JOHNS HOPKINS
WHITING SCHOOL of ENGINEERING

645.800 - Systems Engineering Master's Project

Safety Sentinel System

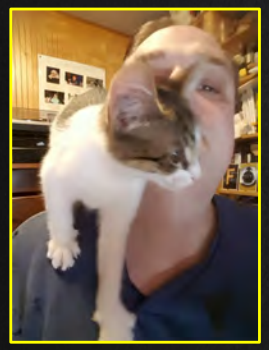
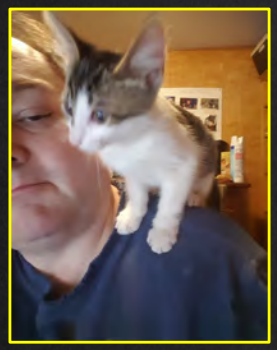
(Gary) Scott Houghton

May 4, 2019

Project Mentor: -Steven Biemer

- Biography
- Introduction & Need
- CONOPS
- Requirements Analysis
- Functional Analysis
- Physical Design
- Trade Study
- Test Plan
- Specification Summary
- Risk Management
- Final Concept
- Lessons Learned
- Recommendations

Biography


- BS, Industrial Safety
- BS, Chemical Engineering
- MBA

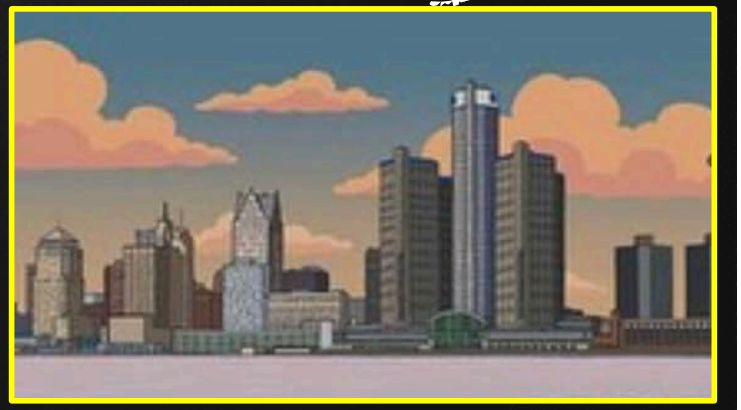
- Corp. Safety Engineer
- Industrial Hygienist Spec

20+ Years at
Ford Motor Company

- 1 wife, 1 son, too many cats

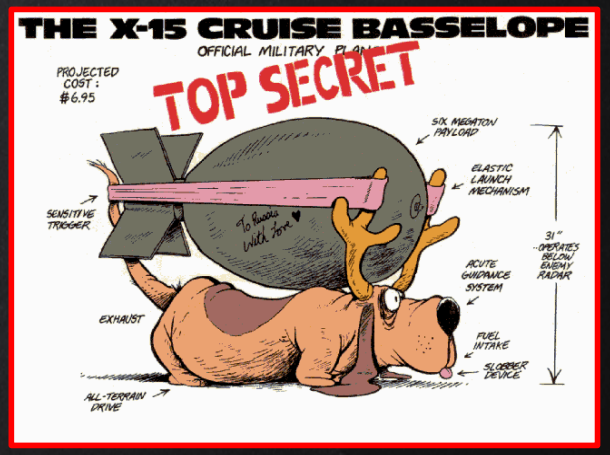
- SE Michigan

UAW-FORD HEALTH SAFETY



Introduction

- ✘ Initial concept development
  - Relevance to manufacturing
  - Leverage SE to improve workplace safety
- ✘ Accidents involving fork lift trucks (FLTs) are a significant risk
  - Pedestrians struck by FLTs
  - FLT rollovers
- ✘ Systems engineering could be leveraged to apply emerging technology to prevent FLT accidents
  - Effective even when people don't pay attention



Need for System

- Fork Lift Trucks characteristics -
  - Very heavy
  - Poor visibility
  - Often driven in reverse
- Widely used, even with new technology such as AGVs
  - 860,000 in use in U.S.[1]
- Accident Stats (NIOSH and NSC) -
  - 35,000 serious injuries annually[2]
  - Direct cost = $38K, Indirect cost = $150K[3]
  - 85 fatalities annually

1. https://www.oshasafetymanagement.com/blog/forklift-safety-infographic/
2. https://www.cdc.gov/niosh/docs/2001-109/default.html
3. https://www.ehstoday.com/forklift-safety/national-forklift-safety-day-giving-forklift-safety-platform

Need for System

RECENT ADVANCES

- ✘ Increase visibility of FLTs
  - Blue LED lights – many options
  - RF Proximity sensors, such as ZoneSafe
- ✘ Dependent upon increasing awareness of FLT operators and pedestrians

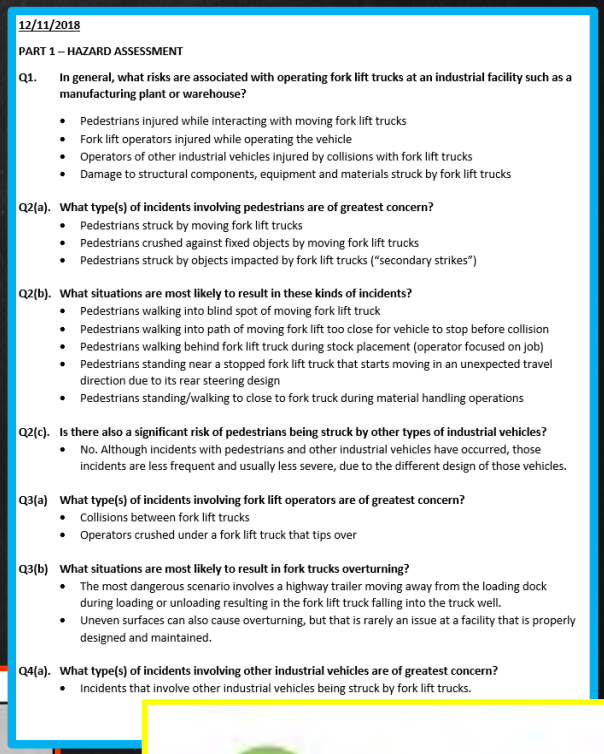
Need for System

→ EMERGING TECHNOLOGY

- ✘ Real time positioning systems - "indoor GPS"
  - Tracking inventory, people
  - Limited applications for tracking FLTs
  - Several technologies - Optical, RFID, UWB
  - A few safety systems - Q-Track SafeSpot
- ✘ Increase awareness but no capability for prevention

Requirements Development

- ✘ Stakeholders' questionnaire
  - Safety personnel
  - Logistics personnel
  - Material handling vendor
- ✘ Scenario development
- ✘ Online research about enabling technology



12/11/2018

PART 1 – HAZARD ASSESSMENT

Q1. In general, what risks are associated with operating fork lift trucks at an industrial facility such as a manufacturing plant or warehouse?

- Pedestrians injured while interacting with moving fork lift trucks
- Fork lift operators injured while operating the vehicle
- Operators of other industrial vehicles injured by collisions with fork lift trucks
- Damage to structural components, equipment and materials struck by fork lift trucks

Q2(a). What type(s) of incidents involving pedestrians are of greatest concern?

- Pedestrians struck by moving fork lift trucks
- Pedestrians crushed against fixed objects by moving fork lift trucks
- Pedestrians struck by objects impacted by fork lift trucks ("secondary strikes")

Q2(b). What situations are most likely to result in these kinds of incidents?

- Pedestrians walking into blind spot of moving fork lift truck
- Pedestrians walking into path of moving fork lift too close for vehicle to stop before collision
- Pedestrians walking behind fork lift truck during stock placement (operator focused on job)
- Pedestrians standing near a stopped fork lift truck that starts moving in an unexpected travel direction due to its rear steering design
- Pedestrians standing/walking to close to fork truck during material handling operations

Q2(c). Is there also a significant risk of pedestrians being struck by other types of industrial vehicles?

- No. Although incidents with pedestrians and other industrial vehicles have occurred, those incidents are less frequent and usually less severe, due to the different design of those vehicles.

Q3(a) What type(s) of incidents involving fork lift operators are of greatest concern?

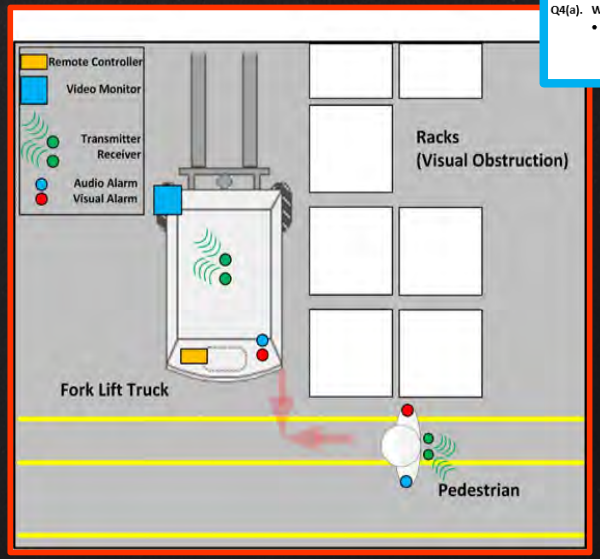
- Collisions between fork lift trucks
- Operators crushed under a fork lift truck that tips over

Q3(b) What situations are most likely to result in fork trucks overturning?

- The most dangerous scenario involves a highway trailer moving away from the loading dock during loading or unloading resulting in the fork lift truck falling into the truck well.
- Uneven surfaces can also cause overturning, but that is rarely an issue at a facility that is properly designed and maintained.

