ANALYSIS OF INFRASTRUCTURE NEEDED TO TEST PRE-CRASH SCENARIOS

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1. INTRODUCTION

The objective of this task is to design a testing facility to be able to simulate real-life crash scenarios. A 44-crashes typology was developed by General Motors. This typology can be described in detail over 37 different scenarios under the Pre-Crash Scenario Typology for Crash Avoidance Research report (1). The main goal of this work is to summarize these crash scenarios and design a physical road testing facility where all crash conflicts can be simulated using autonomous vehicles.

The tasks to be performed during the period of this project are summarized in Table 1.

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Collect information on different crash scenarios to determine the number of intersections needed. Collect information for typical intersection geometric design and specs from ADOT/City</td>
</tr>
<tr>
<td>2</td>
<td>Analyze infrastructure needed / test facility layout (roads, intersections, acreage)</td>
</tr>
<tr>
<td>3</td>
<td>Pavement structure design</td>
</tr>
<tr>
<td>4</td>
<td>Cost estimates to build infrastructure</td>
</tr>
</tbody>
</table>

Project Milestones and Deliverables (expected start date: May 15th, 2018)

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Timeline</th>
<th>Deliverable</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>2 months</td>
<td>Present the layout for test facility (ID1&amp;2)</td>
</tr>
<tr>
<td>M2</td>
<td>3 months</td>
<td>Provide a cost estimate to build the facility with final layout design (ID3&amp;4)</td>
</tr>
</tbody>
</table>
2. LITERATURE REVIEW

2.1 Crash Scenarios

The National Highway Traffic Safety Administration published in April 2007 a report named “Pre-Crash Scenario Typology for Crash Avoidance Research”. This report was based on the 2004 General Estimates Systems crash database statistics. The report describes the different typology of pre-crash scenarios and the critical events prior to a crash. There are more than 40 pre-crash scenarios that can be compressed into 36 as shown in Table 3. A more detailed description of the pre-crash scenarios typology can be found in Appendix A.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vehicle Failure</td>
</tr>
<tr>
<td>2</td>
<td>Control loss with prior vehicle action</td>
</tr>
<tr>
<td>3</td>
<td>Control loss without prior vehicle action</td>
</tr>
<tr>
<td>4</td>
<td>Running red light</td>
</tr>
<tr>
<td>5</td>
<td>Running stop light</td>
</tr>
<tr>
<td>6</td>
<td>Road edge departure with prior vehicle maneuver</td>
</tr>
<tr>
<td>7</td>
<td>Road edge departure without prior vehicle maneuver</td>
</tr>
<tr>
<td>8</td>
<td>Road edge departure while backing up</td>
</tr>
<tr>
<td>9</td>
<td>Animal crash with prior maneuver</td>
</tr>
<tr>
<td>10</td>
<td>Animal crash without prior vehicle maneuver</td>
</tr>
<tr>
<td>11</td>
<td>Pedestrian crash with prior vehicle maneuver</td>
</tr>
<tr>
<td>12</td>
<td>Pedestrian crash without prior vehicle maneuver</td>
</tr>
<tr>
<td>13</td>
<td>Pedalcyclist crash with prior vehicle maneuver</td>
</tr>
<tr>
<td>14</td>
<td>Pedalcyclist crash without prior vehicle maneuver</td>
</tr>
<tr>
<td>15</td>
<td>Backing up into another vehicle</td>
</tr>
<tr>
<td>16</td>
<td>Vehicle turning – same direction</td>
</tr>
<tr>
<td>17</td>
<td>Vehicle parking – same direction</td>
</tr>
<tr>
<td>18</td>
<td>Vehicle changing lanes – same direction</td>
</tr>
<tr>
<td>19</td>
<td>Vehicle drifting – same direction</td>
</tr>
</tbody>
</table>
2.2 Existing Track Facilities

Ohio’s TRC
The project comes from a $45 million grant from Ohio State University, Ohio state funds and Jobs Ohio. Their proving grounds are designed for safety, energy, fuel economy, emissions, durability, noise, crash, crash simulation, performance and more. Vehicle type test include trucks, buses, recreational vehicles, motorcycles, electric vehicles, passenger cars and components. They also test road surfaces. They have private workrooms and garage spaces for rent.

What they do:
- R&D
- Compliance and certification testing
- Crash avoidance and crashworthiness testing
- Emissions testing,
- Dynamic and durability testing
- Safety

Partners:
- Ohio State University
- PMG Technologies Inc.
- Ohio State
- Jobs Ohio

Figure 1. Ohio TRC’s Test Track.

Thomas D. Larson Pennsylvania Transportation Institute
The institute was awarded a UTC grant for $14.17 million and matched funds from non-federal funds (State DOTs from participating universities), and industry partners that total $28.4 million. Penn State will work to improve the durability and extend the life of transportation infrastructure. Consortium will seek to collaborate with materials suppliers, contractors, railroad companies, technical societies and other transportation agencies.
Partners/Consortium
- Penn State
- George Mason University
- Lehigh University
- Morgan State University
- University of Delaware
- Virginia Tech University
- West Virginia University

Figure 2. Pennsylvania Transportation Institute Test Track.

