taking a nap.
70% of five platoons will collide

AHS Safety Analysis

Breakout Briefing

Raja Sengupta

Overview

- Safety Objective:
  - Design AHS for no collision in the absence of malfunctions and improved safety in case of malfunctions or environmental hazards
- MOEs are used to quantify the design objective
  - number of collisions per VMT, severity of each collision, number of vehicles in each collision, etc.
- To determine system MOE values we need to know
  - number of environmental hazards per VMT
  - number of component failures per VMT
  - AHS emergency response strategies
    - requires detailed design, extensive data collection
- At this stage, we need to understand how the key attributes influence the safety properties of future AHS designs

Analysis Approach

NAHSC

- **Assume the malfunction has occurred, i.e., define emergency scenarios**
  - Hard Braking Emergency
    - On a single dedicated lane AHS at full capacity, a vehicle brakes hard in response to a malfunction, until it stops
  - Obstacle Avoidance
    - A stationary obstacle appears suddenly on one lane of a dedicated two lane AHS at full capacity
- **Model emergency response strategies for relevant combinations of key attributes**
  - Distribution of Intelligence, Separation Policy
    - Autonomous, Low or High Cooperative Individual Vehicles, Co-operative Platooned Vehicles
- **Compare attribute combinations with each other and with a baseline synthesized from available data**

Response Strategies: Differentiating Attribute Combinations

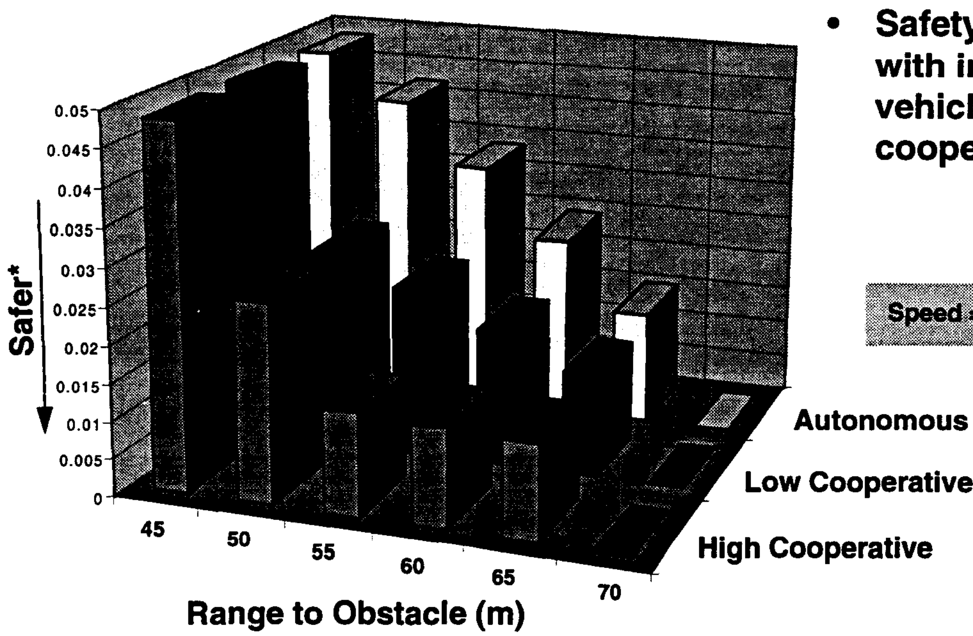
NAHSC

- Autonomous Individual Vehicles
  - No warning to follower during emergency braking
  - No cooperation for emergency lane change
- Low Cooperative Individual Vehicles
  - Slower warning to follower during emergency braking
  - Cooperation for emergency lane change
- High Cooperative Individual Vehicles
  - Faster warning during emergency braking
  - Cooperation and global coordination for emergency lane change
- Cooperative Platooned Vehicles
  - High Cooperative for intra-platoon following and Low Cooperative for inter-platoon following

