CDOT's Autonomous Truck Mounted Attenuator (ATMA) Program

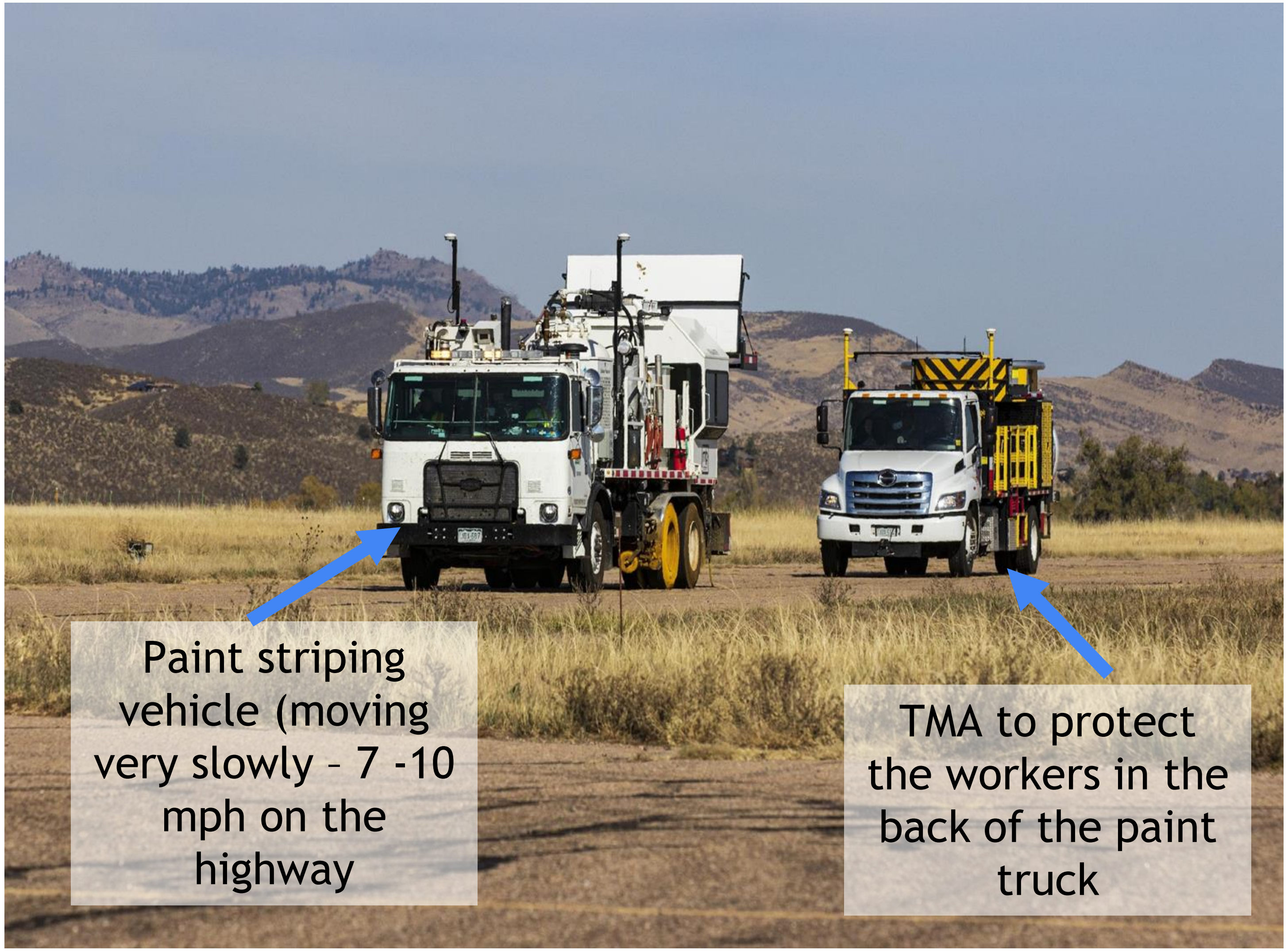
Transportation Research Board,
June 14, 2022

Agenda

- Program Overview and Goals
- Deployment in Colorado
- Autonomous Maintenance Technology (AMT) Pool Fund - TPF 5(380)
- AMT Deployment Toolkit
- Questions/Discussion

Program Goals: What is a truck mounted attenuator and why does a DOT use it?

- Remove driver from the maintenance truck
- Decrease risk of operations
- Increase efficiency of operations
- Pursue cutting-edge technology to improve highway management



CDOT ATMA Goals and Timeline

CDOT Program Goals

1. Installation
2. Evaluation
3. Operational
4. Versatility
5. Statewide expansion

Phase 1 (Summer 2018 - Early 2020)

- Purchase of ATMA
- Testing of ATMA
- Completion of the Colorado Task Force Mobility Process
- Operational Deployment of ATMA in CDOT daily operations in Northern Colorado
- Approval on CDOT roads less than 2,500 AADT

Phase 2 (Early 2020 - Dec 2021)

- Request for expansion on CDOT roads less than 5,000 AADT
- Addition of CDOT's second ATMA
  - Testing and validation of CDOT's 2nd ATMA (in southwestern Colorado)
  - Operational deployment of 2nd ATMA
- Evaluation

System Overview

- The ATMA retrofit autonomous kit converts Impact Protection Vehicle into ATMA Leader / Follower system
  - ATMA system increases worker safety by eliminating the need for a human driver in the attenuator
  - During operations, the ATMA follows the path of the Leader vehicle (paint striping vehicle, sweeper vehicle, etc.) while maintaining a user-defined safe distance
  - Leader vehicle and ATMA maintain constant communications with each other over multiple Vehicle-to-Vehicle (V2V) communication links
  - Safety – Redundancy, cameras, navigation, A-Stop, E-Stop, Independent E-Stop, and Human in the Loop

What do we do to get one of these on road?

…. After procurement and installation, the fun begins! CDOT led validation/acceptance test (closed course).

Testing scenarios

To adequately ensure safe operation of the ATMA following the recent automated driving system upgrade, the team has prioritized 15 scenarios that must be performed in the test environment.

1. Follow Distance Set by UI

Using the UI to remotely set follow distances

Operation Procedure	• Activate the Leader and AIPV, set the Commanded Gap Distance to 100', and drive in a straight line at 7mph; • While traveling at a steady 7mph set the Commanded Gap Distance to 100' and allow the Actual Gap Distance to stabilize; • Change the Commanded Gap Distance to 150' and allow the Actual Gap Distance to stabilize; • Repeat the change using the available increments from 100' to 175'
Data to Collect	
Expected Result	
Personne Needed	
Supporti Equipme	

3. Front View Collision Avoidance - Obstacle detection

Collision Avoidance and Redundant Front View Collision Avoidance

Operation Procedure	• Activate Leader and AIPV, drive in a straight line at 7.5mph with the GAP set to 200' • Set a barrel to mark the start of the GAP • Once the rear of the Leader passes the marker barrel for the front of the GAP, use a rope to pull a traffic barrel, detectable by radar/LIDAR into the path of the AIPV in the center of the lane • Test team will pull Leader and AIPV log data after each test • Repeat each test 3 times for statistical accuracy.
Data to Collect	• At what distance the AIPV detects the traffic barrel • Distance between front of AIPV and traffic cone after AIPV stops
Expected Result	AIPV detects the traffic barrel and executes an A-Stop.
Personnel Needed	Leader vehicle driver, AIPV driver, and technician moving the barrel/recording data.
Supporting Equipment	Laptop, cables to connect with vehicle, traffic barrel, measuring equipment.

2021 Validation Test Report
Example test result: Emergency Stop

Scenario 8 Emergency Stop ATMA External Button

Scenario 8 focused on testing the stopping distance of the ATMA upon initiation of an emergency stop of the follower vehicle by a test participant located on the exterior of both vehicles (mimicking a roadway worker or other individual located to the side of the vehicle that may want to emergency stop the vehicle). This test entails the test participating hitting a red stop button located on the driver side of the vehicle. The team recorded the stopping time and distance observed in the field for the data result. Data results for all runs are captured in the following tables.