Texas AV Proving Grounds Partnerships
Members of the partnership are contributing by providing their facilities and expertise. Texas A&M RELLIS Campus- Proving Grounds. The Texas A&M Transportation Institute (TTI) conducts about 600 research projects annually with over 200 public and private sponsors. The University of Texas at Austin (CTR, Austin) has an annual budget of $13 million. The Southwest Research Institute (SwRI) has a 1200-acre campus with a 1.2-mile track; the campus also has gravel and dirt roads.

Partners
- Texas A&M Transportation Institute (TTI)
- University of Texas (CTR)
- Southwest Research Institute (SwRI)
- Cities (Austin, Houston, Dallas/Fort Worth/Arlington, San Antonio, El Paso, Corpus Christi, Bryan/College Station))
- Prairie View A&M University
American Center for Mobility-Willow Run
The American Center for Mobility (ACM) intends to be a facility focused on testing, verification and self-certification of connected and automated vehicles and other mobility technologies. The site at Willow Run consists of a 500-acre facility. It will have the capability to test vehicles, roads, infrastructure and communication systems. The facility already includes double overpasses, railroad crossing, and a highway loop for high-speed testing. This facility will allow companies to lease space for office and research use, garages, and other amenities.

Partners/Sponsors
- Toyota Motor North America, $5 million
- Ford Motor Company, $5 million
- Hyundai America technical Center Inc., $5 million
- Siemens, $1 million
- Michigan State collaboration with Texas A&M
- IEEE
- Michigan DOT
- Michigan Economic Development Corporation
- Business Leaders from Michigan and Ann Arbor SPARK

Figure 3. Layout Plan for the Texas AV Proving Grounds.
Figure 4. American Center for Mobility – Willow Run Facility.

*Contra Costa Transportation Authority & GoMentum Station*
This is so far the largest secure testing facility for autonomous vehicles and connected vehicle technology. It is a 5000-acre facility with 20 miles of paved roadways and built in a public/private partnership model. Current research includes private, shared, and commercial vehicles, in a multimodal environment.

Partners/Sponsors
- Contra Costa Transportation Authority
- Sumitomo Electric
- Lyft
- Uber Advanced Technology Group
- EasyMile Shuttles
- Honda Research Institute
- Stantec
- City of Concord
- BestMile
- TriDelta Transit
- Bishop Ranch
- Bay Area Rapid Transit District
- Bay Area Air Quality Management District
- ITS America
- ITS Australia
- ITS California
• Ministry of Transport, Singapore
• ITS New Zealand
• Canadian Automated Vehicle Center of Excellence
• Tongji University
• California Polytechnic State university

Figure 5. GoMentum Test Track Facility.

San Diego Regional Proving Ground
The San Diego Regional Proving Ground is one of the ten AV proving ground sites in the US. Three testing locations: I-15 Express Lanes, Southern segment of the South Bay Expressway, and local streets and roads in Chula Vista. Current areas of focus include: autonomous vehicles, public outreach and education, mobility hubs, cybersecurity, smart cities, and smart transportation.

Partners
• SANDAG
• City of Chula Vista
• Caltrans District 11
Figure 6. San Diego Regional Proving Ground Sections.

HORIBA MIRA Ltd-UK
HORIBA MIRA Technology Park is located in the United Kingdom. The facility sits on 840 acres estate with 2.0 million sq. ft. available space. It has over 100 km of test tracks. This makes MIRA Technology Park the largest testing facility in Europe. Some of the other characteristics from this facility are outlined as follows:

- Close to the automotive OEMs and surrounded by supply chain companies based on the Midlands Region.
- R&D facilities and 38 major laboratory facilities that include: crash, impact simulation, pedestrian, full scale aerodynamic wind tunnel; vehicle and component environmental facilities.
- Offers over a quarter of a million sq. ft. of lease space including 63 workshops, and 16 office suites.
- Access to skilled labor. Given the location, high technical labor force is concentrated in the area.
- Support team to aid in setting up operations.
- Test tracks available 24 hours per day.