Obstacle Avoidance: Analysis Method

- Collision characteristics depend on following inputs
  - maximum braking rate, brake actuation delay
  - lane change distance and time
    - depends on attribute combination
    - longitudinal acceleration/deceleration capabilities
    - lateral acceleration/deceleration capabilities
    - lane width, vehicle length, lane speed differential
  - AHS inter-vehicle spacing, speed
  - obstacle detection range, false alarm and misdetection probability
- Outputs: safety metric for first collision
  - mean square collision velocity
- To obtain system MOE's multiply by number of obstacles/VMT

Obstacle Avoidance: Safety & Detection Range

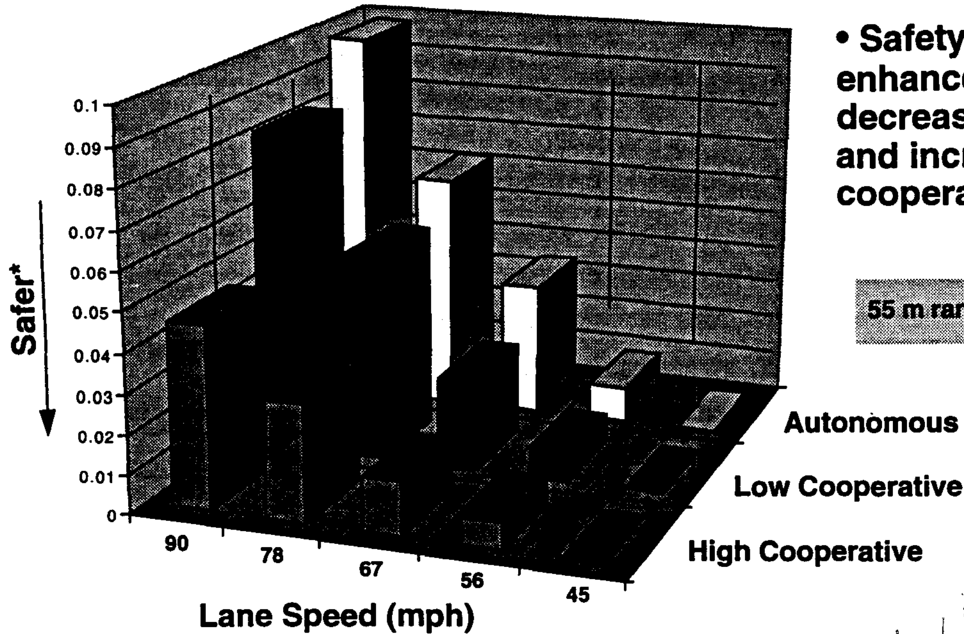


*Mean Square Collision Velocity $(m/s)^2$

- Safety increases with inter-vehicle cooperation

Speed = 67 mph

Obstacle Avoidance: Safety and Speed



*Mean Square Collision Velocity (m/s)²

- Safety is enhanced with decreased speed and increased cooperation

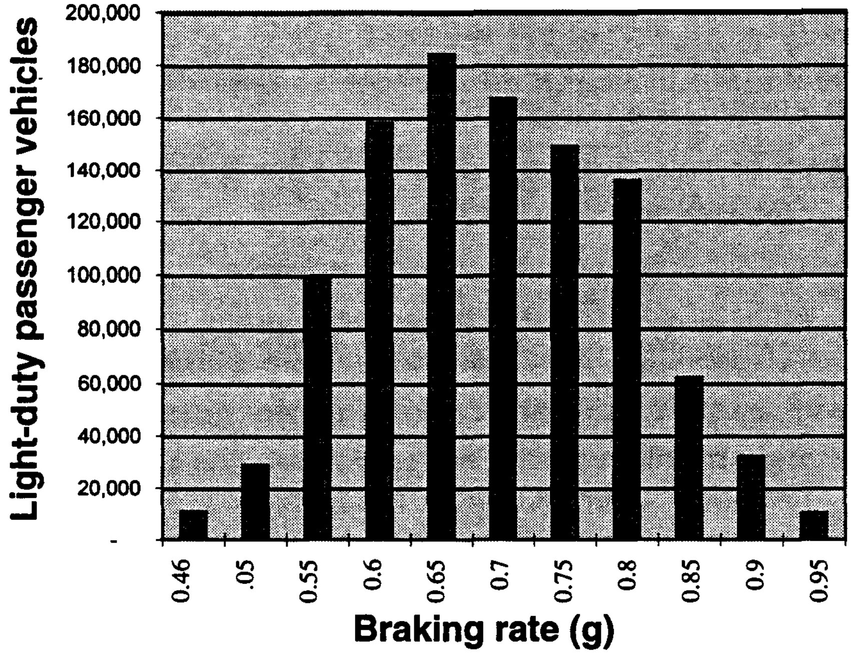
55 m range to obstacle

Hard Braking Emergency: Analysis Method

- Collision characteristics depend on following inputs
  - variation in maximum braking rates of leader & follower
  - AHS inter-vehicle spacing and speed