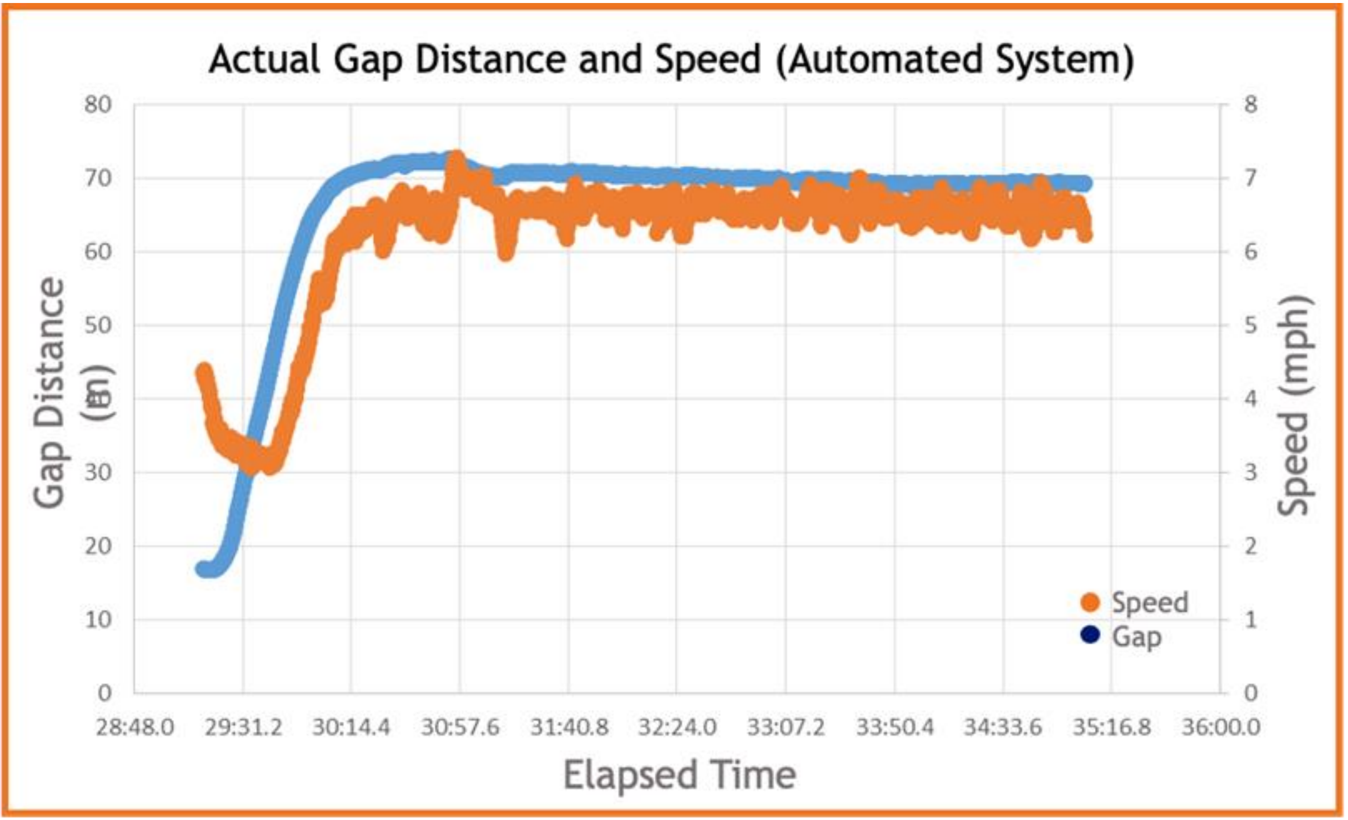
Operation Procedure	• Set gap to ≥150 feet • Activate Leader and AIPV, drive in a straight line at 5 mph; • Activate E-Stop button located on driver side of ATMA; • Repeat test 3 times for statistical accuracy. • Repeat test 3 times on passenger button.
Data to Collect	• The stopping distance of ATMA; • The stopping time of ATMA • Status of the Engine
Expected Result	• The AIPV should stop, the stop distance and time shall be recorded, and the engine should be shut off.
Personnel needed	Leader vehicle driver, AIPV driver, a technician to hit the E-Stop button, and a technician to record data (external).
Supporting Equipment	Traffic cones, measurement Equipment.

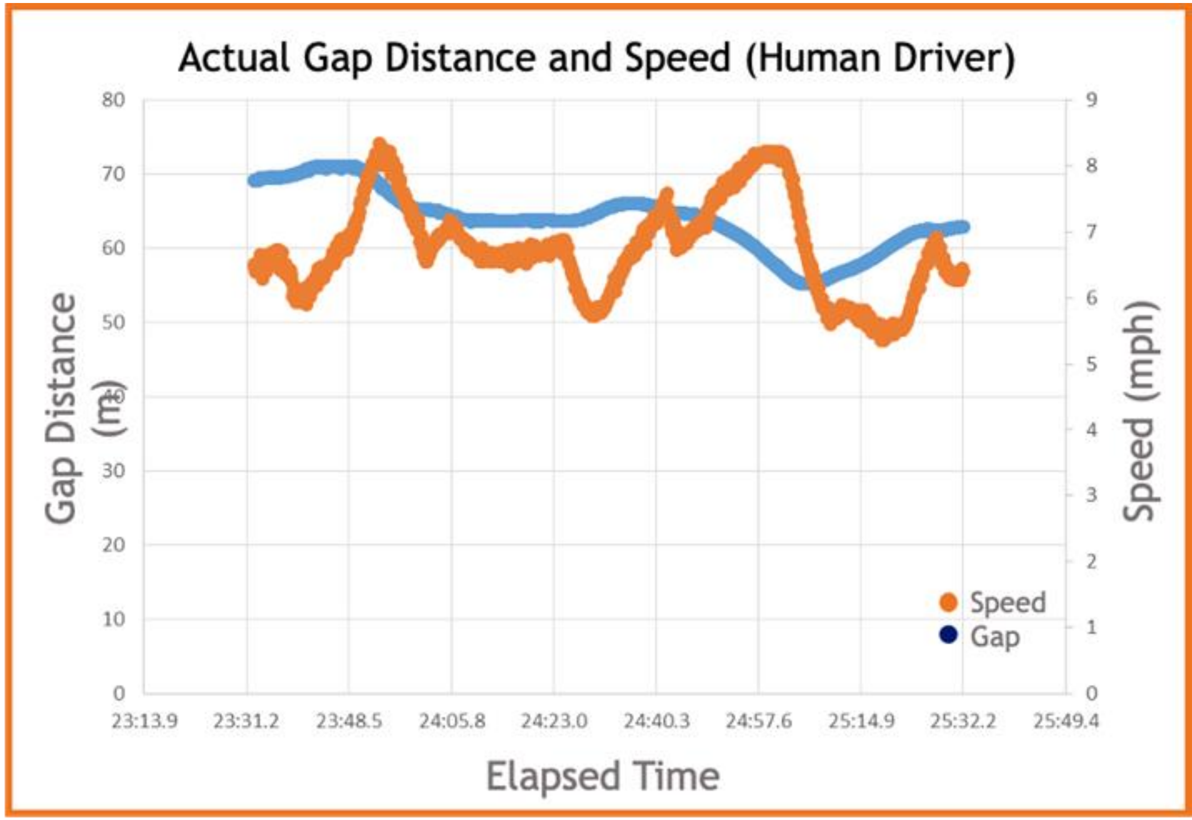
Data Results

#	Stopping distance of AIPV (measure)	Stopping time of AIPV (measure)	Status of engine
1.	14.4 ft	2.9 sec	Engine Kill
2.	14.6 ft	3.3 sec	Engine Kill
3.	14.8 ft	2.9 sec	Engine Kill
4.	14.3 ft	3.2 sec	Engine Kill

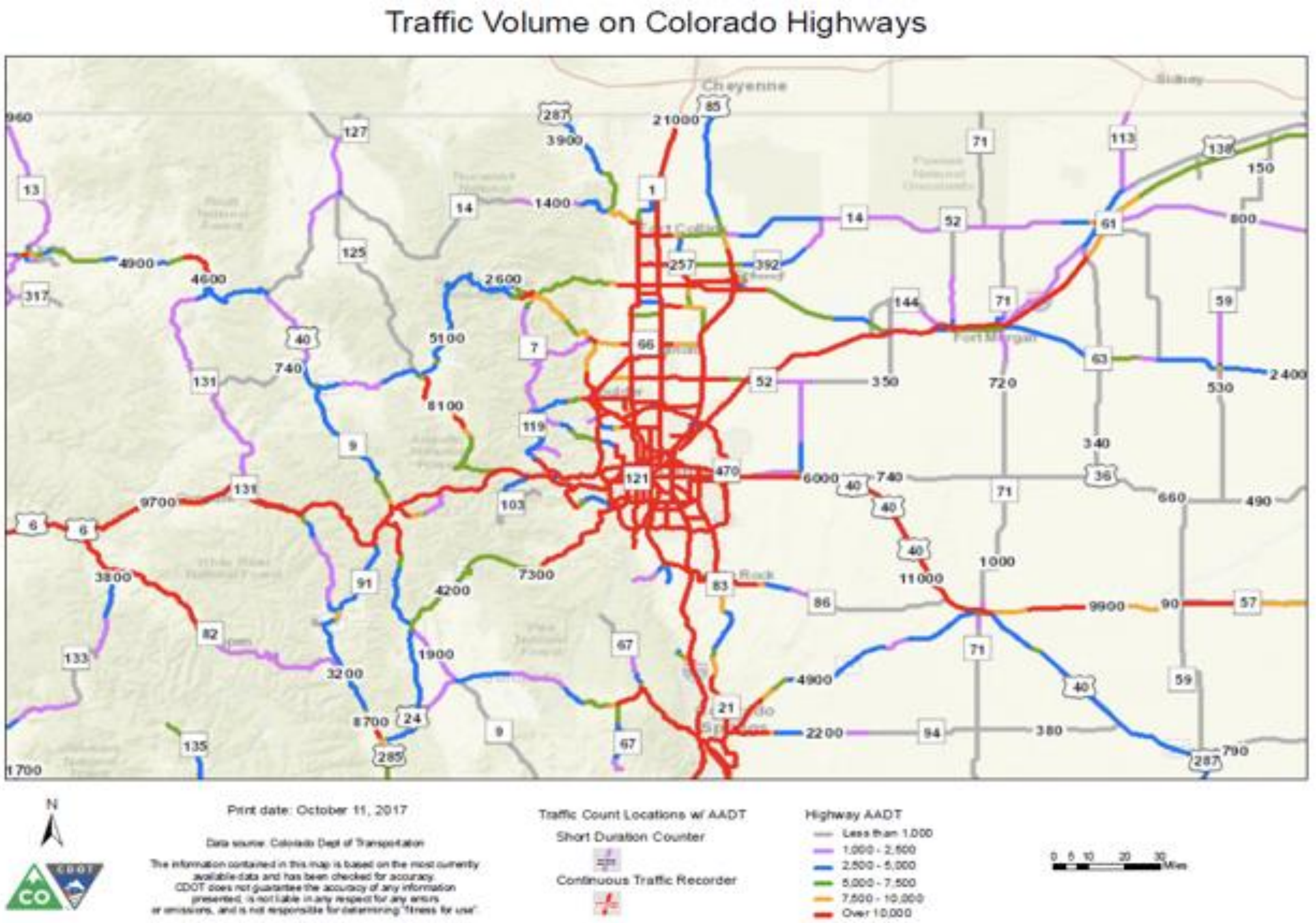
2018 Example test result: Gap control – Human Driver vs Automated System