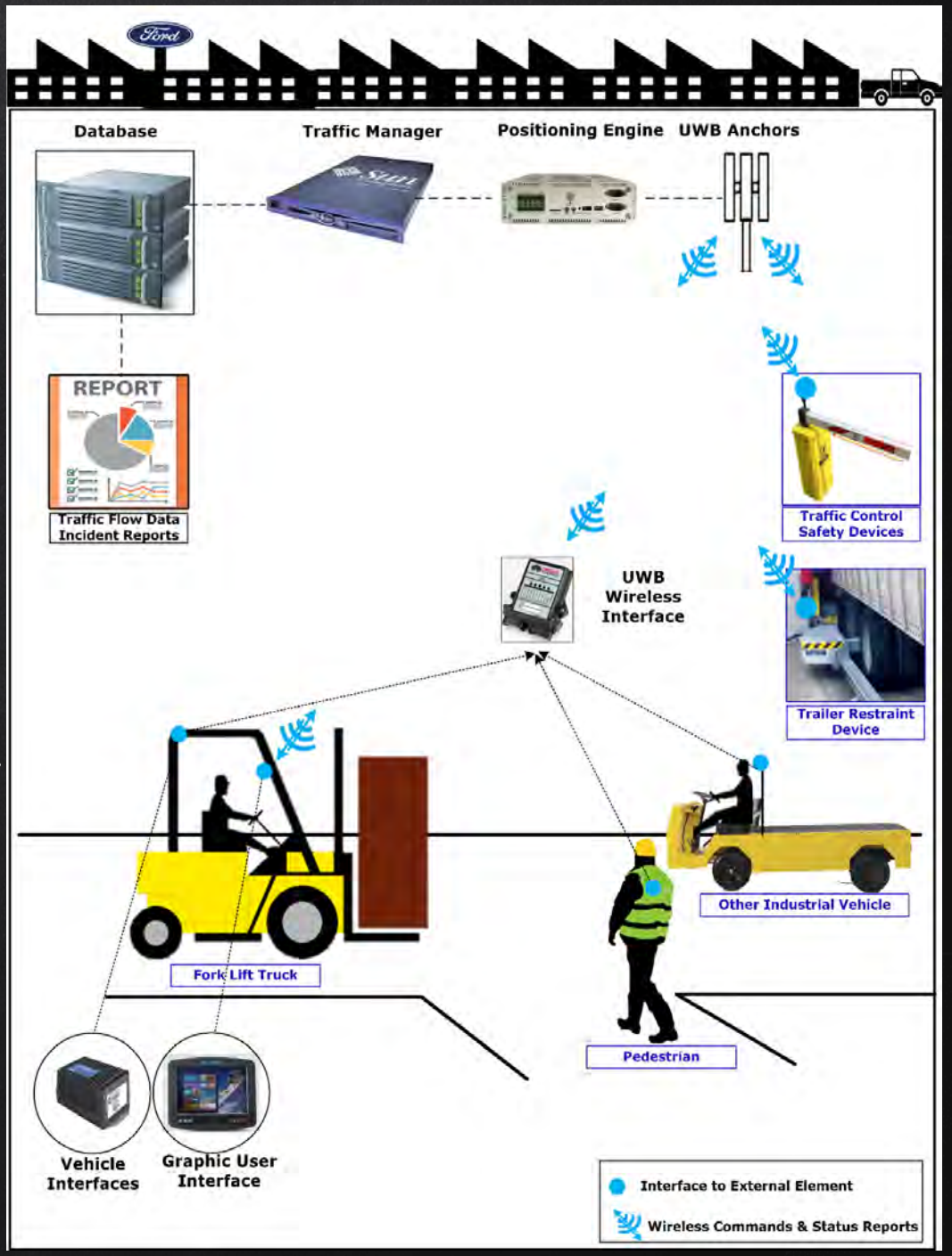
Q4(a). What type(s) of incidents involving other industrial vehicles are of greatest concern?

- Incidents that involve other industrial vehicles being struck by fork lift trucks.



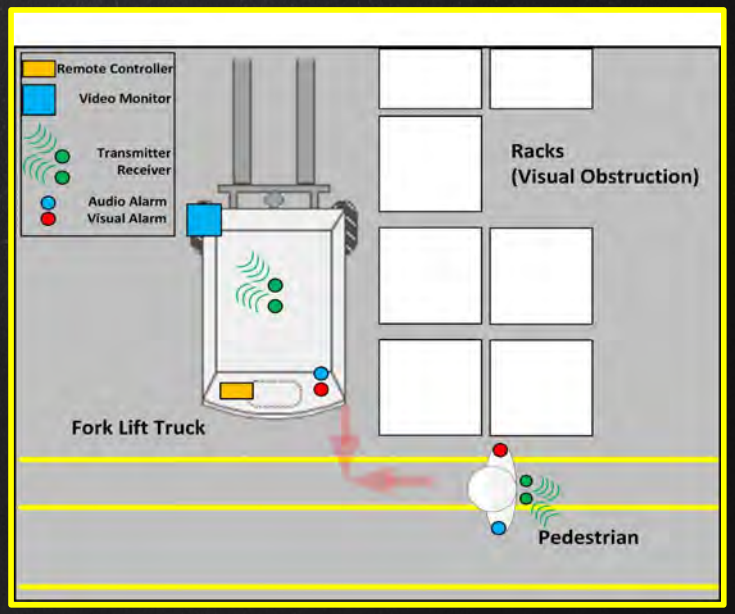
CONOPS

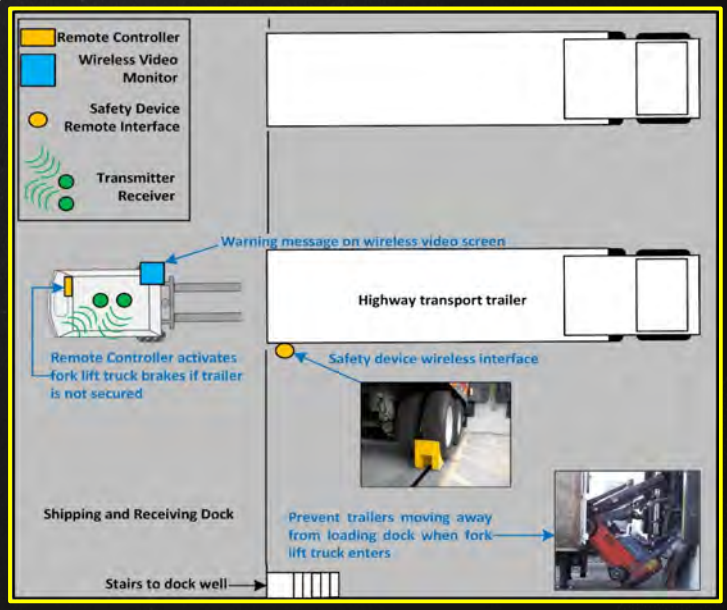
- ✘ Track locations with ultra wideband (UWB) RFID network
- ✘ Use locations to identify potential collisions
- ✘ Send warning to FLT operator
- ✘ Send command to E-stop FLT
- ✘ Prevent entry into unsecured trailer
- ✘ Reduce congestion
  - Control traffic devices
  - Identify best route to FLT operator
- ✘ Archive data for reports



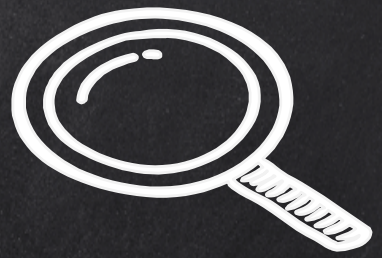
Scenarios

- ✘ Prevent pedestrians (or other vehicles) struck by FLT
- ✘ Prevent of FLT entering unsecured trailers
- ✘ In-plant navigation to least-congested route
  - Less congestion = fewer accidents
  - Control traffic devices
- ✘ Operate in safe mode (added)
  - Avoid production operation