**Figure 7. MIRA Technology Park.**

**MCity**
The MCity test facility sits on a 32-acre site on the University of Michigan North Campus, with 16 acres of road and traffic infrastructure. MCity’s partners include industry, government and academia with the idea of collaborating together for mutual benefits. MCity was the first testing facility build specifically for connected and automated vehicles and other technologies in a simulated urban environment. The test facility has five lane-miles of roads, signalized intersections, sidewalks, and other features to simulate typical urban settings. Some other features include:

- Different road surfaces
- Different road configurations
- Variety of traffic control devices
- Fixed or movable buildings
- Limited and control access to the facility
- Pedestrian avoidance set up
- A unique tunnel that blocks vehicles from wireless and satellite signals

Some partnerships/collaboration include:
• APTIV
• DENSO
• ECONOLITE
• Ford
• GM
• Honda
• Intel
• LG
• Toyota
• Verizon
• 3M
• The Goodyear Tire & Rubber Company

Figure 8. Mcity Test Facility.
U.S. Army Aberdeen Test Center
The U.S. Army Aberdeen Test Center was one of the designated proving ground pilot sites for the testing of automated vehicles by the U.S. Department of Transportation, Figure 9. The facility is designed for use in tests of wheeled and tracked vehicles, including vehicular weapon systems. Some of the characteristics of the test tracks are as follows:

- 3.6 miles of hilly cross-country course
- 1.5 miles of hilly secondary road
- 40 miles of automotive test courses on more than 3300 acres of land

Figure 9. U.S. Army Aberdeen Test Center.

Iowa City Area Development Group
Iowa City passed a proclamation allowing for open road testing for autonomous vehicles in local streets, freeways and highways. Besides the use of open roads, they are home to the National Advanced Driving Simulator at the University of Iowa. Some of the key features of what this initiative offers are as follows:

- Virtual testing at the University
- Access to open roads throughout Johnson County
- Access to closed course testing
- Research collaboration with the University of Iowa
Wisconsin Automated Vehicle Proving Grounds
The Wisconsin AV Proving Grounds’ mission is “to provide a path to public road evaluation by contributing to the safe and rapid advancement of automated vehicle development and deployment, and providing a full suite of test environments, coupled with research, open data, and stakeholder communication.” Some of the features for this initiative are as follows:

- Provide the vehicles with high quality description of the roadway.
- Research to determine best practices and safety on automated commercial trucks on public roads
- Protect identity from autonomous vehicles and provide data security
- Study interactions between autonomous vehicles and humans
- Test and validate autonomous vehicle systems

Proving ground facilities include:

- Private proving grounds
- Race tracks
- City of Madison
- Automotive proving ground facility owned by MGA Research Corporation

Central Florida Automated Vehicle Partners
In 2016 a bill was passed which cleared the way for all forms of autonomous vehicle testing. The research will be conducted in some areas around the University of Central Florida and Florida Polytechnic University, the roadway network and swamp works lab at NASA’s Kennedy Space Center, the downtown of City of Orlando, interstates, expressways, and SunTrax. Some of the partners for this initiative are:

- Florida Turnpike Enterprise
- Florida Department of Transportation District Five and District One
- Florida Polytechnic University
- Florida Agricultural Mechanical University – Florida State University College of Engineering (FAMU-FSU)
- Lynx
- City of Orlando
- University of Central Florida
- Central Florida Expressway
- NASA – Kennedy Space Center
**Arizona Existing Test Tracks**

There are some existing test tracks in Arizona. Usually, these test tracks have limited access due to confidential research done by automobile manufacturers. Figure 10 to Figure 13 show the locations of these tracks with some descriptive information.

**Figure 10. Toyota Arizona Proving Ground.**

- 12,000-acre facility
- 10-mile oval track

**Figure 11. Chrysler Proving Ground Arizona.**

- 3836-acre facility
- 4-mile oval track
- 1.7-mile oval track
- Built intersections
Figure 12. Yucca Chrysler Proving Ground.

- 3840-acre facility
- 5-mile oval track
- Wet traction surfaces
- Variety of concrete test surfaces
- Water ingestion test area
- Low friction facility

Figure 13. Ford/Volvo Proving Ground.

- 1498-acre facility
- 2-mile oval track with banked curves
- 2-mile straight road
The City of Gilbert will vote for $84 million to build a public safety training facility for police and fire department. The facility is planned in a 32 acre property next to the ASU Polytechnic Campus. This facility includes a 6/10 of a mile test track for accident avoidance training and pit maneuver zone. Figure 14 shows the location and layout of the facility.

Figure 14. City of Gilbert Public Safety Training Facility.
3. TEST FACILITY OPTIONS

The feasibility analysis was carried out in different locations around the City of Phoenix Metro Area. This section only presents the two most feasible options: 1) Arizona State University at the Polytechnic Campus, and 2) The Exponent Test Facility. The other alternatives are included in Appendix B.

3.1 Arizona State University – Polytech Campus

One of the proposed locations for building the test track is at the Arizona State University – Polytechnic Campus located in Mesa, Arizona. This proposed alternative consists of two phases: Phase 1 which includes the use of existing road infrastructure from South Desert Village and the reconstruction of existing “internal” ASU roads, and Phase 2 which includes the construction of a higher speed loop with different intersection configurations. The layout plan for this alternative is shown in Figure 14.