- Straight line following for 4000’ with desired speed 7 mph (striping operation speed) and desired gap 60m
- Recorded gap is measured antenna to antenna: 60m bumper to bumper is 68.89m antenna to antenna





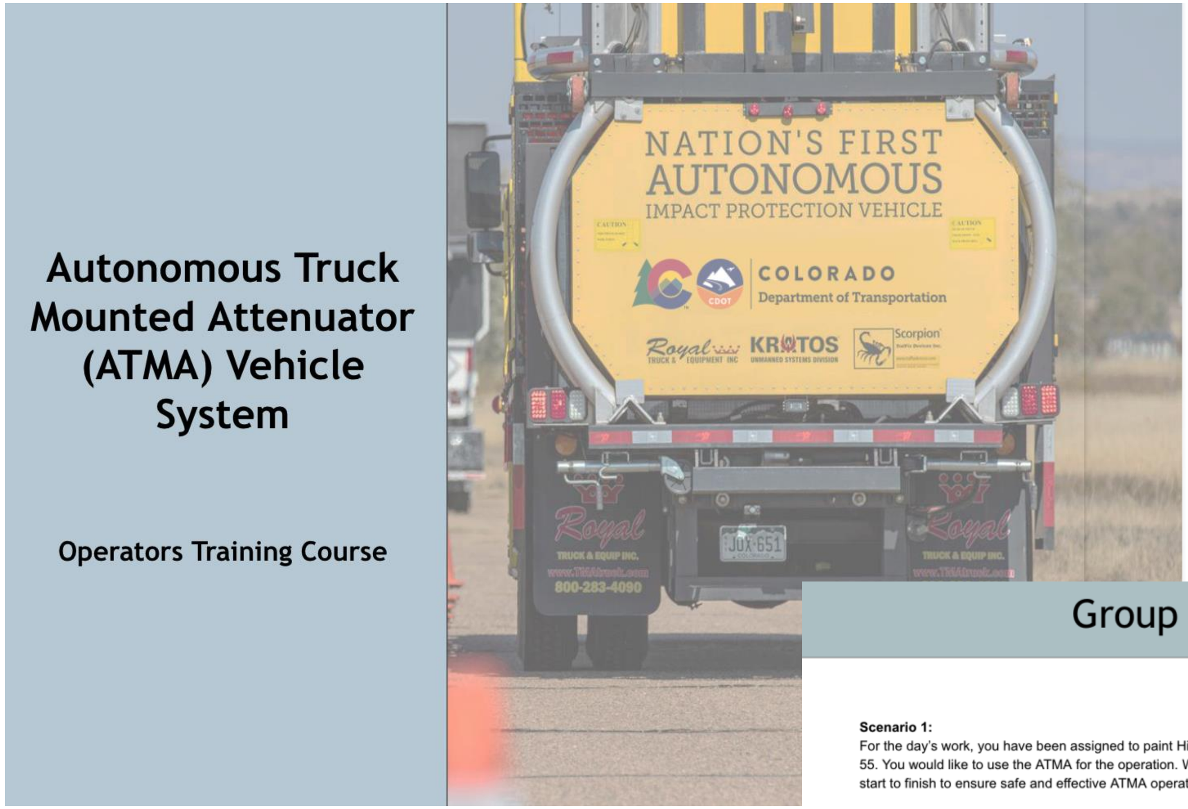
Operational Deployment



CDOT ATMAs approved for operations on **Blue**, **Purple**, **and** **Grey** roadways.

- 27 state highways
- 41 roadway segments

Annual Operator Training



Group Exercise

Scenario 1:
For the day's work, you have been assigned to paint Highway 52, Route 052A from Mile Marker 45 to 55. You would like to use the ATMA for the operation. What are the steps you would need to do from start to finish to ensure safe and effective ATMA operation?

Scenario 2:
You and the crew are operating the ATMA autonomously when during the middle of operation on the public roadway, the system disengages and stops. Please document how you and the crew would respond to ensure safety of the workers and the public roadway.

Scenario 3:
You and the crew are operating the ATMA when it is struck in the rear by a motorist. Please document how you would respond and the immediate actions you would take.

Scenario 4:
You are operating the ATMA on the public roadway when it A-stops several times on a roadway during your operation and it's unknown what is causing the continual A-stops. What are the actions you would take? Would you continue to operate the ATMA autonomously or would you put into manual mode? Please provide explanation for your answer and how you'd ensure safety of the crew.

Developing a community of practice – Autonomous Maintenance Technology Pool Fund

Autonomous Maintenance Technology Pool Fund TPF-5(380)

*"To **develop** and **deploy ATMA or AIPVs** to protect highway workers lives by enhancing cooperative inter-agency research that improves the safety and effectiveness of ATMA or AIPV operations, and to facilitate communication between transportation agencies that encounter challenges with implementation."*

Check out our Google Site:
https://sites.google.com/state.co.us/amt-pooled-fund/home

Research efforts sponsored by the AMT Pool Fund

1. 5380-19-02: Evaluating the Human-Automated Maintenance Vehicle for Improved Safety and Facilitating Long Term Trust,
   Dr. Erika Miller, Colorado State University

2. 5380-19-03: Development of ATMA/AIPV Deployment Guidelines,
   Dr. XB Hu, Missouri Science and Technology

3. 5380-20-04: ATMA Tabletop,
   All Clear Emergency Management Group

4. 5380-20-05: ATMA Tabletop, Cyber Securit
   Complement,
   Dr. Jeremy Daily, Colorado State University

5. 5380-20-06: ATMA Documentation,
   Dr. XB Hu, Missouri Science and Technolog

Evaluating Human-Automated Maintenance Vehicle for Improved Safety Summary Findings (5380-19-02)

- Workers reported a **positive acceptance of the ATMA technology**
  - Reduce crash severity
  - Reasonable workload for operating
  - Overall trust in automation's reliability
- Concerns relating to trust under **poor visibility and denser traffic**
- Workers with **higher levels of ATMA training and longer experience working with the ATMA** had the greatest trust in the technology
- Framework for data collection and add analysis can easily be reproduced as use of ATMAs becomes more widespread

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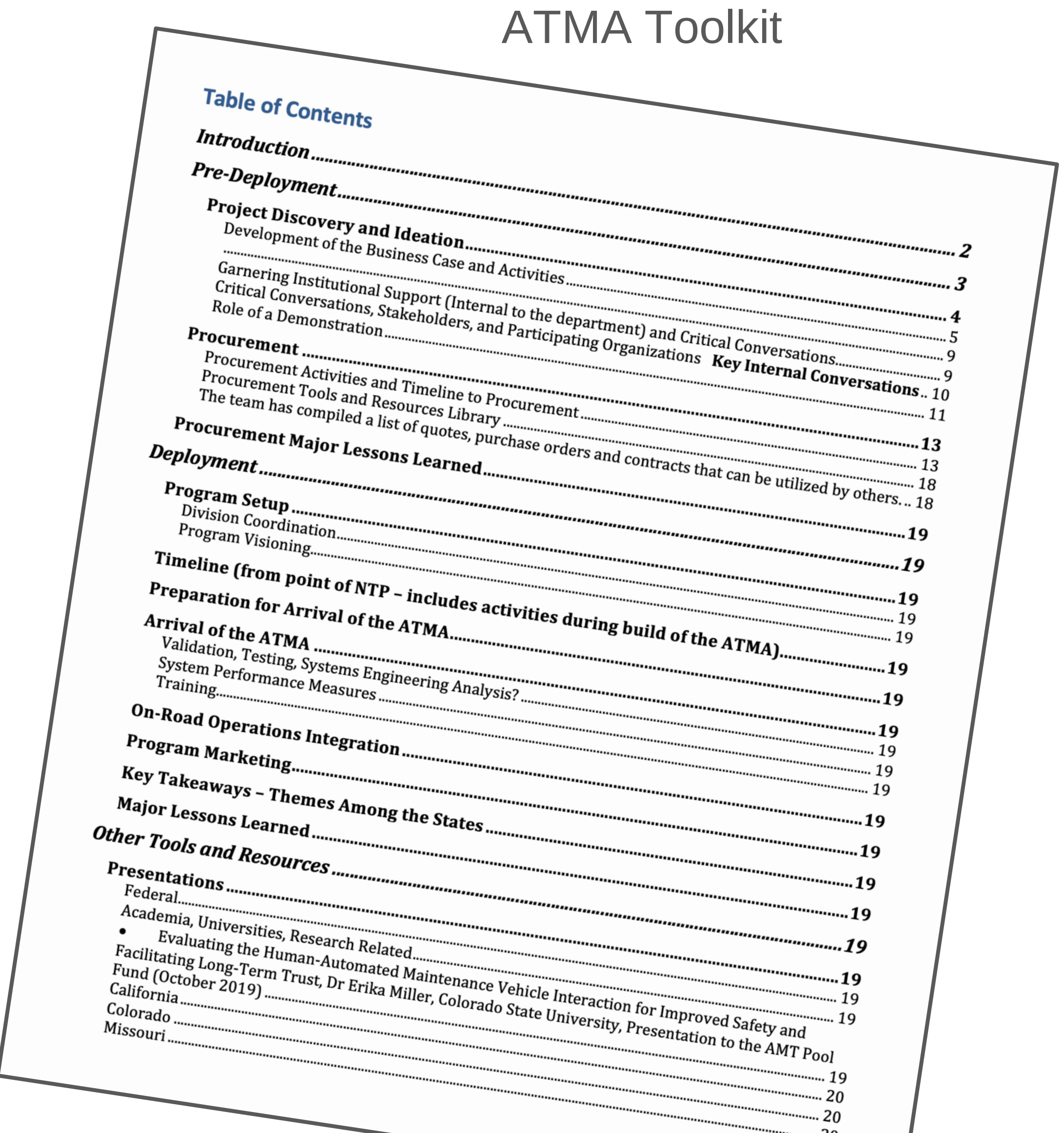
ATMA Tabletop Exercise to simulate and facilitate what would happen if a crash occurred:

- Standard operating procedures and practices following a crash
- Data to secure from the vehicle
- Preparation for if an

ATMA Toolkit - Developed by Members of the Toolkit - Preview



ATMA Toolkit

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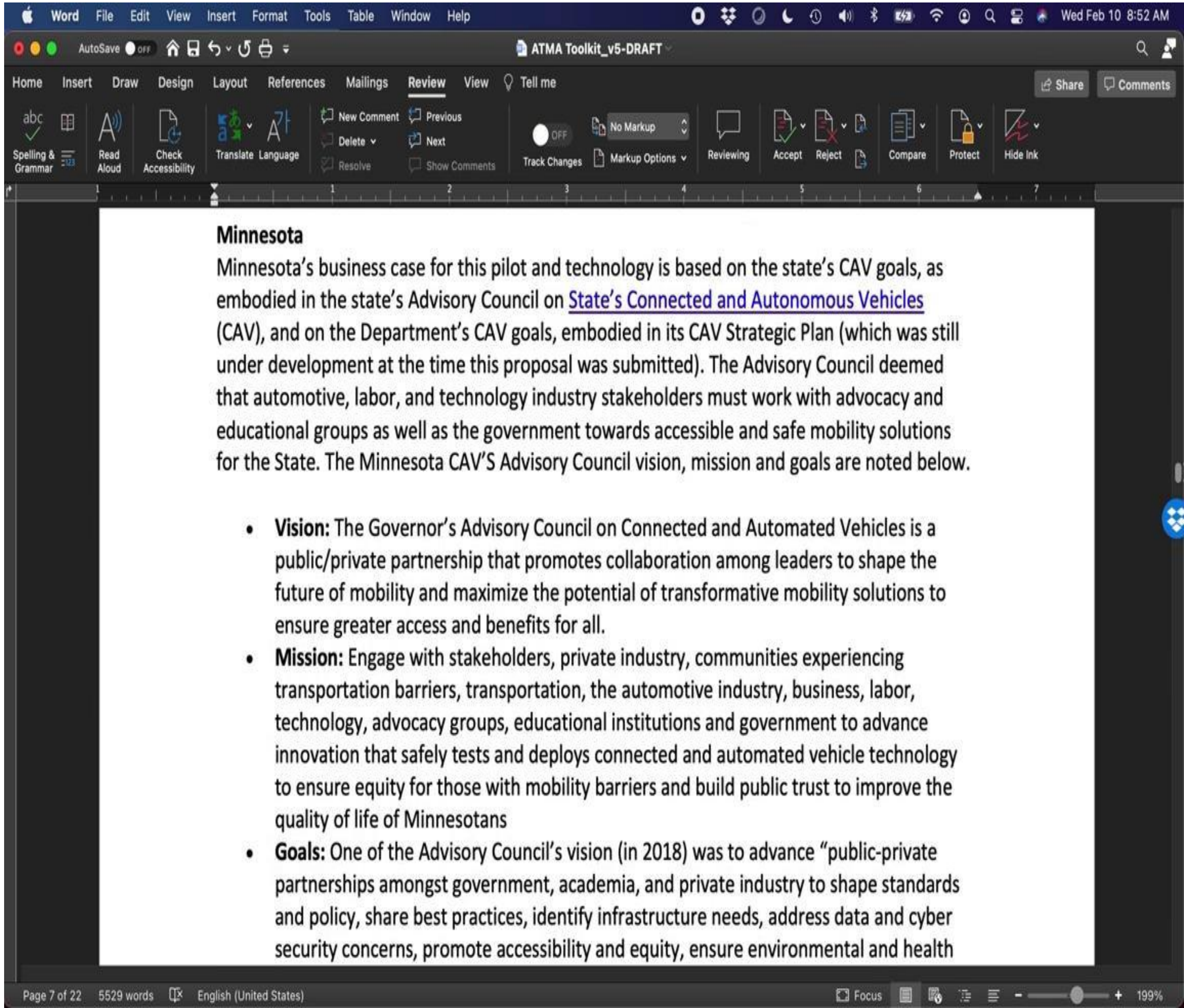

ATMA Toolkit_v5-DRAFT

Minnesota

Minnesota's business case for this pilot and technology is based on the state's CAV goals, as embodied in the state's Advisory Council on State's Connected and Autonomous Vehicles (CAV), and on the Department's CAV goals, embodied in its CAV Strategic Plan (which was still under development at the time this proposal was submitted). The Advisory Council deemed that automotive, labor, and technology industry stakeholders must work with advocacy and educational groups as well as the government towards accessible and safe mobility solutions for the State. The Minnesota CAV'S Advisory Council vision, mission and goals are noted below.

- **Vision:** The Governor's Advisory Council on Connected and Automated Vehicles is a public/private partnership that promotes collaboration among leaders to shape the future of mobility and maximize the potential of transformative mobility solutions to ensure greater access and benefits for all.
- **Mission:** Engage with stakeholders, private industry, communities experiencing transportation barriers, transportation, the automotive industry, business, labor, technology, advocacy groups, educational institutions and government to advance innovation that safely tests and deploys connected and automated vehicle technology to ensure equity for those with mobility barriers and build public trust to improve the quality of life of Minnesotans
- **Goals:** One of the Advisory Council's vision (in 2018) was to advance "public-private partnerships amongst government, academia, and private industry to shape standards and policy, share best practices, identify infrastructure needs, address data and cyber security concerns, promote accessibility and equity, ensure environmental and health

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Colorado Lessons Learned

Program Initiation

- Interdisciplinary approach (Multiple divisions involved)
- Lead Sponsoring Division
- Procurement challenges (rates, service agreement, lack of comparable data)
  - Lack of comparable data = importance of compiling quotes/contracts in toolkit

Program Start Up and Operations

- Importance of having a crew level member level champion
- Technology challenges will present themselves given the innovative nature of the technology (i.e. GPS card issue, follow up issues)
- COVID restrictions delayed start and delayed identification of technology challenges
  - Solution = still use the ATMA with operator behind wheel
- Season start up training

Colorado Department of Transportation

Thank you!

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Autonomous Truck Mounted Attenuator (ATMA)

Using Driverless Technology to Increase Work Zone Safety

ATMA™
AUTONOMOUS TMA TRUCK

The ATMA drastically increases the safety of roadway maintenance staff by eliminating one of the most dangerous assignments in the work zone

KRATOS® UNMANNED SYSTEMS DIVISION

Royal TRUCK & EQUIPMENT INC.

Unmanned Systems Division
Maynard Factor
PH: (850) 461-4457
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Kratos Corporate Overview

Kratos Defense & Security Solutions, Inc. (Nasdaq: KTOS) develops and fields transformative, affordable systems, platforms, and products for national security needs.

Primary focus areas are unmanned systems, satellite communications, cyber security / warfare, microwave electronics, missile defense, training, and combat systems for a diverse range of platforms and programs

- Over 3,000 Employees
- Over $700M Revenue
- NASDAQ: KTOS
- 60/40% Products/Services
- 60+ Locations Worldwide
- San Diego Headquarters

Kratos Unmanned Systems Division

Kratos Unmanned Systems Division is developer of leading-edge near-term solutions to improve operational effectiveness and significantly increase safety.

A global leader in the design, development, and manufacturing of unmanned system solutions that provide tactical competitive advantage for air and surface battlefield dominance. Unmanned system solutions include;

- Tactical Unmanned Aerial Vehicles – Valkyrie, MAKO/UTAP-22, Gremlins
- Aerial Target Drones – BQM-167, BQM-177, BQM-178 (Firejet)
- Training/Tactical Unmanned Ground Vehicles – HMMWV, T-72 Tanks, Resupply Vehicles, cars/trucks/SUVs/ATVs






What is a TMA

Roadway work zones are complex environments with potential conflict points existing between traveling vehicles, vulnerable workers, and slow-moving heavy equipment.