Scenarios



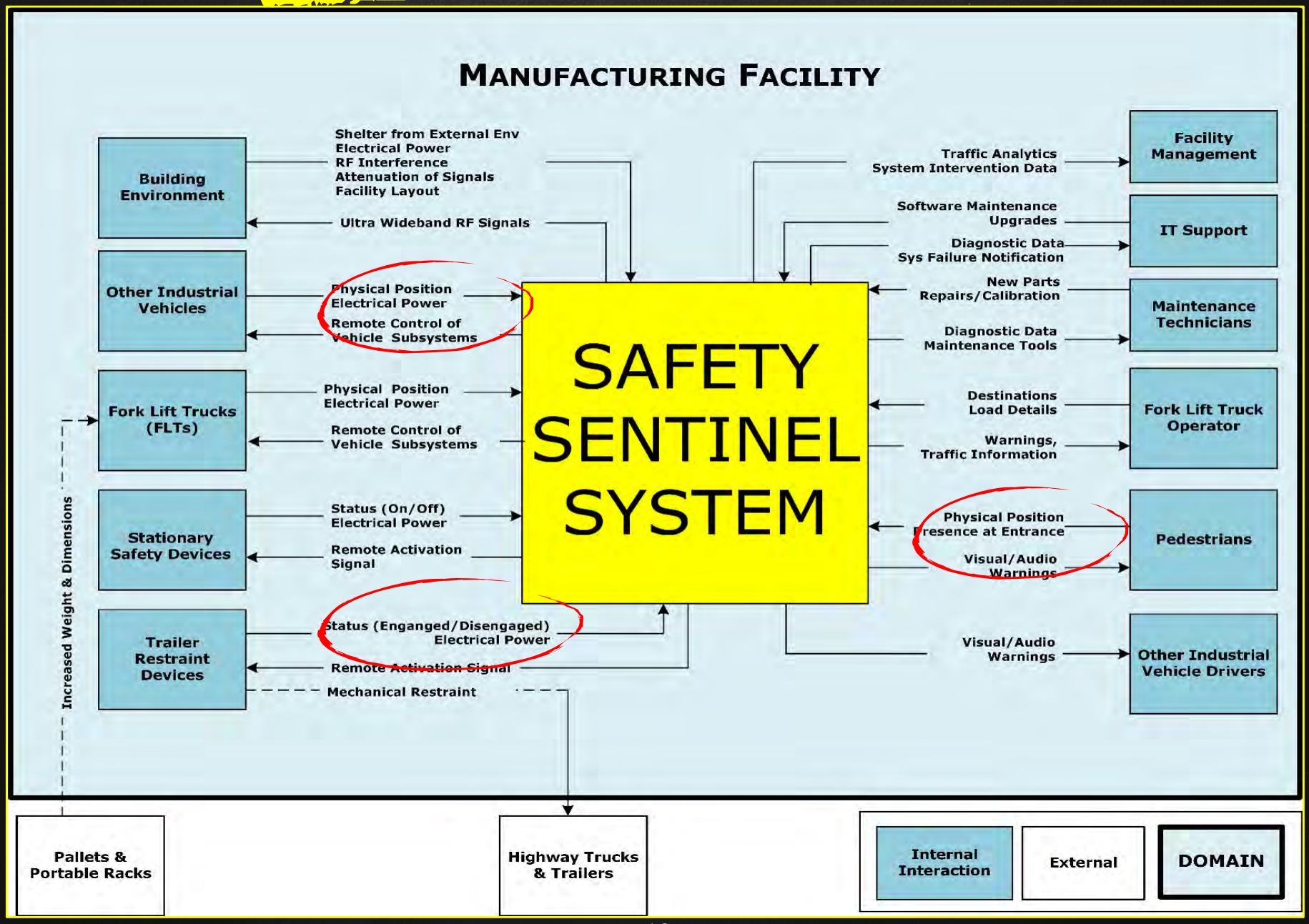
Prevent Pedestrians Struck by FLT

- ✘ Pedestrian or FLT driver does not see each other
- ✘ System identifies potential collision
  - Message to FLT GUI
  - Sound horn and lights
- ✘ Collision imminent
  - E-stop FLT

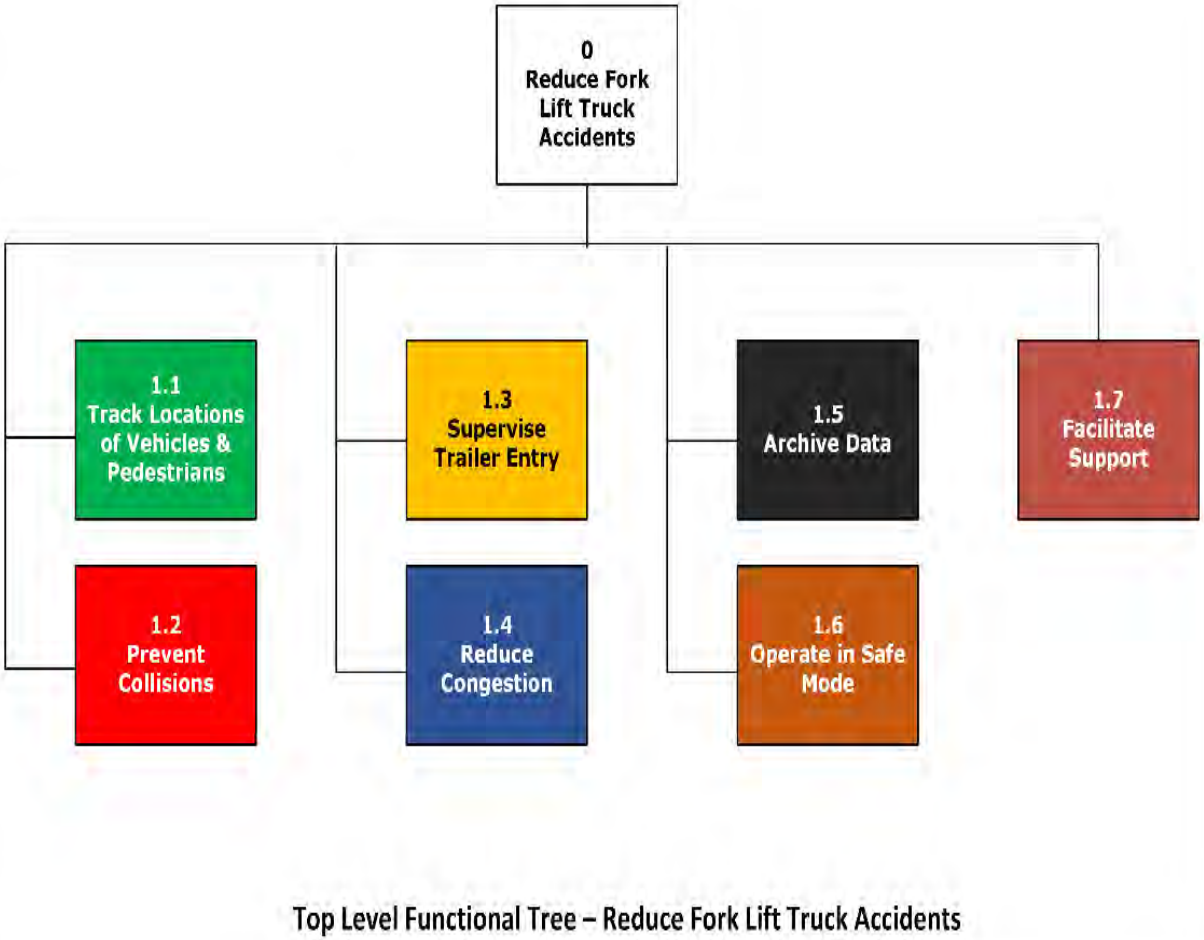
Prevent FLT Entering Unsecured Trailer

- ✘ FLT approaches trailer
- ✘ System checks status of trailer restraint
- ✘ If trailer not secured -
  - Message to FLT GUI
  - E-stop FLT before it enters trailer
- ✘ Prevent release of trailer restraint if FLT inside trailer