Figure 15. ASU Polytechnic - Possible Test Track Surface Areas. Shown land location is for illustration purposes only and does not represent the actual location of the test track.
Phase 1
The proposed infrastructure is a combination of existing roadways and the construction of new roads. There are approximately 0.9 miles of existing roadways that can be used for pre-crash scenario testing. Some of that existing infrastructure needs to be rehabilitated or fully reconstructed. It is proposed to re-build 0.3 mile of a new arterial road, and 0.2 mile of a new collector road, as well as the rehabilitation of about 0.3 mile of existing pavement. These approximate estimates are shown in Table 4.

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Lanes</th>
<th>Lane Width (ft)</th>
<th>Length (mi.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Arterial</td>
<td>3</td>
<td>12</td>
<td>0.3</td>
</tr>
<tr>
<td>Minor Collector</td>
<td>2</td>
<td>12</td>
<td>0.4</td>
</tr>
<tr>
<td>Rehabilitation</td>
<td>2</td>
<td>12</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Figure 15 shows the location of South Desert Village and existing infrastructure. The road on the north side of this location and shown in Figure 15 (a) is proposed to have a full reconstruction to make a minor collector with 2 lanes. The road shown in Figure 15 (b) will be a 3-lane minor arterial.

Figure 16 to Figure 18 show examples of possible existing condition and future reconstruction of existing roads, and the construction of a new minor collector to intersect with these two existing roads.
Figure 17. Phase 1 Minor Arterial before and after Reconstruction. Shown land location is for illustration purposes only and does not represent the actual location of the test track.

Figure 18. Phase 1 Minor Collector before and after Reconstruction. Shown land location is for illustration purposes only and does not represent the actual location of the test track.
Phase 1 also includes about 4 miles of local/residential roads existing in South Desert Village. These roads can be used to simulate scenarios, with pedestrians and low speed. Figure 19 shows the existing infrastructure of South Desert Village.

**Phase 2**

The proposed track is located in a 104-acre lot south from South Desert Village. Figure 20 shows the location and existing infrastructure. The test track proposed for Phase 2 consists of a 1.4 miles loop to be constructed as a four 12-ft. lane arterial road, and 0.9 miles of three 12-ft. lane
collectors that intersect different locations on the loop. These approximate quantities are summarized in Table 5.

![Figure 21. Phase 2 Area and Existing Ground Condition. Shown land location is for illustration purposes only and does not represent the actual location of the test track.](image)

Table 5. Estimated Quantities for Phase 2.

<table>
<thead>
<tr>
<th>Phase 2</th>
<th>Lanes</th>
<th>Lane Width (ft)</th>
<th>Length (mi.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arterial Loop</td>
<td>4</td>
<td>12</td>
<td>1.4</td>
</tr>
<tr>
<td>Minor Collector</td>
<td>3</td>
<td>12</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Additionally, the proposed test track has 11 potential intersections that can be configured in different ways to simulate a wider variety of pre-crash scenarios. It also includes a 4-arm roundabout to simulate merge traffic scenarios. A preliminary design of this test track can be seen in Figure 20.

![Figure 22. Phase 2 Test Track. Shown land location is for illustration purposes only and does not represent the actual location of the test track.](image)
3.2 Exponent

Exponent is a multi-disciplinary engineering and scientific consulting firm that brings together more than 90 different disciplines to solve engineering, science, regulatory, and business issues facing potential clients. Some of Exponent’s capabilities are as follows.

- Accident and failure analysis.
- Accident prevention analysis.
- Working with automated vehicles in adapting new technologies.
- Technical assistance in a wide multidisciplinary areas.

Furthermore, Exponent’s Phoenix office sits on a 147-acre Test and Engineering Center (TEC). Their large facility and Phoenix’s climatic conditions provide a space for projects both indoors and out. At their test location, they have evaluated different crashes including motorcycles into trucks, cars into cars, and heavy trucks into car. The test facility has also the ability to conduct impacts of two moving vehicles at nearly any relative angle, impact configuration, and at speed ratios ranging from 1:1 to 11:1.

Test and Engineering Center

The Test and Engineering Center (TEC) is located in Phoenix, Arizona. The TEC comprises a combination of specialized test and prototyping equipment with reconfigurable test areas and instrumentation. The TEC maintains a vehicle proving ground and full-scale crash facility; indoor space of nearly 27,000 square feet space. The test track is a 2-mile oval test track with accident-site features such as ditches, poles, trees, walls, guard rails, and ramps. Figure 22 shows the layout of the existing test facility.

![Exponent Test Facility](image)

Figure 23. Exponent Test Facility.
3.3 Comparison between different alternatives

Table 6 shows some of the advantages and disadvantages from the two feasible locations. One of the main advantages of building the test track at the ASU Polytech Campus is the operational control that ASPACE can have on the facility. On the other hand, Exponent’s major advantage is the existing infrastructure that they have and the year of expertise in testing vehicles and related fields.