A Truck Mounted Attenuator (TMA) is a ***human-driven mobile crash barrier*** that is used to follow behind a highway maintenance operations, shielding workers and equipment ahead from errant drivers entering the work zone.

TMA's are…

- Operated in all 50 states
- Deployed daily / nightly
- Support mobile maintenance operations:
  - Line Painting
  - Sweeping
  - Patching
  - Crack Sealing
  - Weed Spraying
  - Roadway Clean-up
  - Falling Weight Deflectometry
  - GPS Surveying
  - Specialty Applications

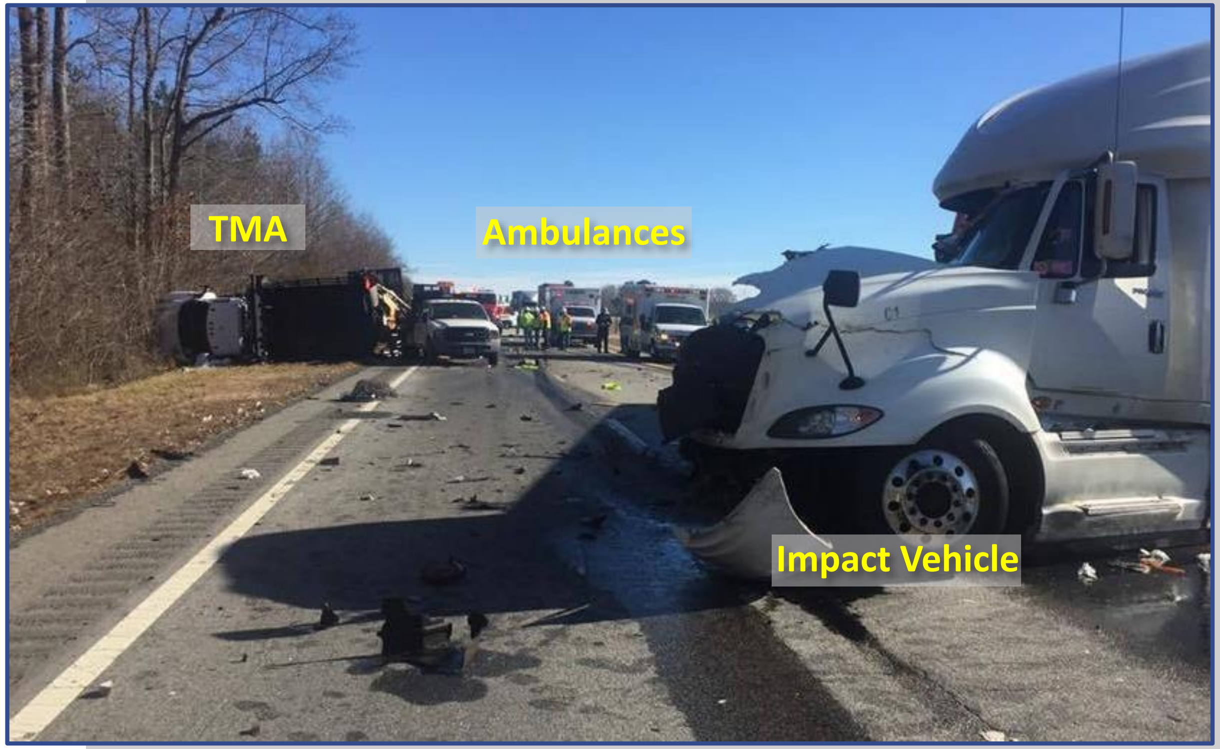



Why Automate

Driving a TMA is recognized as one of the **most dangerous assignments in the work zone**.

- Across the US there are over **90 crash-related injuries** and **11 fatalities** every week in the work zone (ref: Federal Highway Administration)
- TMA drivers are at significant risk of lifelong injury, painful rehabilitation, and even death
- Impact vehicles can be 80,000 lb. tractor-trailers traveling at 65+ mph

THE ATMA REMOVES THE DRIVER FROM A "HIGH RISK" SITUATION



*Tractor-trailer impact of a Virginia Department of Transportation (VDOT) TMA

Crash Statistics

Kratos Defense has made a push for the ATMA innovation as a result of a number of brutal national statistics.

Work Zones 2019

In the U.S.
*Federal Highway Administration

- **90** Crash-related Injuries Daily
- **11** Crash-related Fatalities Weekly
- **710** Crash-related Fatalities In 2017

In the U.K.
*Highways England

- **741** Crash-related Fatalities In 2017

A game changing solution for improving saftey and efficiency in the work zone.

*crash highlights value of ATMA

- **32,719** - # of motor vehicle fatalities from 2012-2013
  *Fars Annual Report
- **92,626** - # of crashes in work zones in 2015
  *US DOT FHA Facts & Statistics
- **41%** - of crashes were rear-end collisions in work zones
  *"Identification of Work Zone Crash Characteristics"
- **90%** - of traffic crashes in Florida are due to human error
  *2015 FL Department of Transportation

TMA Driver Testimony

An actual TMA Truck survivor providing testimony about the benefits of the Autonomous TMA

"This is going to save lives. This is going to prevent any of us to have to come back here and talk about how we almost died and how we could have not seen our kids"

Legislation passed the Senate and House unanimously and is now law in PA (ACT 117)

The Technology

The Autonomous Truck Mounted Attenuator (ATMA) is a CAV solution that **removes the human** from the **most dangerous assignment in mobile highway operations**.

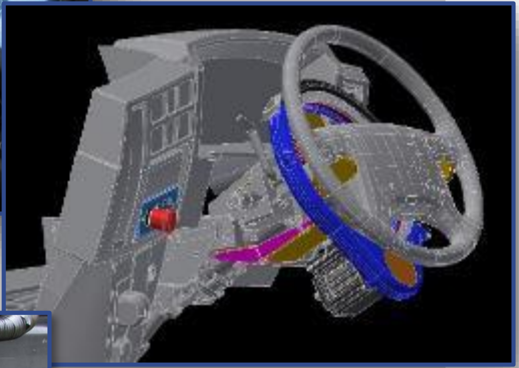
Key Features

- **Driver and Driverless Modes**– system easily switches from a manned operation to an unmanned operations
- **System Redundancy** – reduces possibility of single point failures
- **Cybersecurity Precautions** – prevents malicious hacking
- **Advanced Active Safety System** – automated E-Stop capabilities
- **Enhanced Obstacle Detection** – front and side view protections
- **User Controls** – user adjustable gap and lateral alignment
- **GPS-denied Navigation** – status-at-a-glance and operator controls

Navigation data transmitted from a Manned Leader Vehicle enables the ATMA to follow behind **completely driverless** in a “Leader/Follower” configuration.

The Technology

Steering Actuator



Obstacle
Detection
& Avoidance

A **retrofit kit** solution enables any fleet vehicle to be converted into an autonomous system. System components include on-board computer, navigation system, actuators, user interface, and active safety system.

Leader Vehicle User Interface

E-Stop Safety

Deployments

There is significant worldwide interest in the deployment of the ATMA which uses currently available **driverless technology** to solve a real world problem.

England - COLAS

Colorado DOT

Missouri DOT

Caltrans

Minnesota DOT

Tennessee DOT - Leased

Florida DOT – Leased

North Dakota DOT

Indiana DOT – Leased

Deployments

- **More than 2,000 miles of operation since 2017**
- Deployed 11 systems to date in locations that include
  - England, CO, MO, CA, MN, TN, FL, ND, IN
- Pooled Fund – hosted by CDOT serves an ATMA discussion forum for topics such as:
  - system improvements
  - expansion of use
  - refining policy and operational procedures
  - Investigation of additional applications of technology
  - 13 participating states to include:
    - AL, CA, CO, IL, KS, MN, MO, NV, OH, OK, TX, VA, WA

Testimonials

“The ATMA removes drivers from the follower truck during highway maintenance operations. As a result, there is a tremendous decrease in exposure risk to the operator during operations; namely, the risk of potential injury or death to the individuals who would otherwise man the attenuator is greatly diminished. The ATMA is an example of how CDOT is pursuing cutting-edge technology to improve highway management and increase safety of our roadways for the people who manage and maintain them. The ATMA sets the foundation and ground work for automation to be more broadly introduced to DOT work zone and maintenance operations.”

“It is great when military technology can be adapted for civilian use. Especially when it has the potential such as this (ATMA) to save lives. This is important because this truck will save lives and help prevent serious crash injuries to workers in construction zones. NDOT is committed to using innovation and technology to improve safety and operations throughout North Dakota”

NDDOT North Dakota Department of Transportation

Notable Awards

2015 American Road and Transportation Builders Association (ARTBA) Work Zone Safety Award for the Autonomous TMA Truck

2018 International Road Federation (IRF) Global Road Achievement Award for the Autonomous TMA

CIHT

2018 Chartered Institution of Highways and Transportation (CIHT) Ringway Innovation Award Runner Up and Highly Commended for Autonomous Impact Protection Vehicle (AIPV)

ASCE
AMERICAN SOCIETY OF CIVIL ENGINEERS

2021 American Society of Civil Engineers (ASCE) recognizes the ATMA as an “Infrastructure Gamechanger”

2022 Award Announcement To Be Released Soon….

Benefits

The ATMA aligns with Federal Highways **work zone safety** objectives and is a great implementation of CAV technologies to improve the day-to-day lives of our workers.