Functional Concept – Context Diagram



Functional Concept



Top Level Functional Tree – Reduce Fork Lift Truck Accidents

Functional Tree

- From Req'ts
- From CONOPs
- To refine higher level functions

Functional Concept

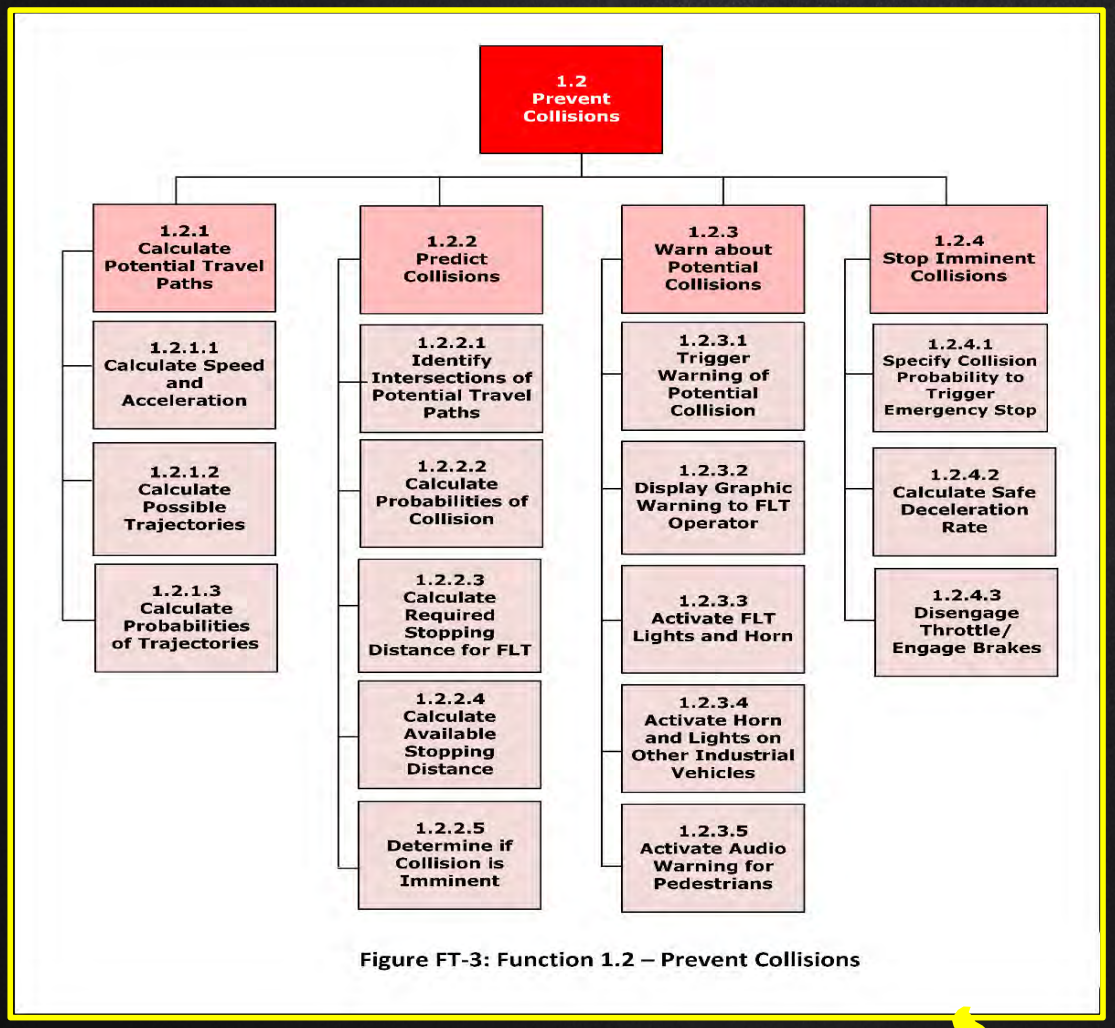


Figure FT-3: Function 1.2 – Prevent Collisions

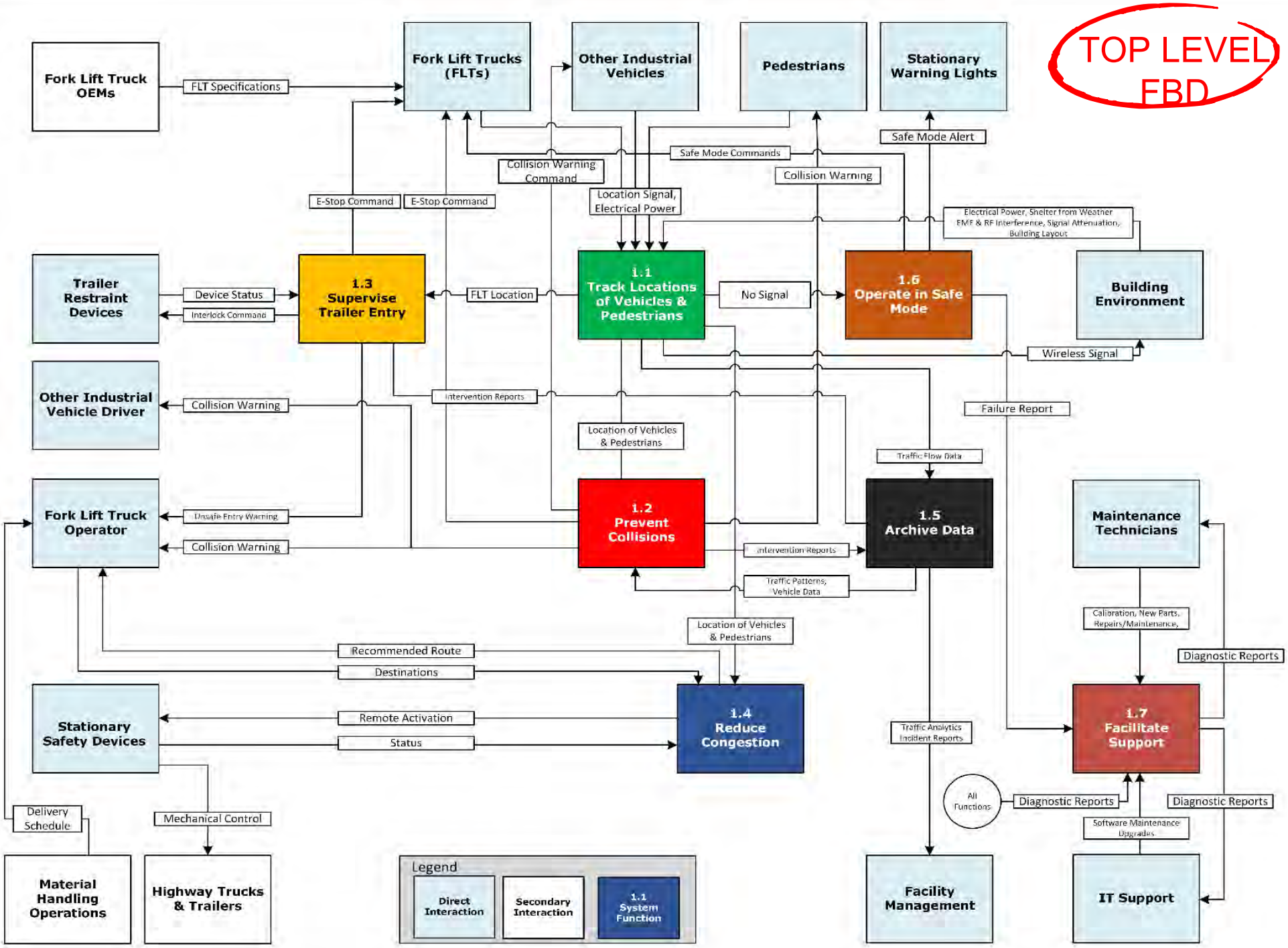
Functional Tree

- ✘ All functions traced to requirements
- ✘ All requirements traced to functions

= COMPLETENESS

LOOSE COUPLING

STRONG BINDING

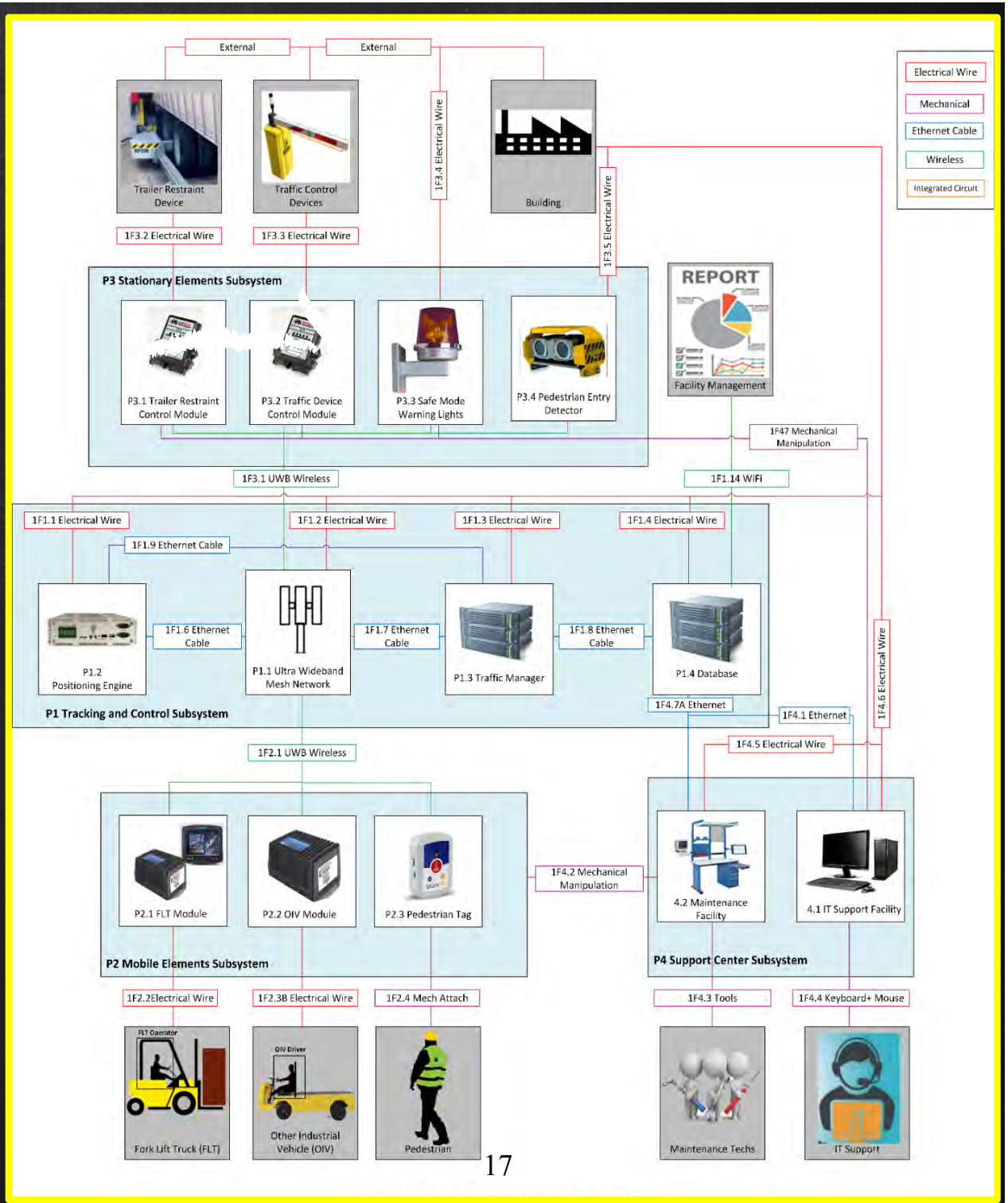

TOP LEVEL FBD
Fork Lift Truck OEMs
FLT Specifications
Fork Lift Trucks (FLTs)
Other Industrial Vehicles
Pedestrians
Stationary Warning Lights
Safe Mode Alert
Safe Mode Commands
Collision Warning Command
Collision Warning
Location Signal, Electrical Power
E-Stop Command
E-Stop Command
Electrical Power, Shelter from Weather EMF & RF Interference, Signal Attenuation, Building Layout
Trailer Restraint Devices
Device Status
Interlock Command
1.3 Supervise Trailer Entry
FLT Location
1.1 Track Locations of Vehicles & Pedestrians
No Signal
1.6 Operate in Safe Mode
Building Environment
Wireless Signal
Other Industrial Vehicle Driver
Collision Warning
Intervention Reports
Failure Report
Location of Vehicles & Pedestrians
Traffic Flow Data
Fork Lift Truck Operator
Unsafe Entry Warning
Collision Warning
1.2 Prevent Collisions
1.5 Archive Data
Maintenance Technicians
Intervention Reports
Traffic Patterns, Vehicle Data
Location of Vehicles & Pedestrians
Calibration, New Parts, Repairs/Maintenance,
Diagnostic Reports
Recommended Route
Destinations
Stationary Safety Devices
Remote Activation
Status
1.4 Reduce Congestion
Traffic Analytics Incident Reports
1.7 Facilitate Support
All Functions
Diagnostic Reports
Diagnostic Reports
Software Maintenance Upgrades
Delivery Schedule
Mechanical Control
Material Handling Operations
Highway Trucks & Trailers
Legend
Direct Interaction
Secondary Interaction
1.1 System Function
Facility Management
IT Support