<table>
<thead>
<tr>
<th>Location</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASU-Polytechnic Campus</td>
<td>✓ ASU ownership</td>
<td>✓ No built facility</td>
</tr>
<tr>
<td></td>
<td>✓ Future Team research</td>
<td>✓ No utilities</td>
</tr>
<tr>
<td></td>
<td>✓ Possibility to expand</td>
<td>✓ Drainage</td>
</tr>
<tr>
<td></td>
<td>✓ Multiple intersection scenarios</td>
<td></td>
</tr>
<tr>
<td></td>
<td>✓ Perform simultaneous crash scenarios</td>
<td></td>
</tr>
<tr>
<td></td>
<td>✓ More than 7 miles of roads (including South Desert Village)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>✓ Early start with existing infrastructure</td>
<td></td>
</tr>
<tr>
<td>Exponent</td>
<td>✓ Existing 2-mile high-speed track</td>
<td>✓ Split ownership</td>
</tr>
<tr>
<td></td>
<td>✓ Experience and expertise in different vehicle testing fields,</td>
<td>✓ Far from ASU Campus</td>
</tr>
<tr>
<td></td>
<td>including autonomous vehicles</td>
<td>✓ Probably less control by ASU</td>
</tr>
<tr>
<td></td>
<td>✓ Share investment costs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>✓ Early start with existing infrastructure</td>
<td></td>
</tr>
</tbody>
</table>
4. COST ESTIMATES

Components of a cost per mile estimate are based on the information provided in (2).

Roadway Costs
- Lane miles (Length x No. of Lanes + account for shoulders).
- Lane miles of resurfacing.

There are two methods to make preliminary cost estimates on new highway projects. These two methods will depend on the complexity of each individual project. There are eight main categories that need to be considered for the cost estimates and those are:

Category 1 – Preliminary
Category 2 – Earthwork
Category 3 – Drainage
Category 4 – Structures
Category 5 – Paving
Category 6 – Shoulders
Category 7 – Landscaping
Category 8 – Signing, Marking, Lightning and Signalization

Cost estimate Method 1 will consider categories 2, 5 and 6 only. Depending on the pavement structures and road classification, the costs per mile can range from $1.5 up to $6 million dollars. This number will depend on how much earthwork has to be done and the pavement structure design, and the road classification (i.e., number of lanes).

Cost estimate Method 2 will consider all eight categories. For cost estimate Method 2, the cost per mile can vary from $3 up to $15 million dollars. Method 2 includes all categories (1-8), but still needs to add storm water, utility, and environmental mitigation costs. As a general recommendation, a contingency cost of 40% must be added for cost per mile.

For this particular project, where heavy traffic is not considered (heavy trucks), the estimated costs per mile of a typical four-lane arterial road or a three-lane collector road are summarized in Table 7. These are estimated costs based on local Arizona experience, and for the type of pavement structure that is needed.

<table>
<thead>
<tr>
<th>Road Type</th>
<th>Method 1</th>
<th>Method 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arterial</td>
<td>$1,500,000.00</td>
<td>$5,000,000.00</td>
</tr>
<tr>
<td>Collector</td>
<td>$1,000,000.00</td>
<td>$3,000,000.00</td>
</tr>
</tbody>
</table>
4.1 ASU – Polytech Location

Table 8 shows the approximate costs using the cost estimate Methods 1 and 2 for Phase 1. This phase includes the construction of approximately 0.3 miles of a 3-lane arterial road, 0.4 miles of a 2-lane collector road, and the rehabilitation of 0.3 miles of existing road.

Table 8. Phase 1 Approximate Cost Estimate.

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Lanes</th>
<th>Lane Width (ft.)</th>
<th>Length (mi.)</th>
<th>Cost Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Arterial</td>
<td>3</td>
<td>12</td>
<td>0.3</td>
<td>$450,000.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1,500,000.00</td>
</tr>
<tr>
<td>Minor Collector</td>
<td>2</td>
<td>12</td>
<td>0.4</td>
<td>$400,000.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1,200,000.00</td>
</tr>
<tr>
<td>Rehabilitation</td>
<td>2</td>
<td>12</td>
<td>0.3</td>
<td>$30,000.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$30,000.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>$880,000.00</strong></td>
</tr>
</tbody>
</table>

Table 9 shows the estimated cost for construction Phase 2 using both Methods 1 and 2. This phase includes the construction of a new arterial road loop about 1.4 miles long and 0.9 miles of collector roads that intersect the arterial road at different locations. It is important to note that, as a recommendation, a 30-40% contingency cost has to be considered.

Table 9. Phase 2 Approximate Cost Estimate.

