Pedestrian and Bicyclist Safety and Comfort on Water Street

A Technical Report submitted to the Department of Systems and Information Engineering

Presented to the Faculty of the School of Engineering and Applied Science
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Bachelor of Science, School of Engineering

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On my honor as a University Student, I have neither given nor received
unauthorized aid on this assignment as defined by the Honor Guidelines
for Thesis-Related Assignments

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Background and Problem Statement

In their 2018 Pedestrian Safety Action Plan (PSAP), The Virginia Department of Transportation (VDOT) has identified the West Water Street corridor in downtown Charlottesville as an area of focus due to a high rate of pedestrian crashes between 2012 to 2016 (Cole and Read, 2018). Water Street also hosts one of the main bicycle routes in the city; however, there is a high level of traffic stress for bicyclists. Therefore, it is critical to determine pedestrian and bicyclist safety countermeasures. Ideally, Water Street would be able to accommodate vehicles, pedestrians, and bicyclists in a safe and efficient manner.

The objective of this project was to research, create, and test alternative roadway designs to improve bicyclist and pedestrian safety and comfort on the Water Street corridor. The design team analyzed best practices from other bicycle- and pedestrian-friendly cities to inspire design ideas for the specific Water Street corridor. The team then tested those designs using virtual reality (VR) and biometric data.

The research team was composed of both undergraduate Civil and Systems Engineering students. Available as external resources were PhD graduate student mentors, faculty advisors, and subject matter experts who helped support the team and offer guidance.

Planning level design documents were created in order to communicate the team's design solution alternatives. These solutions stem in part from research on the reactions of bicyclist and pedestrian test subjects who were introduced to a VR simulation of the Water Street corridor; however, due to the COVID-19 outbreak user testing was limited. Despite the lack of testing the team created preliminary designs of the alternatives and determined the preferred alternative through Multi-Criteria Analysis.

The design and alternative evaluation processes ensured that the proposed Water Street infrastructure changes would meet design standards and are feasible. The specific design changes were implementable in VR and focused on the roadway characteristics as there were certain requirements for what could be changed. These include:

- Pavement markings and additional roadway infrastructure (e.g., bicyclist and pedestrian safety barriers)
- Re-allocation of space within the existing right-of-way
- Signage

The user feedback part of the project was to be used to evaluate the preferred alternative(s), and was to be collected via:

- Physiological indicators (i.e. heart-rate, skin temperature, arm movement - collected through wearables)
- Survey-based methods

Since the project was focused on formulating design alternatives at a planning level, detailed design documents used for construction purposes were not a part of its scope. Similarly, only preliminary cost estimates were developed for the alternatives, rather than detailed cost breakdowns. Furthermore, the team was not responsible for implementing any of the alternatives, including the final preferred alternative on Water Street.

For the design changes, certain parameters were not considered, as they would have been difficult to test in VR and were infeasible within the project's constraints. These include:

- The removal of buildings
- Signal timing changes
- Changes that require additional right-of-way
- Widening of the roadway

The approach taken to complete this project was split into five major tasks:

- Understanding project scope
- Designing alternative solutions
- Implementing design alternatives in the Unity software
- Completing testing of subjects in the Unity software
- Completing the final report

A Systems and Information Engineering Design Symposium (SIEDS) paper and presentation were created and after the approval of an abstract by SIEDS. The end of this project culminates with this technical report that describes the design alternatives for the project as well as the final design that was chosen based upon a technical analysis of the design. Along with this final report, a final presentation has been developed to convey the information within the technical report.

Design Requirements

The following design requirements were created based on the current infrastructure in Water Street and from the feedback given from industry mentors. There are also requirements listed that are based on city infrastructure standards (see Appendix A).

- Accommodate vehicular and bicyclist traffic in a minimum road width of 35’ 8” to a maximum of 65’ 5” (current dimensions)
- Maintain speed limit at 25 mph
- Have car lanes be at least 10’ wide
    - 11’+ is ideal (to account for busses)
- Have any included bicycle lanes be at least 5’ wide
- Design for at least 50% of users tested in the environment to report at least an “intermediate” comfort level
- Meet ADA requirements
    - Keep at least the current level of walkability for pedestrians
- Implement better signage and lighting

Below are images of the city’s preliminary plans for the corridor (Fig. 1 and 2). These plans and dimension information also helped guide the requirements above.