  - delay in detection by the follower of hard braking
  - brake actuation delays, velocity tracking errors
- Probabilistic model of braking capability variation
  - new vehicle maximum braking rates for different models from Consumer Reports 1995
  - North American first quarter of 1996 production for different models from Automotive News
  - applied 10% degradation factor to the vehicle population at each braking rate

Braking Capability Distribution

NAHSC



Hard Braking Emergency: Analysis Method

NAHSC

- AHS inter-vehicle spacing
  - Individual vehicle: select for no collision during hard braking amongst a high percentage of the vehicle population
  - Inter-platoon: select for zero inter-platoon collision during hard braking
  - Intra-platoon: select for stable, platoon operation
    - no collision in the absence of malfunctions
- Delay in detection of hard braking by follower
    - depends on attribute combination
- Outputs: safety metrics
  - collision velocity distribution for first forward collision
  - total collision probability (frequency)
  - mean square collision velocity (severity)
- To obtain system MOE's multiply by number of malfunctions per VMT

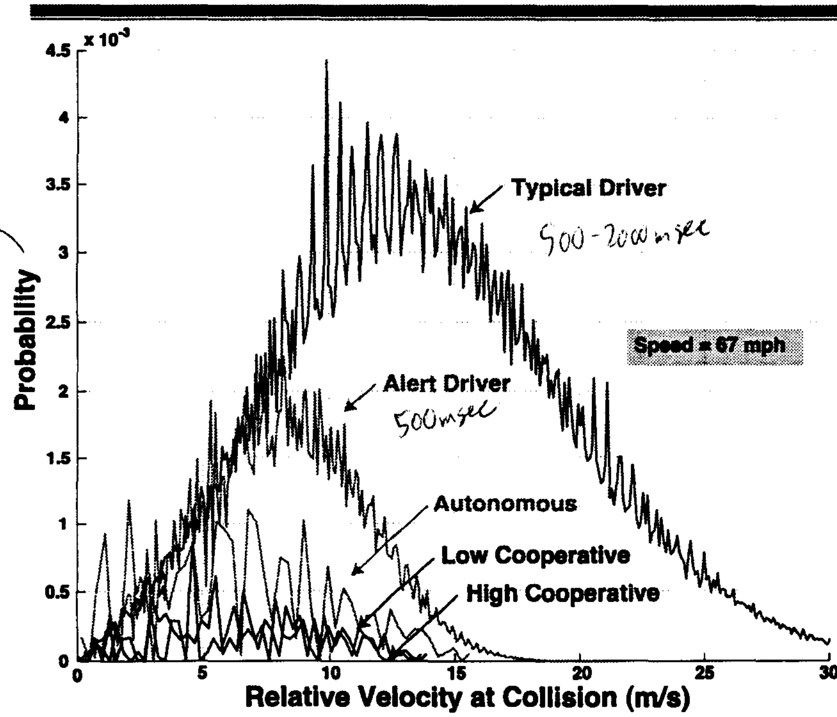
Hard Braking Emergency: Baseline Modelling