INPUT FROM EXTERNAL →↓		Pedestrians ↓							OUTPUT TO EXTERNAL →	
		Other Industrial Vehicles ↓								
		Fork Lift Trucks ↓		Trailer Restraint Device ↓	Fork Lift Truck Operator ↓			Maintenance Technicians ↓		
		Location Signal, Electrical Power		Device Status	Destinations			Calibration, New Parts, Repairs, Maintenance		
Building Environment →	Electrical Power, Shelter, Interference, Signal Attenuation, Building Layout	**1.1 Track Locations of Vehicles & Pedestsrians**	Location of Vehicles & Pedestrians	Fork Lift Truck Locations	Location of Vehicles & Pedestrians	Traffic Flow Data	No Signal	Diagnostic Reports	Wireless Signal	Building Environment
			1.2 Prevent Collisions			Intervention Reports		Diagnostic Reports	Warning Command	OIVs
									E-Stop Command	FLTs
									Collision Warning	Pedestrians
									Collision Warning	FLT Operator
									Collision Warning	OIV Driver
				1.3 Supervise Trailer Entry		Intervention Reports		Diagnostic Reports	E-Stop Command	FLTs
									Entry Warning	FLT Operator
									Interlock Command	Trailer Restraint
Stationary Safety Device →	Status				**1.4 Reduce Congestion**			Diagnostic Reports	Recommended Route	FLT Operator
									Remote Activation	Stationary Safety Device
			Traffic Patterns, Vehicle Data			**1.5 Archive Data**		Diagnostic Reports	Traffic Analystics, Intervention Reports	Facility Management
							1.6 Operate in Safe Mode	Diagnostic Reports Failure Report	Safe Mode Alert	Stationary Warning Lights
									Safe Mode Command	FLTs
IT Support →	Software Maintenance, Upgrades							**1.7 Facilitate Support**	Diagnostic Reports	Maintenance Technicians
									Diagnostic Reports	IT Support