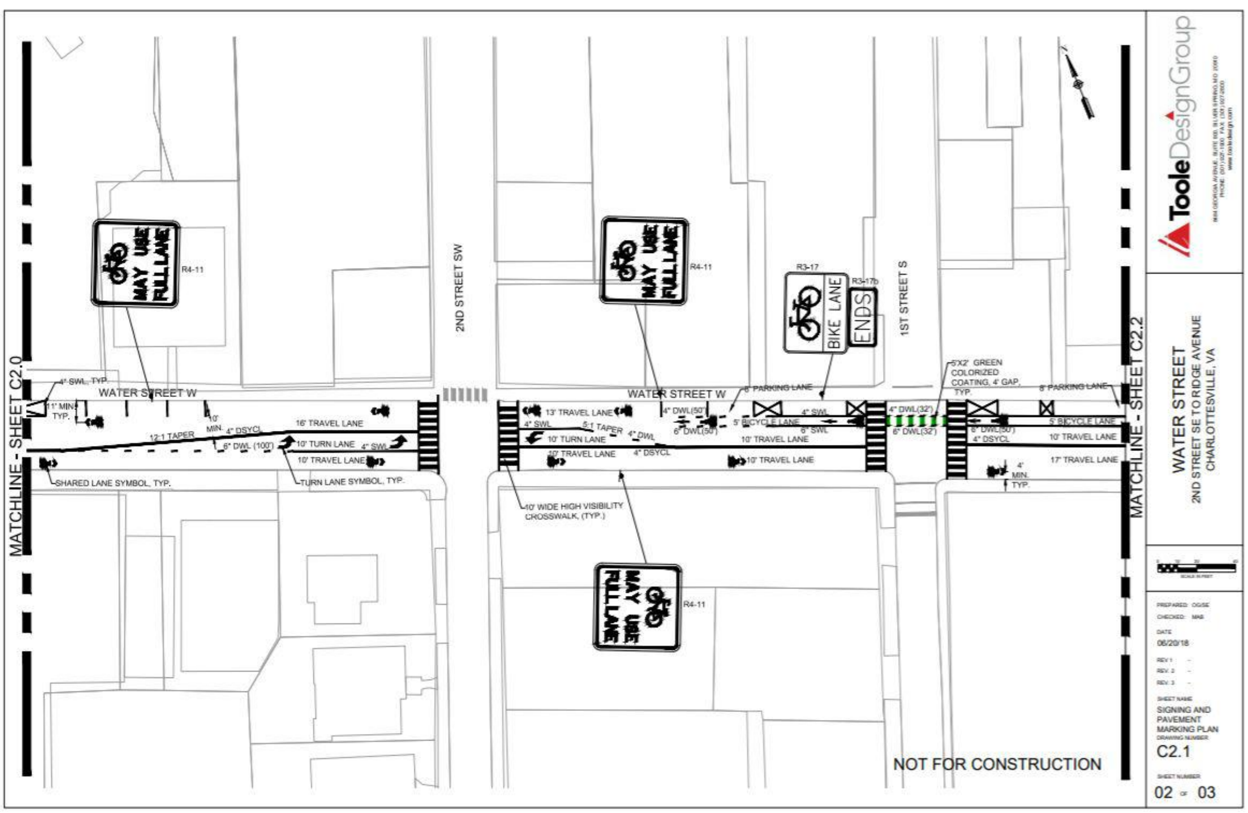

Figure 1: Water St city plan, by Toole Design Group

Figure 2: Existing Water St roadway widths

Preliminary Design Alternatives

Three preliminary design concepts were determined after observing the design requirements, scope of the project, and current best practices. The first design concept is based off of existing Charlottesville city plan improvements that consist of two-way travel lanes and a five-foot westbound bicycle lane. The second concept is a one-way street because it eliminates risk and fear of collisions with vehicular traffic (National Association of City Transportation Officials). Historically, many two-way downtown streets were converted to one-way streets in the mid-20th century to streamline traffic operations and reduce conflicts. Therefore, the one-way concept consists of a one-way travel lane, an expanded parking lane for ease of loading (for delivery vehicles, especially those that need to access the pedestrian-only downtown mall), a 5 feet two-directional cycle track, and a 1 foot expansion of both sidewalks. The third concept is to remove parking in order to allow for wider travel and bicycle lanes. This design has two-way travel lanes, 5’ two-directional bicycle lanes, and the 1 foot sidewalk expansions.