NAHSC

- **Safety metrics are computed for manual vehicle following in the hard braking emergency scenario at 65 mph, medium density inter-urban traffic**
- **Variation in max. braking rates of leader & follower**
  - **probabilistic model as described**
- **Inter-vehicle spacing and relative speed**
  - **probabilistic model obtained from range, range rate data in DOT-HS-808437 collected for vehicle following field tests**
- **Delay in detection of hard braking by the follower**
  - **probabilistic model of driver reaction times obtained from Taoka, ITE Journal, Vol 59, No.3, March 1989**
- **Brake actuation delays same as automated vehicles**

Hard Braking Emergency: Individual Vehicles

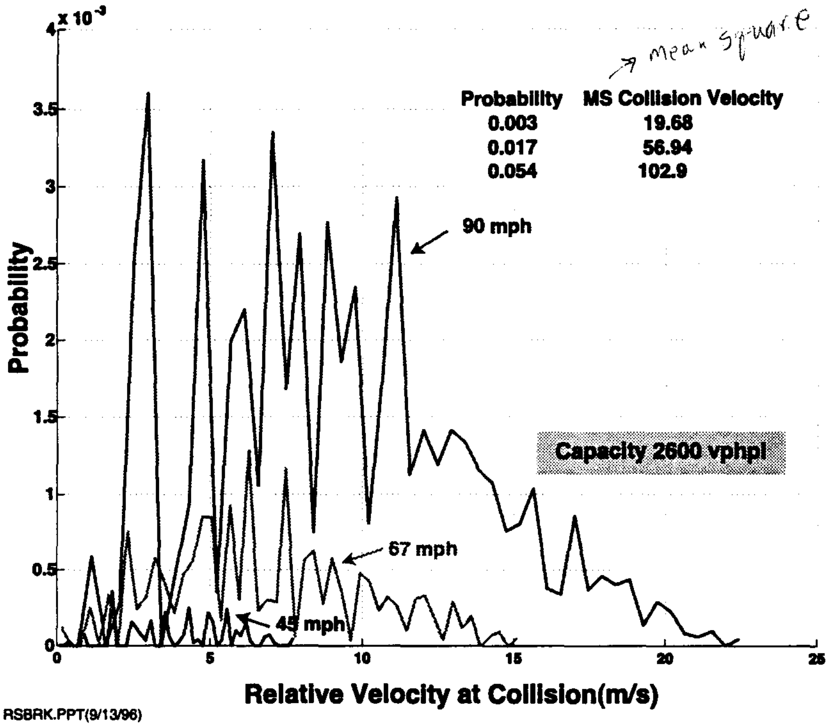
NAHSC



- **Safety increases with inter-vehicle co-operation**
- **AHS compares favorably with even the fast reacting alert driver**