Work Zone Safety

Reduced Worker Exposure to Danger

- **Increased Safety** – keep your workers out of harm's way – now protected by the ATMA
- **Improved Worker Quality of Life** – reduced work zone anxiety
- **Lower Costs** – fewer injuries means fewer liability claims
- **Work Zone Optimization** – increased efficiency means less time on the road

Ideal for CAV Program

Easy to Use, Easy to Deploy

- **Clearly Defined Objective** – Safety
- **Operates in Specific Environment** – mobile highway maintenance operations
- **Operates at Slow Speed** – typical <15 mph
- **Requires 0 Mods to Existing Infrastructure** – deployable any time/where
- **Positive Public Awareness** – a feel-good story that everyone can understand

Better Employee Experience

Enhanced With Technology

- **Safety** – TMA vehicles are now operated from a safe location; the lead vehicle
- **Strategic Workforce Development** – an opportunity to work with CAV technologies
- **Availability** – able to support other work zone activities – cross training

Questions


KRATOS
LEADING
THE WAY
SPEED LIMIT
25
YOUR SPEED
LIVE RECORDING

Development of Operation Guidelines for Leader-Follower Autonomous Maintenance Vehicles at Work Zone Locations

Qing Tang, PhD Student, qingtang@psu.edu

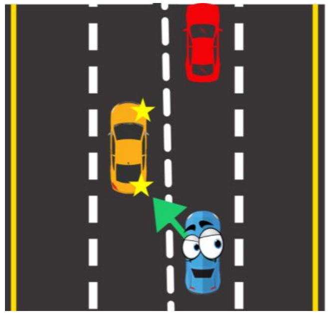
Advisor: Dr. Xianbiao (XB) Hu

Department of Civil and Environmental Engineering

Pennsylvania State University

How to drive Autonomous Truck Mounted Attenuator (ATMA) vehicles?

- What are minimum requirements?
  - Car-following distance
  - Lane-changing gap
  - Intersection clearance time



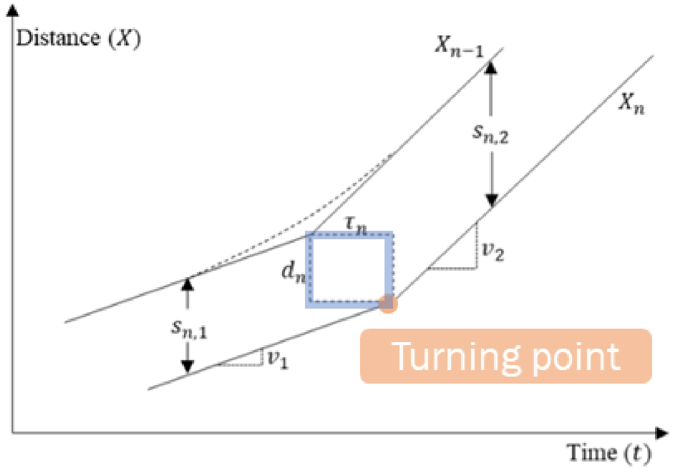
Preliminaries

- Newell's car-following model (2002)
  - Following vehicle n's trajectory

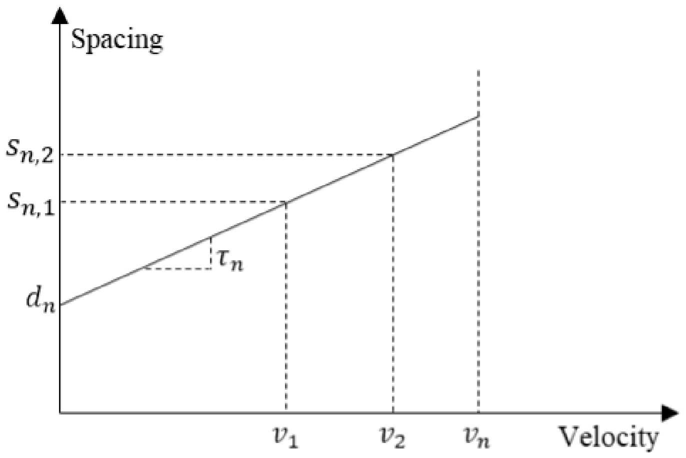
$$x_n(t + \tau_n) = x_{n-1}(t) + d_n$$

  - Required car-following distance

$$s_{n,i} = d_n + v_i \cdot \tau_n$$



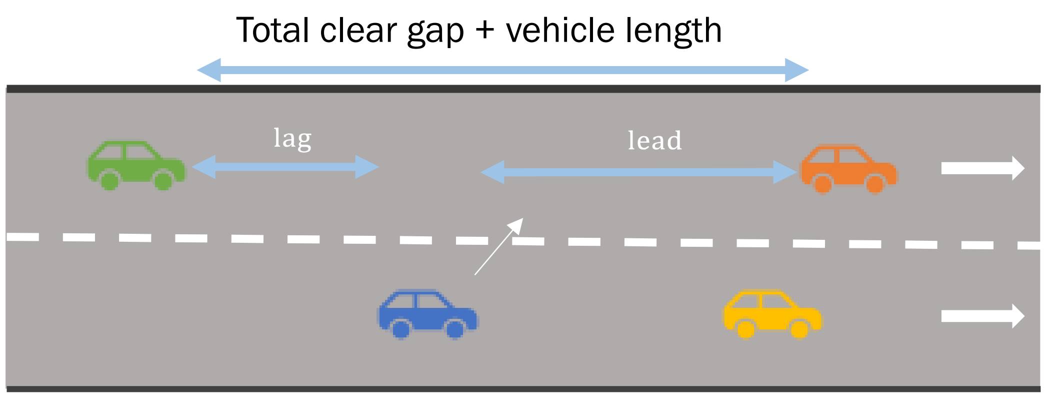
Time-space Diagram of Newell's car-following model



Relationship between Spacing and Velocity for A Single Vehicle

Preliminaries

- Critical Gaps for Lane-changing
  - Lane-changing model
    - Proposed by Yang and Koutsopoulos (1996)
  - Acceptable gap
    - $L = L_{\text{lead}} + L_{\text{lag}} + L_{\text{vehicle length}}$

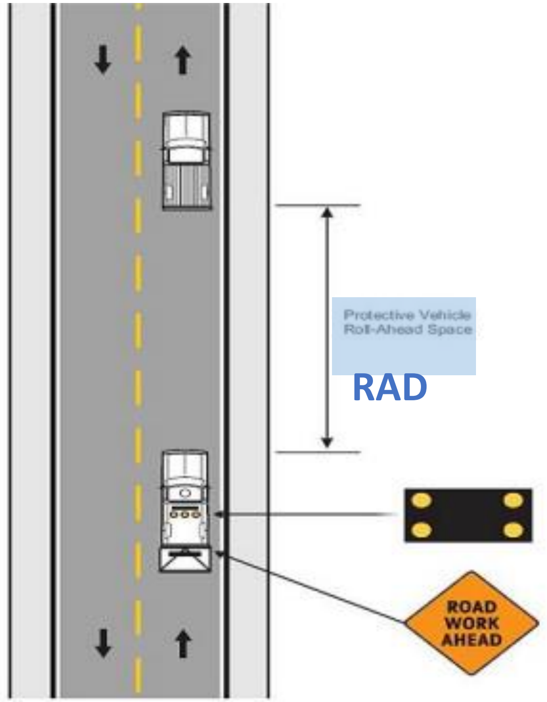


Preliminaries

- Roll-ahead Distance (RAD)
  - In the work zone, a truck mounted attenuator (TMA)-equipped vehicle should be positioned as a sufficient distance in advance of the workers or equipment being protected.
  - The RAD varies depending on the weights and speeds of the two vehicles involved, the extent to which the shadow vehicle is restrained, and certain pavement characteristics.
  - ATMA follower truck: 23.365 lbs

Guidelines for spacing of shadow vehicles (from AASHTO Roadside Design Guide)

Weight of shadow vehicle (lb)	Traffic operating speed (mph)	Recommended RAD for moving operation (ft)
$\geq 22{,}000$	> 55	172
	$45 - 55$	150
	< 45	100



Data Collection

- Leader Truck

	LCB	CRUMB	STAMP	LAT	LON	ALT	HEADING	VELOCITY
40:04.1	LDR	9802	18400390	38.69313	-93.2612	-0.018	280.999	2.28
40:04.2	LDR	9803	18400400	38.69313	-93.2612	-0.015	280.959	2.42
40:04.2	LDR	9804	18400410	38.69313	-93.2612	-0.02	281.009	2.54
40:04.4	LDR	9805	18400420	38.69313	-93.2612	-0.033	280.969	2.67
40:04.4	LDR	9806	18400430	38.69313	-93.2612	-0.027	280.929	2.8
40:04.6	LDR	9807	18400440	38.69313	-93.2612	-0.018	280.929	2.93
40:04.7	LDR	9808	18400450	38.69313	-93.2612	-0.017	280.899	3.03