After these three preliminary designs were drafted and designed in AutoCAD, the team discussed the designs with industry mentors. The feedback received was that additional lane width can encourage higher speeds. The designs originally had 12-foot travel lanes, so this was then reduced to 10-foot travel lanes. Slightly narrower travel lanes also allocate more space for sidewalk expansion and bicycle buffers. In addition, in the one-way concept, the two-way separated bicycle lane needed a buffer. This was addressed by taking 1 foot from the travel lane and 2 feet from the parking lane to create a buffer. Lastly, in the no parking concept, the industry mentors did not think it was worthwhile to expand a sidewalk's width by only 1 foot given the construction work involved. It was recommended to expand one side of the sidewalk by 2 feet and leave the other side alone. Ultimately, accommodations were made following feedback from the industry mentors.

The three design concepts are shown in Figures 3, 4, and 5.

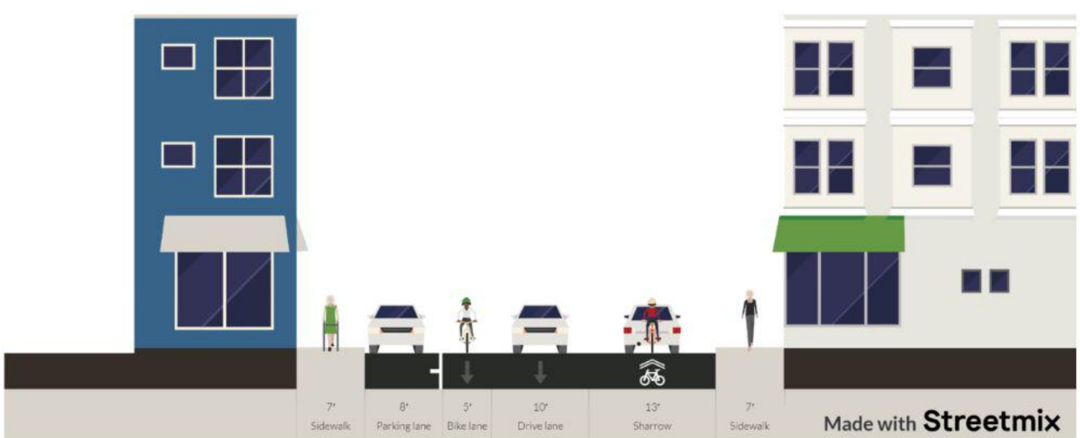

Figure 3: The modified city plan design concept

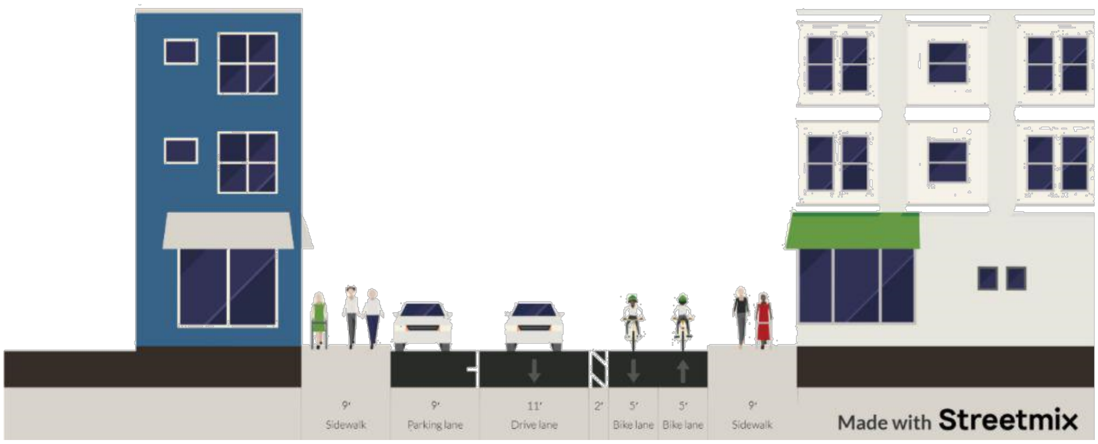

Figure 4: The one-way design concept

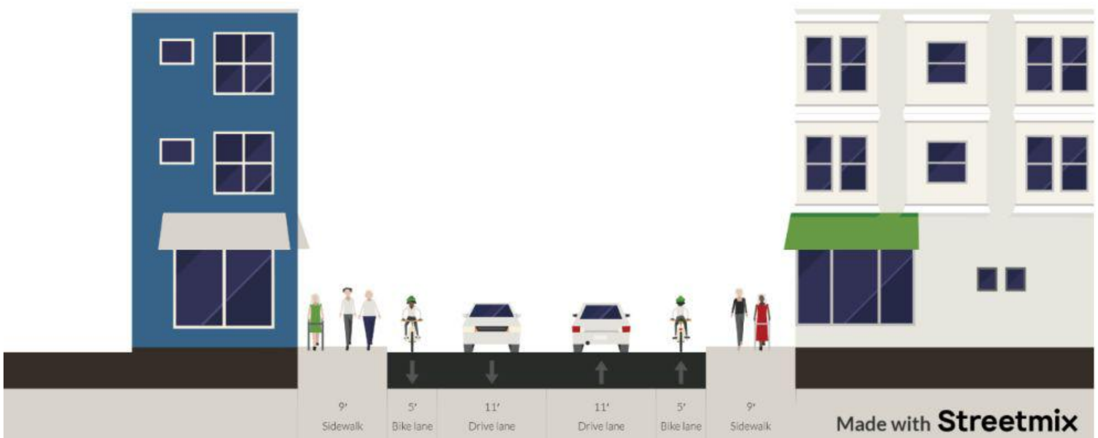

Figure 5: The no parking design concept

Cost Estimates and Financial Considerations

The preliminary design alternatives chosen have different recommended construction components associated with them, which were factored into the preliminary MCA. Construction costs include:

- Pavement markings
- Sidewalk expansion
- Milling and overlay
- Additional signage
- ADA considerations
- Rectangular rapid flashing beacons (RRFB)