Hard Braking Emergency: Safety & Speed for Individual Vehicles

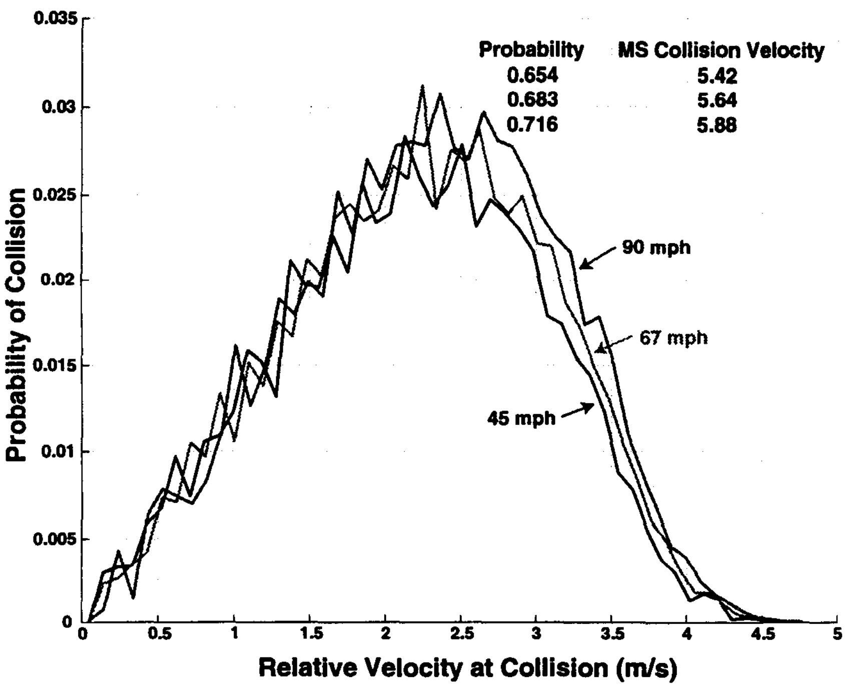
NAHSC



- **Safety has high negative sensitivity to speed**

Hard Braking Emergency: Safety & Speed for Platoons

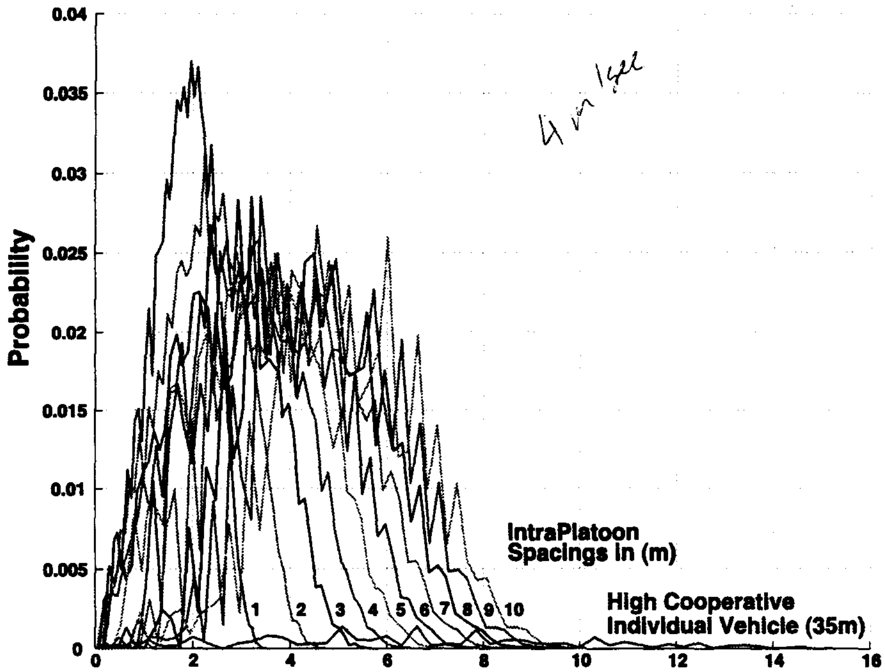
NAHSC



- **Safety in first forward collision decreases with increases in speed, but is significantly less sensitive**