- Follower Truck

49:44.8	VEH	CRUMB	STAMP	LAT	LON	ALT	HEADING	HDG(Desi	VELOCITY	VEL(Desir	GAP	GAP(Desi	#SATS	VALID	CTE	ACCEL	STEER	STATE
49:45.1	FLW	0	13494510	38.69365	-93.2617	234.129	299.138	290.476	3.91	4.44	8.83	7.6	21	1	0	-100	0	IDLE
49:45.2	FLW	0	13494520	38.69365	-93.2617	234.138	298.638	290.476	3.95	4.44	8.83	7.6	21	1	0	-100	0	IDLE
49:45.3	FLW	0	13494530	38.69365	-93.2617	234.147	298.298	290.476	3.95	4.44	8.89	7.6	17	1	0	-100	0	IDLE
49:45.4	FLW	0	13494540	38.69365	-93.2617	234.143	297.808	290.476	4.03	4.44	8.92	7.6	17	1	0	-100	0	IDLE
49:45.5	FLW	0	13494550	38.69365	-93.2617	234.151	297.498	290.476	4.04	4.44	8.95	7.6	17	1	0	-100	0	IDLE
49:45.6	FLW	0	13494560	38.69365	-93.2617	234.154	297.118	290.476	4.04	4.44	8.97	7.6	17	1	0	-100	0	IDLE
49:45.7	FLW	0	13494570	38.69365	-93.2617	234.161	296.898	290.476	3.96	4.44	8.99	7.6	17	1	0	-100	0	IDLE
49:45.8	FLW	0	13494580	38.69365	-93.2617	234.165	296.438	290.476	3.87	4.44	9.03	7.6	17	1	0	-100	0	IDLE
49:45.9	FLW	0	13494590	38.69366	-93.2617	234.18	296.048	290.476	3.79	4.44	9.06	7.6	17	1	0	-100	0	IDLE

Data Collection

- Maximum deceleration of ATMA vehicles from emergency stop test
  - Operation speed is 10 mph
    - Average deceleration is 9.1 $\mathrm{ft/s^2}$
    - Maximum is 9.4 $\mathrm{ft/s^2}$
  - Operation speed is 15 mph
    - Average deceleration is 11.4 $\mathrm{ft/s^2}$
    - Maximum is 12.4 $\mathrm{ft/s^2}$

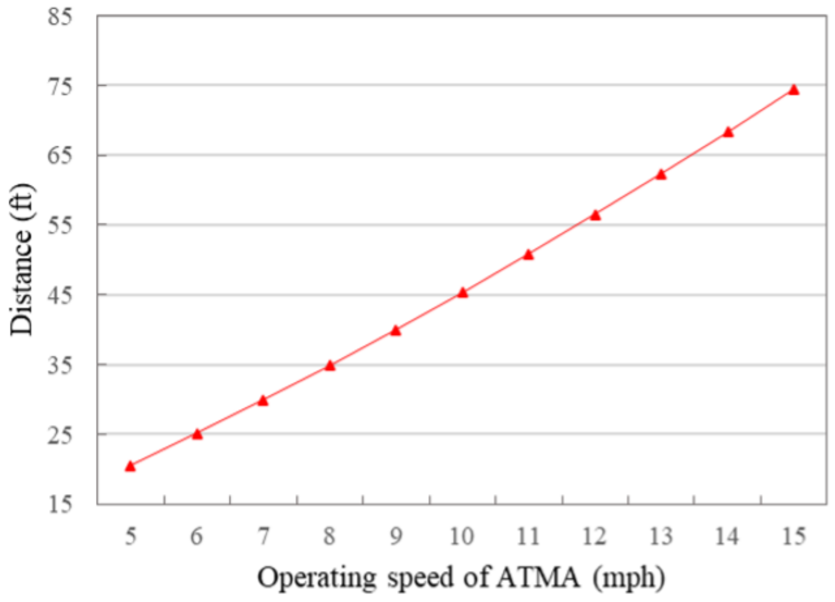
- Breaking reaction time is taken 2.5 s (AASHTO recommend)

The Stop Time and Distance in Emergency Stop Test

Set GAP	Speed	Stop Time			Standard Deviation	Stop Distance			Standard Deviation
		Run 1	Run 2	Run 3		Run 1	Run 2	Run 3	
$\geq 100'$	10 mph	1.56 s	1.56 s	1.75 s	0.09	11.5’	15.75’	20.5’	3.68
	15 mph	1.91 s	2.13 s	1.78 s	0.14	31.08’	37’	26.58’	4.27

Minimum Car-following Distance Requirement

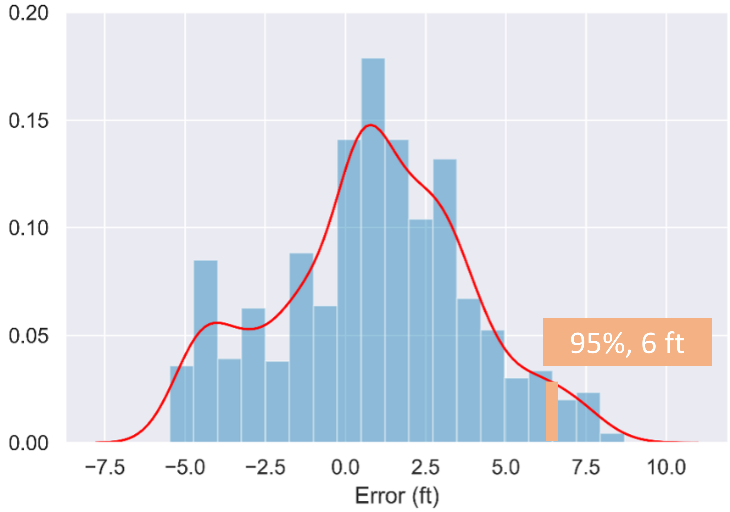
- Minimum car-following distance for Leader Truck (LT)
  - $s_{\mathrm{lt}} = v_{\mathrm{lt}} \cdot \tau_{\mathrm{lt}} + d_{\mathrm{lt}}$
    - $v_{\mathrm{lt}} \cdot \tau_{\mathrm{lt}}$: Distance the leader truck travels before a brake is initialed
    - d_{lt}: Braking distance $d_{\mathrm{lt}} = \frac{{v_{\mathrm{lt}}}^2 - 0}{2 \cdot a_{\mathrm{lt}}} = \frac{{v_{\mathrm{lt}}}^2}{2 a_{\mathrm{lt}}}$
  - Minimum car-following distance: 75 ft



Minimum car-following distance of a leader truck

Minimum Car-following Distance Requirement

- Minimum car-following distance for Follower Truck (FT)
  - $s_{\mathrm{ft}} = \max(\mathrm{RAD}, d_{\mathrm{ft}} + \varepsilon) = \max\left(\mathrm{RAD}, \frac{{v_{\mathrm{ft}}}^2 - 0}{2 \cdot a_{\mathrm{ft}}} + \varepsilon\right)$
    - The 95 percentiles of errors are found to be 6 ft, i.e., $\varepsilon = 6\mathrm{ft}$
    - $\frac{{v_{\mathrm{ft}}}^2}{2 \cdot a_{\mathrm{ft}}} + \varepsilon \leq 26\ \mathrm{ft}\ \ (v_{\mathrm{ft}}: 5 \sim 15\ \mathrm{mph})$
    - $s_{\mathrm{ft}} = \mathrm{RAD}$, 100~172 ft

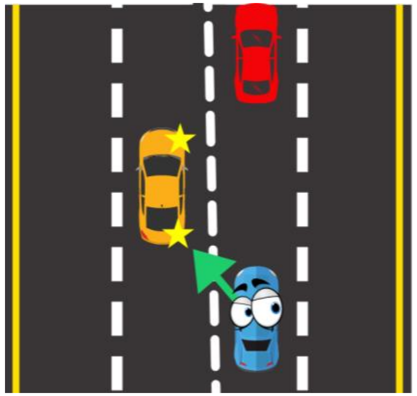


Frequency distribution histogram of error in following distance

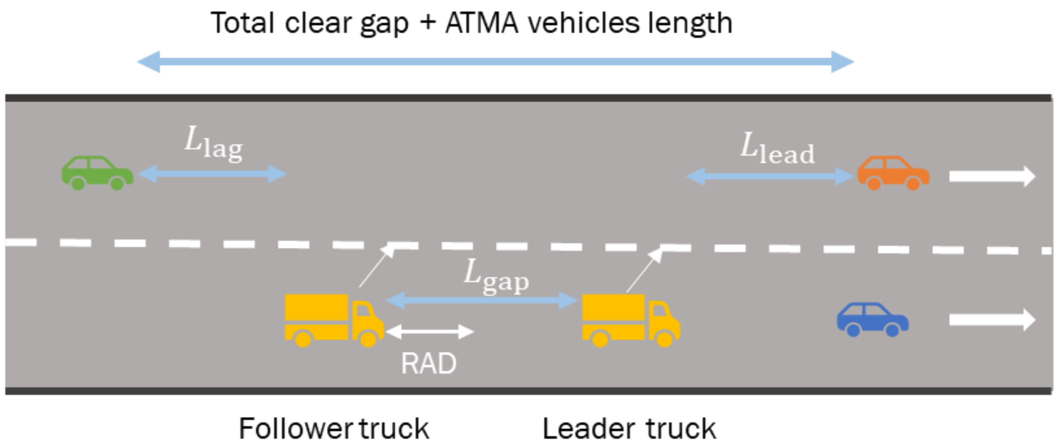
Traffic operating speed (mph)	Recommended RAD for moving operation (ft)
> 55	172
$45 - 55$	150
< 45	100