TOP LEVEL N²

Physical Concept

Top Level Physical Block Diagram



Physical Concept

P1- Tracking & Control Subsystem PBD

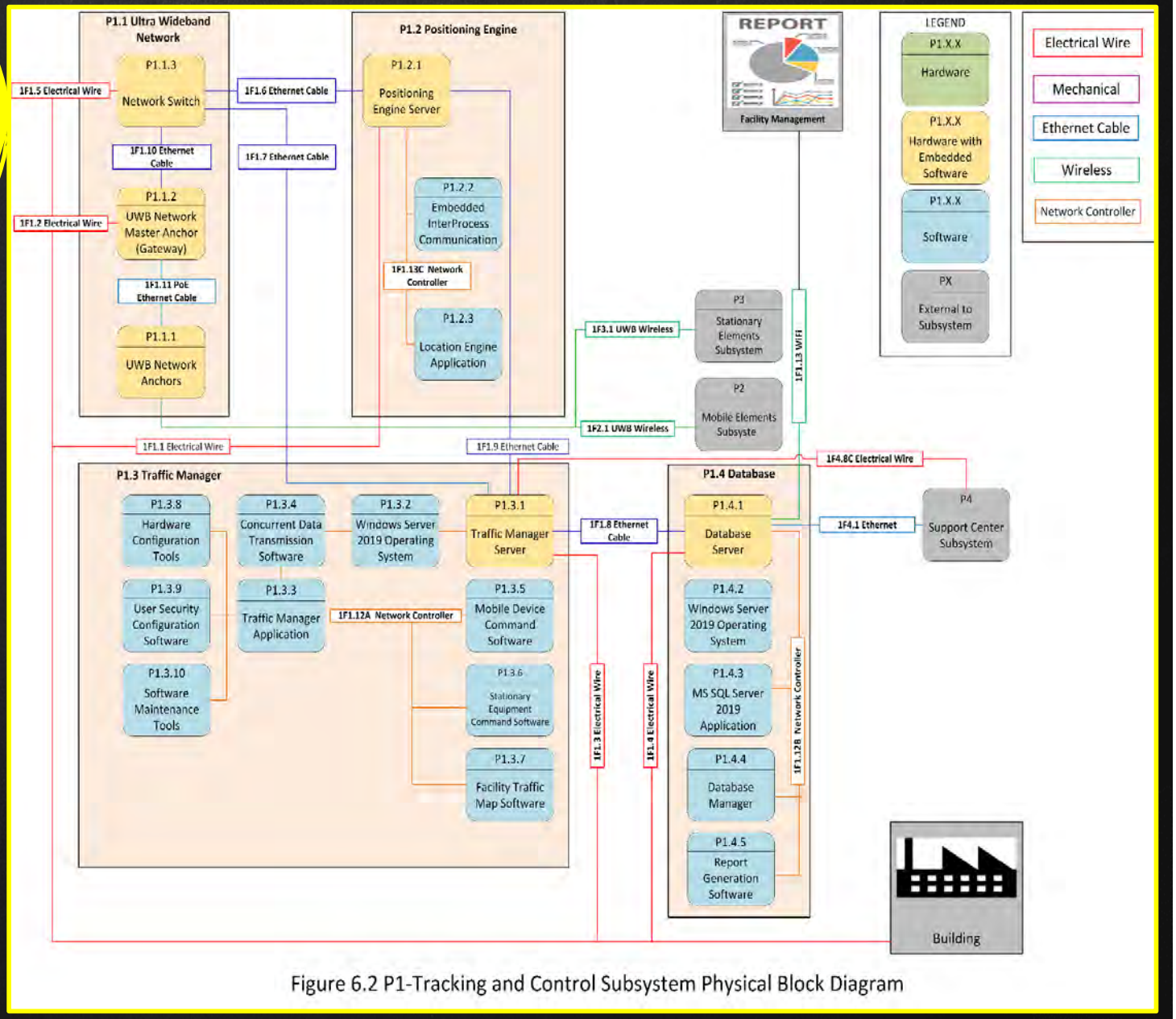


Figure 6.2 P1-Tracking and Control Subsystem Physical Block Diagram

Physical Concept

Data Flow Diagram

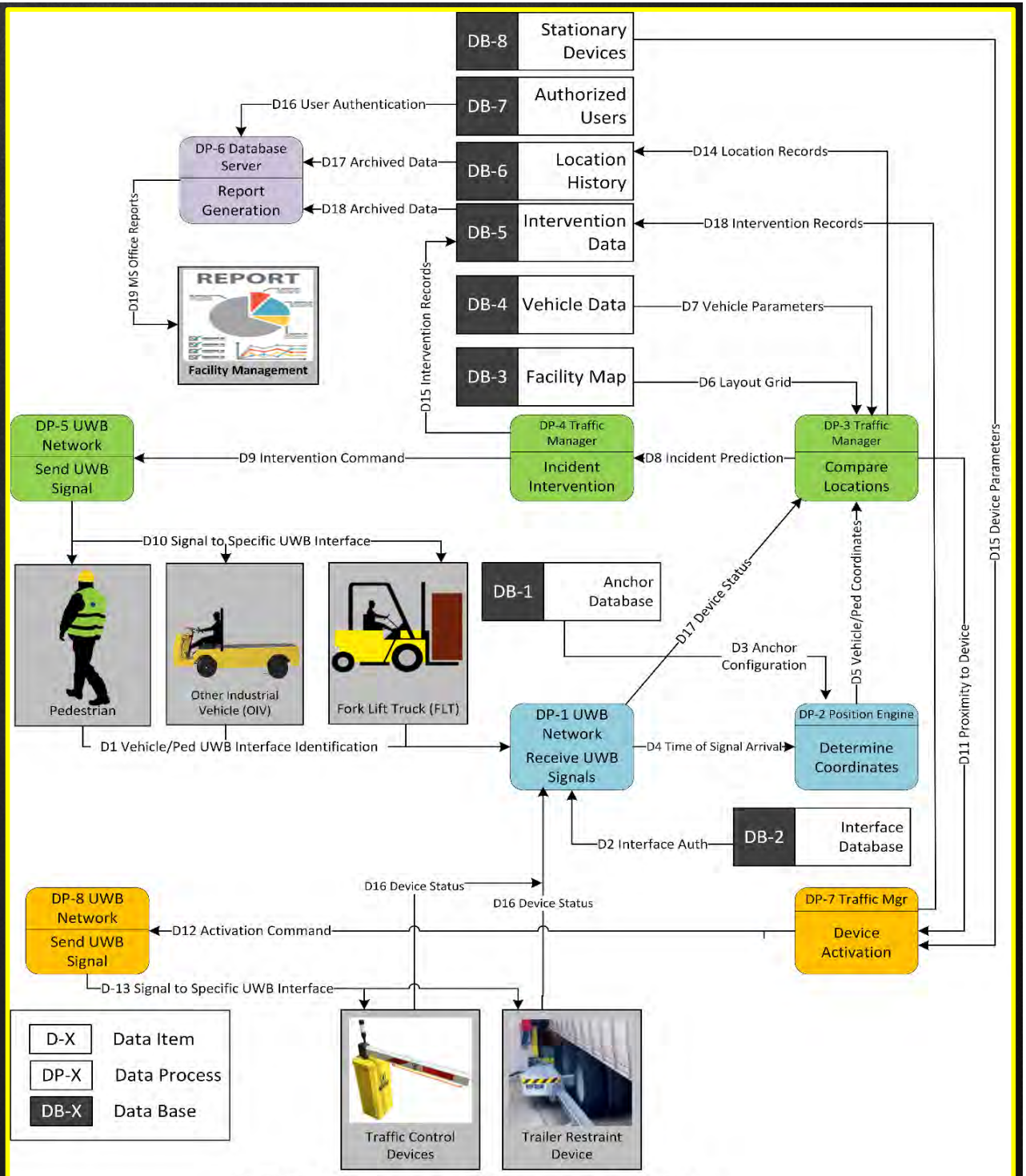


FIGURE 8-1. Top Level Software Data Flow Diagram

Physical Concept

Physical Interfaces

#	From	To	Implementation	What is Passed	Function
1F1.11	P1.1.2 UWB Network Master Anchor	P1.1.1 UWB Network Anchors	PoE Ethernet Cable	48VDC Power Vehicle & Peds Position Data	F1.1.1 Track Locations of FLTs F1.1.2 Track Locations of OIVs F1.1.3 Track Locations of Peds F1.2.3 Transmit Warning Commends to Vehicles & Peds F1.2.4 Transmit Intervention Commands to FLTs F1.3.2Transmit Warnings to FLT GUI F1.3.3 Transmit Intervention Commands to FLTs
1F1.12A	P1.3.1 Traffic Manager Server	Traffic Manager Software	Network Controller	Software Calculations	F1.2.1 Calculate Potential Travel Path
1F1.12B	P1.4.1 Database Server	Database Software	Network Controller	Software Calculations	F1.2 Prevent Collisions
1F1.12C	P1.2.1 Positioning Engine Server	P1.2.3 Location Engine Application	Network Controller	Software Calculations	F1.1.1 Track Locations of FLTs F1.1.2 Track Locations of OIVs F1.1.3 Track Locations of Peds
1F1.13	P1.4.1 Database Server	Facility Management	WiFi	Report Data	F1.5.3 Enable Retrieval of Archived Data
1F2.1A	P1.1.1 UWB Network Anchors	P2.1.1 FLT UWB Interface	UWB Wireless	Location Signals Remote Commands	F1.1.1 Track Locations of FLTs F1.2.4 Transmit Intervention Commands to FLTs F1.3.3 Transmit Intervention Commands to FLTs
1F2.1B	P1.1.1 UWB Network Anchors	P2.2.1 OIV UWB Interface	UWB Wireless	Location Signals Remote Commands	F1.1.2 Track Locations of OIVs F1.2.3 Transmit Warning Commands to Vehicles & Peds
1F2.1C	P1.1.1 UWB Network Anchors	P2.3.1 Ped UWB Interface	UWB Wireless	Location Signals Remote Commands	F1.2.3 Transmit Warnings to Vehicles & Ped
1F2.1D	P1.1.1 UWB Network Anchors	P2.1.5 FLT Graphic User Interface	UWB Wireless	Location Signals Remote Commands	F1.2.3 Transmit Warning Commends to Vehicles & Peds F1.3.2Transmit Warnings to FLT GUI
IF2.2	Fork Lift Truck	P2.1.4 Electro-Hydraulic Brake Control Mod	Electrical Wire	48V DC Electricity	F 1.2.4 Stop Imminent Collisions F1.3.3 Stop FLT Before It Enters Unsecured Trailer F1.6.2 Control FLT Operating Mode
IF2.3A	Other Industrial Vehicle	P2.2.2 OIV Remote Controller	Electrical Wire	48V DC Electricity	F1.2.3 Transmit Warning Commands to Vehicles & Peds

Physical Concept

Physical to Functional Traceability

#	LvL	Physical Heirarchy	Traceability
P0	0	SAFETY SENTINEL SYSTEM	
P1	1	Tracking and Remote Control Subystem	F1.1
P1.1	2	Ultra Wideband (UWB) Network	F1.1.1 F1.1.2 F1.1.3 F1.3.1.4 F1.3.2.1 F1.4.3.1
P1.1.1	3	UWB Network Anchors	F1.1.1.3 F1.1.2.3 F1.3.3.3
P1.1.1.1	4	UWB Transceiver	P1.1.1
P1.1.1.2	4	Embedded Firmware	P1.1.1
P1.1.1.3	4	Antenna	P1.1.1
P1.1.1.4	4	DC Power Supply Adapter	P1.1.1
P1.1.1.5	4	Ethernet Adapter	P1.1.1
P1.1.1.6	4	Housing	P1.1.1
P1.1.1.7	4	Mounting Bracket	P1.1.1

Number	Level	Function	Requirement Traceability	Physical Traceability
F1.1	1	Track Locations of Vehicles and Pedestrians	R0010 R0020	P1 P2
F1.1.1	2	Track Locations of Fork Lift Trucks	R0030 R0040	P1.1 P2.1
F1.1.1.1	3	Confirm Startup Communication	R0050	P1.3.5.3 P2.1.1.
F1.1.1.2	3	Transmit Wireless Signals from FLT	R0050	P2.1.1
F1.1.1.3	3	Receive Wireless Signals from FLT	R0050	P1.1.1 P1.1.2 P1.1.3
F1.1.1.4	3	Interpret Signal Received from FLT	R0070	P1.2 P1.3.5.2
F1.1.1.5	3	Calculate FLT and Load Location	R0071 R0100	P1.2
F1.1.1.6	3	Confirm Periodic Communication	R0090	P1.3.5.3 P2.1.1.
F1.1.1.7	4	Identify Communication Failure to FLT Operator	R0091	P1.3.5 P2.1.5

Note: combine these tables

Trade Study

- ✘ Selection of technology for tracking the locations of vehicles and pedestrians
- ✘ Significant impact on successful implementation of system

Criterion	Rationale
Accuracy	Accuracy of the tracking technology impacts the effectiveness of the system to predict and prevent collisions and perform other functions. There are no options available to compensate for inadequate accuracy.
Refresh Time (Latency)	The refresh rate impacts the ability of the system to provide real time tracking of moving vehicles and pedestrians. A long refresh time to send an update about the transitter's location limits to system's ability to track moving vehicles. Better accurancy can partially compensate for longer refresh times.
Range	Range affects the number and distribution of receivers that are required to communicate with mobile transmitters. Providing additional receivers will compensate for a limited range but will increase installation and maintenance costs.
Ped Tag Battery Time	Short operating time for pedestrian transmitters that requires changing batteries during the work shift will substantially reduce pedestrian participation in the system. Most technology options offer operating times that are at least one work shift in length. Some technologies offer much longer operating times that exceed requirements.
Ped Tag Weight	Excessive weight for pedestrian transmitters will reduce pedestrian participation. Most technologies offer options that are well below the threshold that would result in resistance by pedestrians.

Alternatives

zigbee

Wireless Sensor Network

Bluetooth®

LOW ENERGY (4.0) / SMART

ACTIVE RFID

UWB RFID

Wi Fi™

Trade Study

- ✘ Selection criteria, mapped to requirements
- ✘ Requirements were updated to align with trade study criteria
- ✘ Security protocol and scalability were not used for trade study because all alternatives had similar performance