inter-platoon

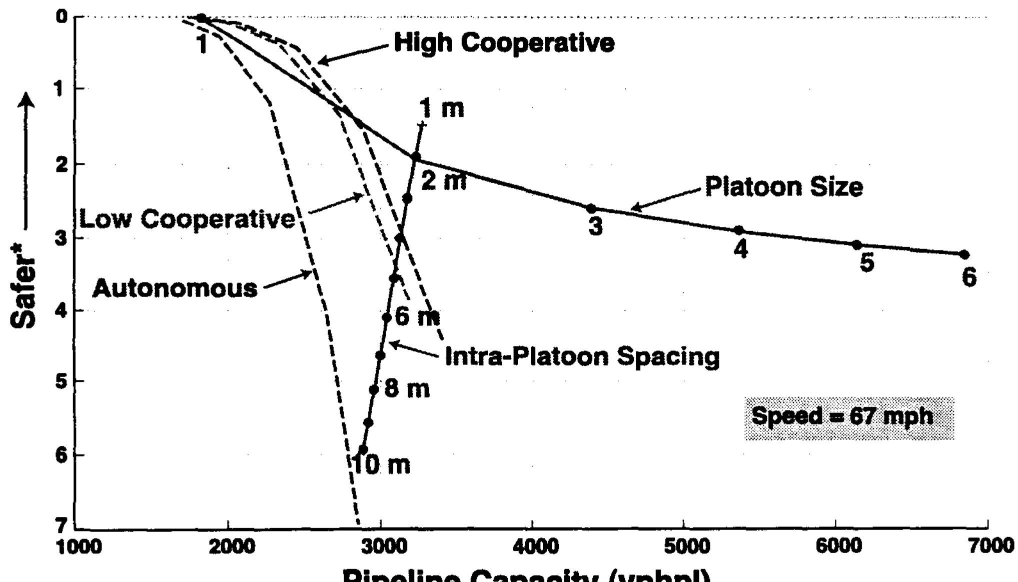
Hard Braking Emergency: Intra-platoon Spacing



- Smaller intra-platoon spacing increases safety by reducing collision severity

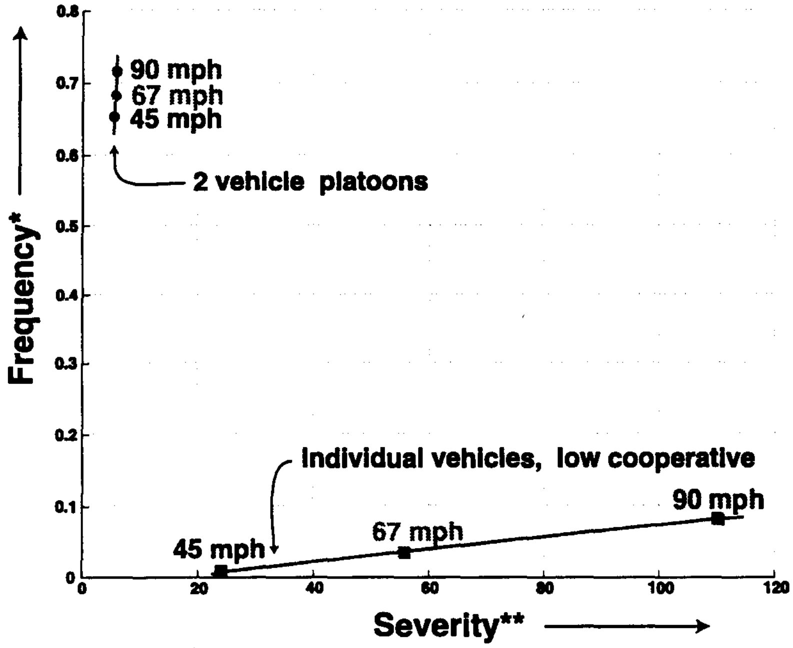
Relationship Between Safety & Capacity (Light Duty Vehicles)

- Safety increases with cooperation



*Mean square collision velocity (m/s)^2

Hard Braking Emergency: Individual Vehicles & Platoons



- One must choose between frequency and severity at medium capacities (3000 vphpl)

*Collision probability during hard braking emergency

**Mean square collision velocity $(m/s)^2$

Summary

- AHS regulation of inter-vehicle spacing promises significant safety improvements over present day conditions (12)
- Inter-vehicle cooperation improves safety (6,7,12,16)
- For medium pipeline capacity (3000 vphpl) (17)
  - collision frequency more important : Individual vehicle AHS
  - collision severity more important: Platooned AHS
- For high pipeline capacity (5000 vphpl +) (16)
  - Platooning much safer in first forward collision
- For platooned operation, smaller intra-platoon spacings enhance safety by reducing collision severity (15)
- In all cases safety decreases with increasing speed (13,14)
- Future Work
  - New alternative: Individual vehicles with non-uniform spacing (4500 vphpl)
  - Multiple collisions
  - Other emergency scenarios