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Lanes</th>
<th>Lane Width (ft.)</th>
<th>Length (mi.)</th>
<th>Cost Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Arterial</td>
<td>4</td>
<td>12</td>
<td>1.4</td>
<td>$2,100,000.00</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>$7,000,000.00</td>
</tr>
<tr>
<td>Minor Collector</td>
<td>3</td>
<td>12</td>
<td>0.9</td>
<td>$900,000.00</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$2,700,000.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>$3,000,000.00</strong></td>
</tr>
</tbody>
</table>

5. SUMMARY

A feasibility study on constructing a test track to simulate real-life crash scenarios around the City of Phoenix, Arizona, was carried out. Different existing test tracks mostly in the United States were reviewed and presented in the literature review sections. For the purpose of this project, different potential test track locations were identified. The two most feasible locations were: 1) Arizona State University Polytechnic Campus, and 2) Exponent’s testing facility in North Phoenix.
6. REFERENCES


7. ACKNOWLEDGMENT

This work was supported by Intel Corporation under grant no. FP00015109 “Intel-ASU A-SPACE Initiative.”
APPENDIX A

Crash Scenarios
Proposed locations where different crash scenarios can be performed. These crash scenarios are grouped with letters $A$, $B$ and $C$.

**Figure A.1. Location for Phase 1.** Shown land location is for illustration purposes only and does not represent the actual location of the test track.

**Figure A.2. Location for Phase 1.** Shown land location is for illustration purposes only and does not represent the actual location of the test track.
The following pre-crash scenario typology descriptions and images were obtained from the reference manual "Pre-crash scenario typology for crash avoidance research" by Wassim G. Najm et al., 2007. Letters in the figure indicates the location where the pre-crash scenario can be simulated in the proposed test tracks.

1. **Vehicle failure**: A vehicle is driving in daylight, under clear weather, dry conditions on a 55 mph posted speed limit, and then a sudden failure of the vehicle, the driver loses control. These failures can be due to tires/wheels, brakes, power train, and steering system.

   ![Vehicle Failure](image)

   **Vehicle Failure**

2. **Control loss with prior vehicle action**: Vehicle is turning left or right at an intersection and loses control due to a wet or slippery road and runs off the road.

   ![Vehicle Loss With Prior Vehicle Action](image)

   **Vehicle Loss With Prior Vehicle Action**

3. **Control loss without prior vehicle action**: Vehicle is driving straight in a highway with a 55 mph posted speed, then loses control due to wet or slippery road and runs off the road.

   ![Vehicle Loss Without Prior Vehicle Action](image)

   **Vehicle Loss Without Prior Vehicle Action**
4. **Running a red light**: Vehicle is going straight on a road with posted speed of 35 mph, and runs a red light, then collides with another vehicle from a lateral direction.

![Diagram of a red light intersection]

1-Running Red Light
2-Running Stop Sign

5. **Running a stop sign**: Vehicle is going straight on a road with posted speed of 35 mph, and runs a stop sign, then collides with another vehicle from a lateral direction.

6. **Road edge departure with prior vehicle maneuver**: Vehicle is turning left or right at an intersection with posted speed of 22 mph and then departs from the edge of the road.

![Diagram of a road edge departure with prior maneuver]

7. **Road edge departure without prior vehicle maneuver**: Vehicle is going straight on a rural road with posted speed of 55 mph and then departs from the edge of the road.

![Diagram of a road edge departure without prior maneuver]

8. **Road edge departure while backing up**: Vehicle is backing up on a road with a posted speed of 25 mph, and then departs from the edge on the shoulder/parking in a driveway location.
9. **Animal crash with prior vehicle maneuver:** vehicle is leaving from parking spot at night and encounters an animal.


10. **Animal crash without prior vehicle maneuver:** Vehicle is going straight on a rural road with posted speed of 55 mph and encounters an animal.


11. **Pedestrian crash with prior vehicle maneuver:** Vehicle is turning left or right at an intersection with speed limit of 35 mph and encounters a pedestrian in the crosswalk.
12. Pedestrian crash without prior vehicle maneuver: Vehicle is going straight on an urban road with speed limit of 25 mph, and then encounters a pedestrian.

13. Pedalcyclist crash with prior vehicle maneuver: Vehicle is turning right in an urban road with speed limit of 25 mph, and then encounters a pedalcyclist at an intersection.

14. Pedalcyclist crash without prior vehicle maneuver: Vehicle is going straight in an urban road with speed limit of 25 mph, and then encounters a pedalcyclist.

15. Backing up into another vehicle: Vehicle is backing up in an urban road with speed limit of 25 mph, and then collides with another vehicle.
16. **Vehicles turning traveling in the same direction**: Vehicle is turning lane at an intersection on an urban road with speed limit of 35 mph, and then cuts across the path of another vehicle traveling on the same direction.

17. **Vehicle parking with other vehicle traveling in the same direction**: Vehicle is leaving a parking position on a urban road with speed limit of 25 mph, and then encounters a vehicle traveling in the same direction.

18. **Vehicles changing lanes traveling in the same direction**: Vehicle is changing lanes in an urban road with posted speed of 55 mph and then encroaches into another vehicle traveling in the same direction.
19. **Vehicles drifting traveling in the same direction:** Vehicle is going straight in an urban road with speed limit of 55 mph, and then drifts into an adjacent vehicle traveling in the same direction.