Rev	Req ID#	Requirement Title	Requirement Text	Category	Rationale	Function Category
			Range			
R	R0010	System Coverage	The system shall track mobile equipment and pedestrians in at least 99% of the indoor areas where fork lift trucks operate at a manufacturing facility of at least 4,000,000 square feet.	Quantitative	Some small/remote areas may be excluded without significant impact on system effectiveness; largest facility size	1.1 Track Locations
N	R0021	System Coverage	The system shall enable tracking receivers to be placed at least 15 meters apart.	Quantitative	Allow placement of stationary hardware on building columns.	1.1 Track Locations
R	R0060	FLT Tracking	The system shall be capable of detecting transmissions from fork lift trucks within 15 meters or more from the receiver.	Quantitative	Provide tracking functionality for Fork Lift Trucks	1.1 Track Locations
R	R0230	OIV Tracking	The system shall be capable of detecting transmissions from other industrial vehicles within 15 meters or more from the receiver.	Quantitative	Provide tracking functionality for Other Industrial Vehicles	1.1 Track Locations
R	R0360	Pedestrian Tracking	The system shall be capable of detecting transmissions from pedestrians within 15 meters or more from the receiver.	Quantitative	Provide tracking functionality for Pedestrians.	1.1 Track Locations
R	R2300	Compatibility with Structure and Layout-1	The system shall track the locations of fork lift trucks, pedestrians and other industrial vehicles in at least 99% the facility without loss connectivity due to configuration of the facility, equipment or stored materials.	Quantitative	Prevent disruption of pedestrians' normal activities.	Constraint
			Accuracy			
R	R0100	Accuracy of Fork Lift Truck Location Tracking	The system shall calculate the location of the fork lift truck and it's load with a margin of error that does not exceed 2 meters in either x-y dimension.	Quantitative	Enable accurate prediction of collisions.	1.1 Track Locations
R	R0270	Accuracy of OIV Tracking	The system shall identify the location of other industrial vehicles with a margin of error that does not exceed 2 meters in either x-y dimension.	Quantitative	Enable accurate prediction of collisions.	1.1 Track Locations
R	R0440	Accuracy of Pedestrian Location	The system shall identify the location of pedestrians with a margin of error that does not exceed 2 meters in either x-y dimension.	Quantitative	Enable accurate prediction of collisions.	1.1 Track Locations
E	R1150	Warning of Unsecured Trailer	The system shall detect fork lift trucks approaching within 3 meters of a dock door.	Quantitative	Function required to meet user need.	1.3 Supervise Entry
E	R1160	Warning of Unsecured Trailer	The system shall verify the status of the corresponding trailer restraint when a fork lift truck is within 3 meters of a dock door.	Quantitative	Function required to meet user need.	1.3 Supervise Entry
R	R1220	Control of Trailer Restraint Disengagement	The system shall verify that a fork lift truck is not within 3 meters of a trailer before withdrawing the interlock from the corresponding trailer restraint.	Quantitative	Enable system control of trailer restraints.	1.3 Supervise Entry
R	R1250	Congestion Mapping	The system shall map the locations of vehicles and pedestrian in all areas where fork lift trucks operate with margin of error that does not exceed 2 meters.	Quantitative	To satisfy user need.	1.4 Reduce Congestion
R	R1460	Stationary Safety Device Activation	The system shall activate a stationary safety device for an approaching fork lift truck when other vehicles or pedestrians are within 3 meters.	Quantitative	Refine operation of device.	1.4 Reduce Congestion
			Refresh Time			
R	R0071	Frequency of Fork Lift Truck Location Refresh	The system shall refresh the tracking location of fork lift trucks at least every 0.1 seconds.	Quantitative	To provide required accuracy at a max travel speed of 5 m/s.	1.1 Track Locations
R	R0241	Frequency of Other Industrial Vehicle Location Refresh	The system shall refresh the tracking location of other industrial vehicles at least every 0.1 seconds.	Quantitative	Based on max speed of 5 m/s and the refresh rate.	1.1 Track Locations
R	R0371	Frequency of Pedestrian Location Refresh	The system shall refresh the tracking locations of pedestrians at least every 0.1 seconds.	Quantitative	To provide required of location accuracy at a max walking speed of 1.4 m/s.	1.1 Track Locations
R	R0570	Accuracy of Fork Lift Truck Speed Calculation	The system shall calculate the speed of the fork lift truck with a margin of error that does not exceed 10% at a speed of 5 m/s.	Quantitative	Based on max speed of 5 m/s and the refresh rate.	1.2 Prevent Collision
R	R0580	Accuracy of Other Industrial Vehicles Speed Calculation	The system shall calculate the speed of other industrial vehicles with a margin of error that does not exceed 10% at a speed of 5 m/s.	Quantitative	Based on max speed of 5 m/s and refresh rate.	1.2 Prevent Collision
R	R0590	Accuracy of Pedestrian Speed Calculation	The system shall calculate the speed of pedestrians with a margin of error that does not exceed 30% at a speed of 1.4 m/s.	Quantitative	Based on max speed of 1.4m/s and the location refresh rate.	1.2 Prevent Collision
R	R1450	Stationary Safety Device Activation	The system shall identify FLTs approaching stationary traffic safety devices at least 10 seconds in advance of their arrival at the device location.	Quantitative	To enable user need	1.4 Reduce Congestion
			Transmitter Power Requirements			
R	R0470	Pedestrian Tracking Time	The system shall track the locations of pedestrians for at least 4 hours without connection to the power grid.	Quantitative	Prevent disruption due to industrial vehicle down-time for charging.	1.1 Track Locations
E	R2310	Fork Truck Electrical Requirements	The system shall not reduce the operating time of a fully-charged electrical fork lift truck by more than 3 percent to supply its power requirements.	Quantitative	Prevent disruption due to fork lift truck down-time for charging.	Constraint
E	R2320	Other Industrial Vehicle Electrical Requirements	The system shall not reduce the operating time of a fully-charged industrial vehicle by more than 3 percent to supply its power requirement.	Quantitative	Prevent disruption due to fork lift truck down-time for charging.	Constraint
			Pedestrian Tag Weight			
E	R2280	Minimum Impact on Production Ops	The system shall track pedestrians using a method that does not reduce their mobility.	Qualitative	User need.	Constraint
R	R2250	Pedestrian Burden	Equipment worn by pedestrians to transmit their location shall not exceed 300 grams in weight.	Quantitative	Prevent disruption of pedestrians' normal activities.	Constraint
			Security Protocol			
E	R2140	System Access	The system shall restrict access to authorized users.	Binary	Prevent unauthorized access.	1.7 Facilitate Support
E	R2180	External Access to System	They system shall require authorized users to log-in using a 2-factor authentication protocol.	Binary	Prevent unauthorized access.	1.7 Facilitate Support
E	R2190	External Access to System	The system shall prevent access without credentials.	Binary	Prevent unauthorized access.	1.7 Facilitate Support
E	R2240	System Security-Wireless	The system shall incorporate conform to IEEE 8-2.1X to prevent access to wireless network components by unauthorized users.	Quantitative	Prevent unauthorized access.	Constraint
			Multiple Users			
E	R0040	Track Fork Truck Locations	The system shall be capable of simultaneously tracking the locations of at least 150 fork lift trucks at a manufacturing or warehouse facility.	Quantitative	Expected maximum utilization at large manufacturing plant.	1.1 Track Locations
E	R0210	Track Other Industrial Vehicle Locations	The system shall be capable of simultaneously tracking the locations of at least 100 other industrial vehicles at a manufacturing or warehouse facility.	Quantitative	Expected maximum utilization at large manufacturing plant.	1.1 Track Locations
E	R0340	Track Pedestrian Locations	The system shall be capable of simultaneously tracking the locations of at least 2500 pedestrians at a manufacturing or warehouse facility.	Quantitative	Expected maximum population at large manufacturing plant.	1.1 Track Locations

Revision: N= New E = Existing R= Revision (Revisions shown in red type.)

Trade Study

Weighting Criteria Matrix

Rank	Criterion	Importance of Accuracy Relative to Criterion	Rationale
1	Accuracy	1	Accuracy of the tracking technology impacts the effectiveness of the system to predict and prevent collisions and perform other functions. There are no options available to compensate for inadequate accuracy.
2	Refresh Time (Latency)	1.5X	The refresh rate impacts the ability of the system to provide real time tracking of moving vehicles and pedestrians. A long refresh time to send an update about the transitter's location limits to system's ability to track moving vehicles. Better accurancy can partially compensate for longer refresh times.
3	Range	3X	Range affects the number and distribution of receivers that are required to communicate with mobile transmitters. Providing additional receivers will compensate for a limited range but will increase installation and maintenance costs.
4	Ped Tag Battery Time	6X	Short operating time for pedestrian transmitters that requires changing batteries during the work shift will substantially reduce pedestrian participation in the system. Most technology options offer operating times that are at least one work shift in length. Some technologies offer much longer operating times that exceed requirements.
5	Ped Tag Weight	9X	Excessive weight for pedestrian transmitters will reduce pedestrian participation. Most technologies offer options that are well below the threshold that would result in resistance by pedestrians.

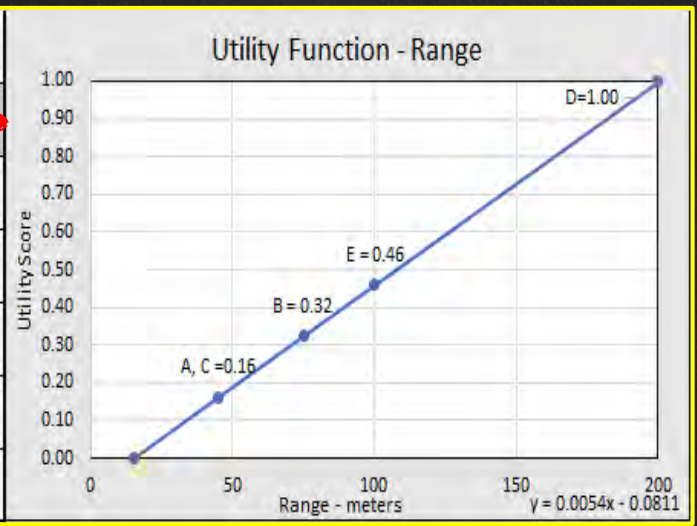
Nth Root Pair Wise Waiting

Criteria		Range	Accuracy	Refresh Rate	Tag Weight	Tag Time	Row Products	Nth Root	Normalized Weighting Factor
		A	B	C	D	E			
Range	A	**1.00**	0.33	0.50	3	2	1.00	1.00	0.15
Accuracy	B	3.00	**1.00**	1.5	9	6	243.24	3.00	0.44
Refresh Rate	C	2.00	0.67	**1.00**	6	4	32.00	2.00	0.29
Tag Weight	D	0.33	0.11	0.17	**1.00**	0.67	0.004	0.33	0.05
Tag Time	E	0.50	0.17	0.25	1.50	**1.00**	0.03	0.50	0.07
								6.83	1.00

Trade Study

Utility Curves for Each Criteria

Alt	Range (m)	Utility Score
Min	15	0.00
A	45	0.16
B	75	0.32
C	45	0.16
D	200	1.00
E	100	0.46



Raw Utility Scores

Alternative		Range	Accuracy	Refresh Rate	Tag Battery	Tag Weight
A	Wireless Sensor Network	0.16	0.57	0.94	0.11	0.88
B	Bluetooth Low Energy (BLE)	0.32	0.10	0.67	1.00	0.71
C	Active RFID	0.16	0.86	0.11	0.22	0.08
D	Ultra Wideband (UWB)	1.00	1.00	1.00	1.00	0.99
E	Wifi (WLAN) 2.4 GHz	0.46	0.10	0.83	1.00	1.00

Trade Study

Final Selection → Ultra Wideband RFID

Criteria		Range	Accuracy	Refresh Rate	Tag Battery	Tag Weight	*Calculations*				
Weights		0.15	0.44	0.29	0.05	0.07					
Alternatives		Utility Scores					Weighted Sum	Normalized	Cost Est.	Cost-Benefit	Normalized
A	Wireless Sensor Network	0.16	0.57	0.94	0.11	0.88	0.62	0.21	$212,500	0.99	0.20
B	Bluetooth Low Energy (BLE)	0.32	0.10	0.67	1.00	0.71	0.39	0.13	$285,000	0.46	0.09
C	Active RFID	0.16	0.86	0.11	0.22	0.08	0.45	0.15	$523,188	0.29	0.06
D	Ultra Wideband (UWB)	1.00	1.00	1.00	1.00	0.99	1.00	0.34	$121,000	2.81	0.56
E	Wifi (WLAN) 2.4 GHz	0.46	0.10	0.83	1.00	1.00	0.48	0.16	$357,500	0.45	0.09