Critical Gap Distance Requirement for Lane-changing

- Required minimum acceptable gap distance
  - $L = L_{\text{lead}} + L_{\text{lag}} + (L_{\text{lt}} + L_{\text{gap}} + L_{\text{ft}})$
- Minimum time headway $t_{\min} = t_{\text{rps}} + \frac{v}{a}$
- Critical gap distance and time headway



1. $L_{\text{lead}} = v_{\text{lt}} t_{\text{rps,lt}} + \frac{v_{\text{lt}}^2}{2a_{\text{lt}}} \Leftrightarrow t_{\min,1} = t_{\text{rps,lt}} + v_{\text{lt}}/a_{\text{lt}}$
2. $L_{\text{lag}} = v_{\text{ffs}} t_{\text{rps,gv}} + v_{\text{ffs}}^2/2a_{\text{gv}} \Leftrightarrow t_{\min,2} = t_{\text{rps,gv}} + v_{\text{ffs}}/a_{\text{gv}}$
3. $L_{\text{lt}} + L_{\text{gap}} + L_{\text{ft}} \Leftrightarrow t_{\min,3} = \frac{L_{\text{gap}} + L_{\text{lt}} + L_{\text{ft}}}{v_{\text{lt}}} = \frac{\max(\text{RAD}, L_{\text{gap},0}) + L_{\text{lt}} + L_{\text{ft}}}{v_{\text{lt}}}$



gv: General vehicle

t_{rps} : Response time

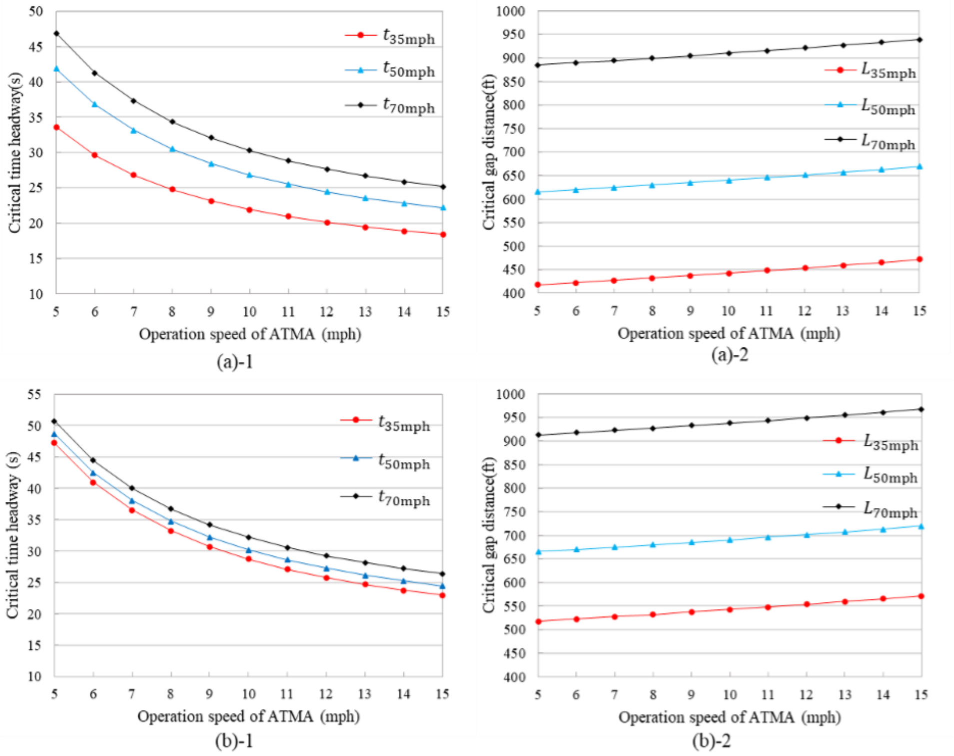
v_{ffs}: Free flow speed

$L_{\text{gap},0}$: Preset gap distance

Critical Gap Distance Requirement for Lane-changing

- FFS=70 mph & preset gap distance ($L_{\text{gap},0} = 100$ ft)
  - Critical gap distance
    - 886 ft ~ 940 ft
  - Time headway: 25~47 s

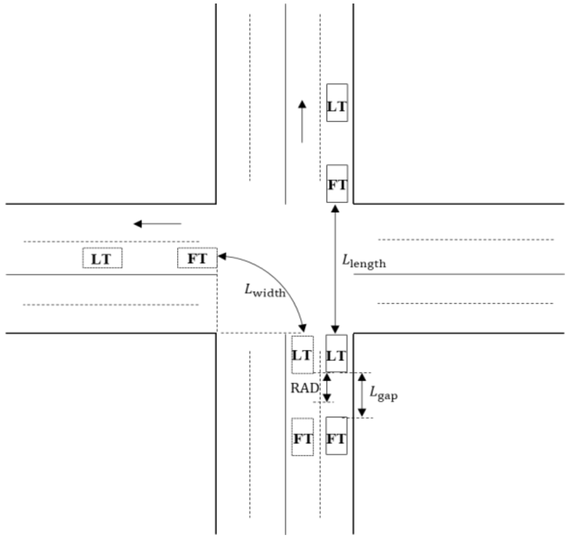
- FFS=70 mph & $L_{\text{gap},0} = 200$ ft
  - Critical gap distance
    - 914 ft ~ 968 ft
  - Time headway: 26~51 s

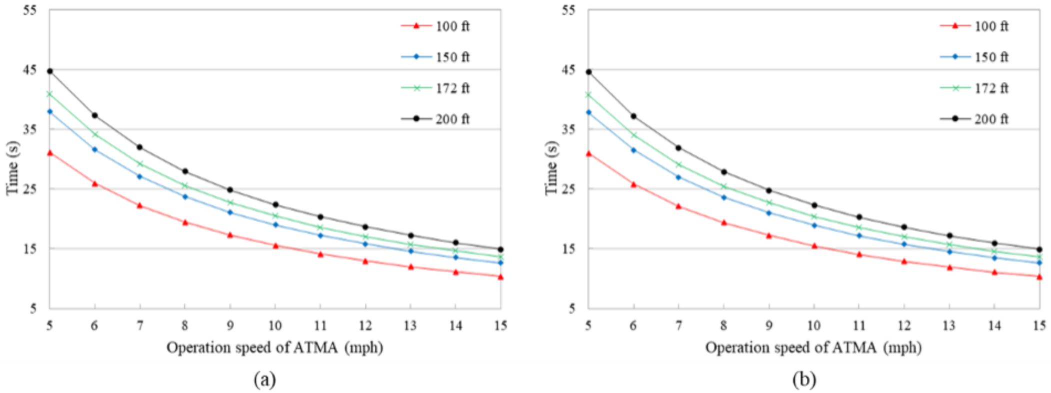


Critical Time Headway and Gap Distance Requirement for Lane Changing : (a) 100 ft Gap Distance; (b) 200 ft Gap Distance.

Intersection Clearance Time Requirement

- Go straight
  - $t_{\text{straight}} = (L_{\text{length}} + \max(\text{RAD}, L_{\text{gap},0}) + L_{\text{lt}} + L_{\text{ft}})/v_{\text{lt}}$
  - $L_{\text{gap},0}$: preset gap distance
- Left turn
  - $t_{\text{turn}} = (L_{\text{width}} + \max(\text{RAD}, L_{\text{gap},0}) + L_{\text{lt}} + L_{\text{ft}})/v_{\text{lt}}$
- Required time
  - 10s to 31s with a gap distance of 100 ft
  - 13s to 38s with a gap distance of 150 ft
  - 15s to 45s with a gap distance of 200 ft.



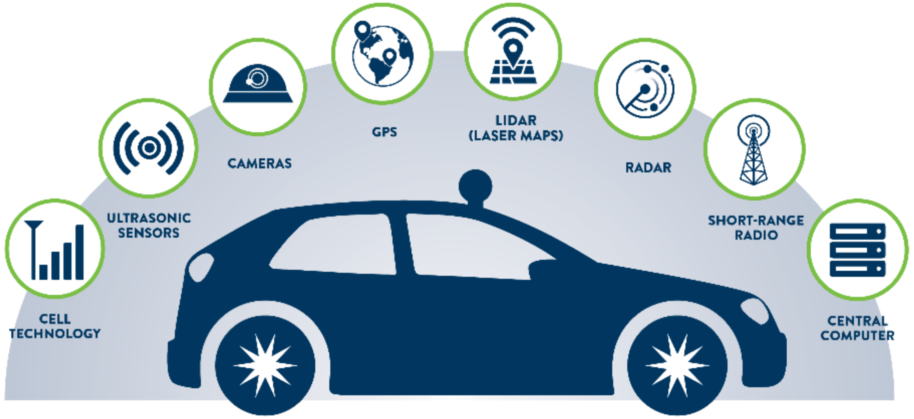


Required Time at An Intersection to: (a) go straight; (b) turn left

- Lane width is set to be 12 ft
- Intersection length: $L_{\text{length}} = 48$ ft
- Intersection width: $L_{\text{width}} = \pi \times (24 + 6) \times 2/4 = 47.1$ ft

How to apply the guidelines?

- Combining with CAV technology
  - Sensors – obstacles detection, gap distance
  - Vehicle-to-infrastructure (V2I) – information from traffic signal controller



Thank you!
Questions?

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*Tang, Q., Hu, X., & Qin, R. (2021). Development of Operation Guidelines for Leader–Follower Autonomous Maintenance Vehicles at Work Zone Locations. *Transportation Research Record*, 03611981211056644.