20. **Vehicles making a maneuver traveling in opposite direction:** Vehicle is passing another vehicle in a rural road with speed limit of 55 mph, and encroaches into another vehicle traveling in opposite direction.

21. **Vehicles not making a maneuver and traveling in opposite direction:** Vehicles are going straight in a rural road at 55 mph, and then drifts and encroaches into another vehicle traveling in the opposite direction.
22. Following vehicle making a maneuver and approaching lead vehicle: Vehicle is changing lanes/passing in an urban road with speed limit of 55 mph, and closes in on a lead vehicle.

23. Following vehicle approaching an accelerating lead vehicle: Vehicle is going straight in an urban road with speed limit of 45 mph, and closes in on an accelerating lead vehicle.

24. Following vehicle approaching a lead vehicle traveling at a lower constant speed: Vehicle is going straight in an urban road with speed limit of 55 mph, and closes in on a vehicle driving at a lower constant speed.
25. Following vehicle approaching a decelerating lead vehicle: Vehicle is going straight in a rural road with speed limit of 55 mph, and closes in on a suddenly decelerating lead vehicle.

26. Following vehicle approaching a stopped lead vehicle: Vehicle is going straight in an urban road with speed limit of 35 mph, and closes in on a stopped lead vehicle.

27. Left turn across path from opposite directions at signalized junction: Vehicle is turning left at a signalized intersection in a road with speed limit of 35 mph, and cuts across the path of another vehicle driving straight from the opposite direction.
28. **Vehicle turning right at a signalized junction**: Vehicle is turning right in an urban road with speed limit of 35 mph, and turns into the same direction of another vehicle crossing straight from a lateral direction.

```
[Diagram of vehicle turning right at a signalized junction]
```

29. **Left turn across path from opposite direction at non-signalized junction**: Vehicle is turning left at a non-signalized intersection in a road with speed limit of 35 mph, and cuts across the path of another vehicle driving straight from the opposite direction.

```
[Diagram of left turn across path from opposite direction at non-signalized junction]
```

30. **Straight crossing paths at non-signalized junction**: Vehicle stops at a stop sign in an urban road with speed limit of 25 mph, and then proceeds against lateral crossing traffic.

```
[Diagram of straight crossing paths at non-signalized junction]
```
31. **Vehicles turning at a non-signalized junction:** Vehicle stops at a stop sign in a rural road with speed limit of 35 mph, and then proceeds to turn left against lateral crossing traffic.

32. **Vehicle taking evasive action with prior vehicle maneuver:** Vehicle is turning left at an intersection in an urban road with speed limit of 35 mph, and then takes evasive action to avoid obstacle.

33. **Vehicle taking evasive action without prior vehicle maneuver:** Vehicle is going straight in an urban road with speed limit of 35 mph, and then takes evasive action to avoid collision with an obstacle.
34. **Non-collision incident:** Vehicle is going straight in a rural road with posted speed limit of 55 mph, and then the vehicle sets on fire.

35. **Vehicle contacting object with prior vehicle maneuver:** Vehicle is leaving a parked position in an urban road with speed limit of 25 mph, and then collides with an object on the road shoulder or parking lane.

36. **Vehicle contacting object without prior vehicle maneuver:** Vehicle going straight in rural road with speed limit of 55 mph, and then collides with an object on the road.
Vehicle Contacting Object
Without Prior Vehicle
Maneuver
APPENDIX B

Other Alternatives
1. Arizona State University – Polytech Campus

Different designs and layout alternatives were proposed for the location at the Polytech Campus, some of these options are shown in the following figures.

Figure B.1 Alternative A at Polytech Campus. *Shown land location is for illustration purposes only and does not represent the actual location of the test track.*

Figure B.2 Alternative B at Polytech Campus. *Shown land location is for illustration purposes only and does not represent the actual location of the test track.*
Figure B.3. Existing Conditions at the Polytech Campus Location.

Figure B.4. Alternative C at Polytech Campus. *Shown land location is for illustration purposes only and does not represent the actual location of the test track.*
2. Gila River Community. “Gila River Memorial Airport

Figure B.5. Alternative A at Gila River Memorial Airport.

Figure B.6. Alternative B at Gila River Memorial Airport.
Figure B.7. Alternative Cat Gila River Memorial Airport.

Table B.1. Advantages and Disadvantages of Gila River Memorial Airport

<table>
<thead>
<tr>
<th>Location</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gila River Memorial Airport</td>
<td>✓ Close to Intel Ocotillo Campus ✓ Existing track (runway)</td>
<td>✓ Abandoned ✓ Negotiations with Gila River Community</td>
</tr>
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</table>
APPENDIX C

Road Design
1. Intersections

ADOT’s, Road Design Guidelines

a. 3 – Leg Intersection

Figure C.1. 3 – Leg Intersection (Source: ADOT).

b. 4 – Leg Intersections

Figure C.2. 4 – Leg Intersection (Source: ADOT).
c. Roundabouts

Key Features and Dimensions

Figure C.3. Roundabout (Source: ADOT).