- ✘ Best utility scores for all criteria
- ✘ Highest cost-benefit score overall
- ✘ Sensitivity analysis confirmed selection

Requirements Summary

Project Stage	Total	Quantitative	%	Binary	Qualitative
Requirements Analysis Report	154	55	36	57	37
Functional Analysis	218	61	28	114	43
Trade Study Report	219	78	36	108	42
Conceptual Design	224	92	41	102	30
System Specifications	223	179	80	44	0
Risk Management Plan	223	179	80	44	0
Test Plan	223	180	80	44	0
FINAL	223	180	80	44	0

Key Performance Parameters

Req ID#	Requirement Title	Requirement Text	Threshold	Objective
A0100	Operator Collision Warning	The system shall warn fork lift truck operators at least 3 seconds in advance of a predicted collision with another industrial vehicle.	Warn operator at least 3 seconds in advance of ≥ 99% of potential collisions	Warn operator at least 3 seconds in advance of 100% of potential collisions
A0150	Autonomous Collision Prevention	The system shall autonomously stop a fork lift truck in time to maintain an open space of 0.5 meters or more between the vehicle and a pedestrian when it predicts that a collision is imminent.	≥99% of all avoidable collisions* prevented	100% of all avoidable collisions* prevented
A0200	Prevention of Entry into Unsecured Trailers	The system shall autonomously stop fork lift trucks when they approach within one meter (+/- 0.1 m) of the dock door to a trailer that is not secured against unintentional movement away from the loading dock	≥99% of fork lift trucks prevented from entering unsecured trailers.	100% of fork lift trucks prevented from entering unsecured trailers
A0250	Stationary Safety Device Activation	The system shall enable the remote activation and deactivation of COTS stationary traffic safety devices when fork lift trucks approach within 10 meters (+/- 0. 1m) of the device.	Activate stationary traffic safety control devices for ≥ 99% of approaching FLTs.	Activate stationary traffic control devices for 100% of approaching FLTs.

* Collisions are considered avoidable when the available stopping distance equals or exceeds the minimum safe stopping distance.

Risk Summary

RISK ID	IDENTIFIED BY	TYPE	RISK NAME	RISK DESCRIPTION	CONSEQUENCE IF REALIZED	INITIAL LIKELIHOOD	INITIAL CONSEQUENCE	RISK MITIGATION STRATEGY	FINAL LIKELIHOOD	FINAL CONSEQUENCE
R-1	Proposal	Technical	Loss of Tracking and Remote Control Subsystem Functionality	The system stops functioning while fork lift trucks, pedestrians, and other industrial vehicles are in operation	Complete loss of functions based on position tracking; lack of functionality will be unrecognized by building occupants	4	5	1. Provide safe mode operation triggered by lack of communication from the system. 2. Provide protection from power surges and power interuption. 3. Test system operation.	2	2
R-2	Proposal	Technical	Failure of Mobile Element Communication	Loss of individual vehicle or pedestrian communication interface.	Limited loss of functions based on position tracking; lack of functionality will be unrecognized by user	4	4	1. Provide safe mode operation. 2. Test components for reliability.	2	2
R-3	Proposal	Technical	Communication Signals Blocked	Signals to/from the Tracking and Remote Control Subsystem are blocked by building structures or stored materials	Locations of fork lift trucks, pedestrians or other industrial vehicles will be temporarily unknown to the system	4	3	1. Select technology with low attenuation factor during Trade Study 2. Conduct system testing at launch to confirm connectivity.	1	3
R-4	Proposal	Technical	Pedestrian Enters Work Area Without Transmitter	A pedestrian enters the facility without a function transmitter to identify their location.	The pedestrian cannot be tracked by the Safety Sentinel System and is at greater risk of being involved in an accident with vehicles	4	3	1. Place pedestrian detectors at entry points. 2. Require pedestrians to wear high visibility vests with UWB tags.	1	2
R-5	Proposal	Technical	Fork Lift Trucks are Not Compatible with Remote Control Module	The remote control module cannot be integrated into a fork lift truck that is a older model or non-standard design.	The system cannot remotely activate fork lift truck systems to prevent a collision.	3	4	1. Select compatible technology during Trade Study. 2. Limit speed and uses of incompatible fork lift trucks.	2	3
R-6	Proposal	Technical	Inadequate Tracking Resolution	The tracking system cannot track the locations of vehicles or pedestrians with sufficient accuracy.	The system cannot provide successful interventions to prevent collisions with the required success rate (≥99%)	3	5	1. Use trade studies and systems engineering methods to maximize system capabilities. 2. Specify buffer distance to provide safety margin.	1	3
R-7	Functional Analysis Report	Technical	Inadequate Simultaneous Tracking Capabililties	The tracking system cannot track all vehicles and pedestrians simultaneously in a high density area.	The system cannot provide successful interventions to prevent collisions (system failure).	4	4	1. Use trade studies and systems engineering methods to maximize system capabilities. 2. Increase density of tracking equipment to provide adequate peak capacity. 3. Test to verify capability.	1	4
R-8	Functional Analysis Report	Technical	Inability to Prevent Collisions	The system cannot identify collisions with adequate advance time.	The system is unable to make a successful intervention to prevent the collision.	3	4	1. Use trade studies and systems engineering methods to maximize system capabilities. 2. Conduct system testing to optimize system performance.	1	4

Risk Example

Risk Title: Loss of Tracking and Remote Control System Functionality

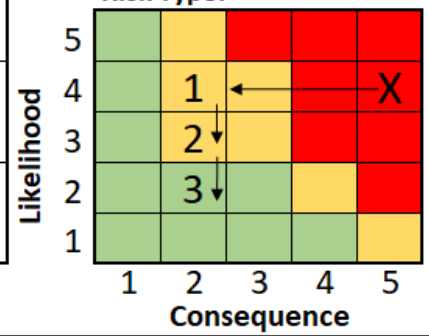
Risk #: 1

Risk Type: Technical

Description of Risk:
The system stops functioning while fork lift trucks, pedestrians and other industrial vehicles are in operation.

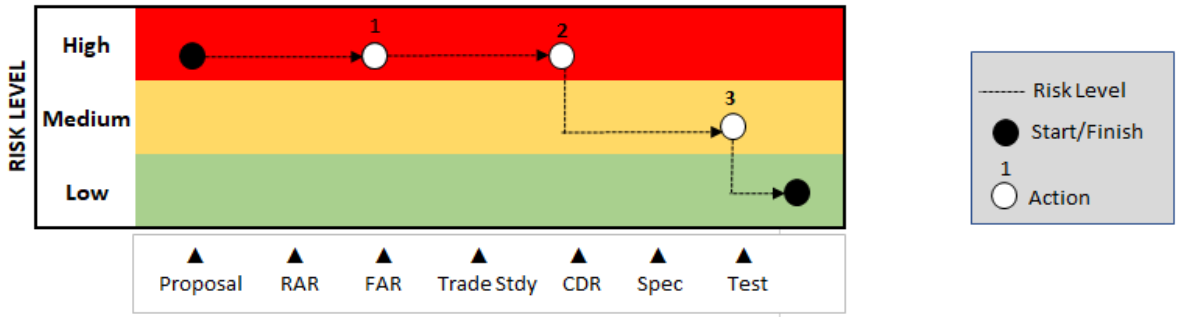
Cause:
Failure of wireless network or Traffic Manager hardware.

Consequence if Realized:
Complete loss of functions dependent on position tracking; lack of functionality will re unrecognized by building occupants.



RISK REDUCTION PLAN

Mitigation Action	Success Criteria	Risk Level if Successful	
		Likelihood	Consequence
1. Provide safe mode operation	Safe mode operation is activated autonomously by mobile and stationary elements when loss of communication is detected.	4	2
2. Provide protection from power surges and loss of grid power.	Spike-free, power supply to Traffic Manager and Wireless Network maintained without interuption.	3	2
3. Test Safety Sentinel System.	Operation of System Sentinel System meets required specification for reliability and availability.	2	2



Comments:
A safe mode operation that allows manufacturing processes to continue in the event of a system failure provides significant reduction of risk by reducing the consequences of system down time. Providing a stable power supply will reduce the likelihood of loss of system functions due to component failures or unexpected system shutdown. Verifying that the Tracking and Remove Control System meets requirements for availability and reliability provides further reduction in the likelihood of a system failure. Together these measures will mitigate the risk to an acceptable level upon completion of the test and verification plan.

Figure 2-1: Risk Management Plan No.1

Final Concept

- ✘ Lots of changes to requirements during project development
- ✘ Final concept enhanced, but still similar to proposal
  - Added safe mode to prevent disruption to production operations
- ✘ Successful implementation of the system will reduce workplace injuries

Further Work

- Successful implementation of the system is highly dependent on development of traffic management software
  - Track simultaneously
  - Predict collisions
  - Make successful interventions
- Need a IT team for software development and architecture
- Further engineering review is needed to validate the quantitative requirements and their aggregate effects
- Cost and complexity may be barriers to customer acceptance
- Pilot project highly recommended

Lessons Learned

- Maintaining traceability was a challenge
- Did not use CORE due to:
  - Perceived learning curve
  - Reduced flexibility in formatting diagrams
- Development of the project was highly iterative
- Version control was important
  - Once change caused a cascade of other changes
  - Would have been unmanageable as a group project without a formal process
- Project may have been too complex - would focus on core capabilities
  - Real time location tracking
  - Collision prevention

Recommendations

- ✘ Liked “applied” approach to program
- ✘ Liked mentor process for final project
- ✘ Recommend breaking up group projects into multiple assignments (some classes already do this)
- ✘ Recommend adding more (but not too much) “systems thinking” topics that go beyond project development
- ✘ More case studies outside of military applications
- ✘ Anything but Adobe Connect….

Thanks!

Questions?

ghought2@ford.com