AASHTO’s A Policy on Geometric Design of Highways and Streets

a. 3 – Leg Intersections

Figure C.4. 3 – Leg Intersection (Source: AASHTO).
b. 4 – Leg Intersections

Figure C.5. 4 – Leg Intersection (Source: AASHTO).

Right-Turn Channelization

Flared and Marked with Right-Turn Lanes

Flared and Marked with Left-Turn Lanes

Divisional Islands

Right-Turn Channelization, Divisional Islands, and Left-Turn Lanes

Figure C.5. 4 – Leg Intersection (Source: AASHTO).

c. Roundabouts

Mini-Roundabout

Single-Lane Roundabout

Multi-Lane Roundabout

Figure C.6. Roundabout (Source: AASHTO).

2. Design Specifications (AASHTO and ADOT)

Recommended Design Vehicles

Table C.1. Recommended Design Vehicles

<table>
<thead>
<tr>
<th>Intersection Type</th>
<th>Recommended Design Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Junction of State Routes</td>
<td>WB-19, WB-15, WB-12</td>
</tr>
<tr>
<td>Other Rural</td>
<td>WB-15, WB-12, SU</td>
</tr>
<tr>
<td>Urban Major Streets</td>
<td>WB-15, WB-12, SU</td>
</tr>
<tr>
<td>Other Urban</td>
<td>WB-12, SU, P</td>
</tr>
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Sight Distance
  a. Stopping sight distance
  b. Intersection sight distance
  c. Decision sight distance
  d. Passing sight distance

<table>
<thead>
<tr>
<th>Design Speed (mph)</th>
<th>Stopping Sight Distance (ft)</th>
<th>Passing Sight Distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>525</td>
<td>918</td>
</tr>
<tr>
<td>50</td>
<td>426</td>
<td>803</td>
</tr>
<tr>
<td>30</td>
<td>213</td>
<td>524</td>
</tr>
</tbody>
</table>

Street Cross-Sections (City of Phoenix’s Street Planning and Design Guidelines)

  a. Arterial

Figure C.7. Typical Design Vehicles.
Figure C.8. Typical Arterial Cross-Section (Source: City of Phoenix)
b. Collector

Figure C.9. Typical Collector Cross-Section (Source: City of Phoenix).

- F - Minor (Residential) Collector
- F - Minor (Industrial) Collector

C. Local

Figure C.8. Typical Local Road Cross-Section (Source: City of Phoenix).

Pavement Design by City of Phoenix Specifications

<table>
<thead>
<tr>
<th>Street Type</th>
<th>Min Thickness of Asphalt Concrete (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arterial</td>
<td>6</td>
</tr>
<tr>
<td>Major Collector</td>
<td>4.5</td>
</tr>
<tr>
<td>Residential Collector</td>
<td>3</td>
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<tr>
<td>Local</td>
<td>2</td>
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### Table C.4. Recommended Base Layer Thickness

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<thead>
<tr>
<th>Base Material</th>
<th>Min Thickness (in)</th>
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<tbody>
<tr>
<td>Aggregate base</td>
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</tr>
<tr>
<td>Cement treated base</td>
<td>6</td>
</tr>
<tr>
<td>Select material</td>
<td>6</td>
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</table>

### Table C.5. Asphalt Concrete Pavement Design for Arterials

<table>
<thead>
<tr>
<th>Arterials Streets</th>
<th>Binder Content</th>
<th>Traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>A- 1 1/2&quot; Base Course</td>
<td>4.3±0.4 %</td>
<td>High Volume</td>
</tr>
<tr>
<td>C- 3/4&quot; Base and Surface Course</td>
<td>5.0±0.4 %</td>
<td>High Volume</td>
</tr>
<tr>
<td>D- 1/2&quot; Surface Course</td>
<td>5.1±0.4 %</td>
<td>High Volume</td>
</tr>
<tr>
<td>D- 1/2&quot; Asphalt Rubber Concrete Surface</td>
<td>8.0±0.4 %</td>
<td>High Volume</td>
</tr>
</tbody>
</table>

### Table C.6. Asphalt Concrete Pavement Design for Local Streets

<table>
<thead>
<tr>
<th>Local Streets</th>
<th>Binder Content</th>
<th>Traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>C- 3/4&quot; Base and Surface Course</td>
<td>5.5±0.4 %</td>
<td>Low Volume</td>
</tr>
<tr>
<td>D- 1/2&quot; Surface Course</td>
<td>5.6±0.4 %</td>
<td>Low Volume</td>
</tr>
<tr>
<td>D- 1/2&quot; Asphalt Rubber Concrete Surface</td>
<td>8.5±0.4 %</td>
<td>Low Volume</td>
</tr>
</tbody>
</table>