Note that the cost of labor is outside the scope of the preliminary cost estimates and will not be included in the financial analysis. Also, all three design alternatives include the same construction of pavement markings, milling and overlay, additional signage, and RRFBs. The only difference in construction costs between the city plans and the [one-way & no parking] designs is the ADA considerations and the amount of sidewalk added. Below is the cost calculation for each construction item described above.

Pavement Markings

The type of pavement markings used in the cost estimate is thermoplastic. Thermoplastic markings are currently the most widely used. They have a short construction time, high abrasion resistance, and low prices. They are thicker and more durable than most other striping paints such as Cold Paint Line Striping. Thermoplastic markings are mainly used for road surfaces. The road suffer from sun, rain, snow, and ice. A road may also be damaged by the quantities of vehicles, so these road lanes require paints with high performance.

With regards to pavement markings, the following needs to be accounted for:

- Two center lines down the middle of the roadway
- Turn lanes
- Bicycle lanes
- Road symbols
- Crosswalk block symbols

As shown in the Fig. 6, below, the corridor of Water Street that is inside the project scope is 0.3 miles long.

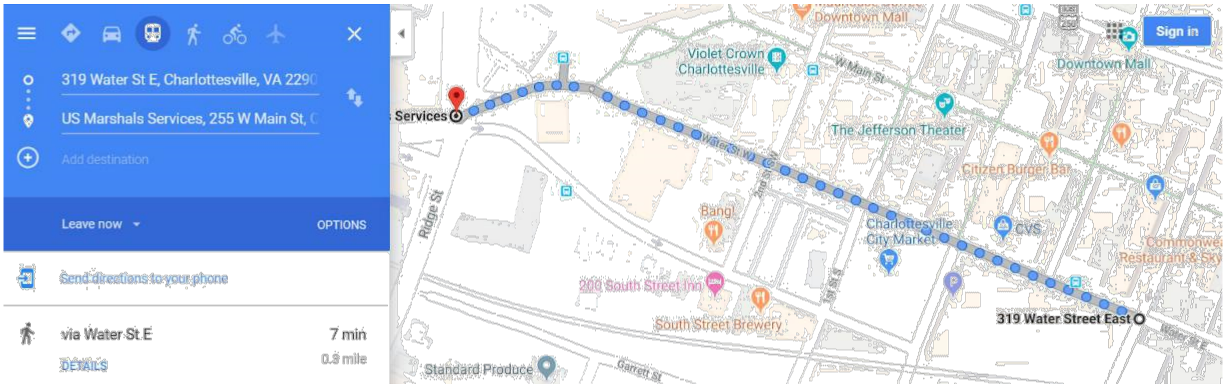

Figure 6: Length of Water St study extents (Google Maps)

The estimate is that each alternative will require 10 times the amount of pavement markings as the length of the corridor. Since the corridor length is 0.3 miles, it is assumed that 3 miles of pavement markings are necessary.

3 miles * 5280 feet/mile = 15,840 feet *(round to 16,000 feet)*

In a benefit-cost analysis of lane markings published by the Federal Highway Administration, it costs $0.33 per linear foot for urban thermoplasticroad markings (Miller, 1993). The average asphalt "rumble" strip in the Culpeper district (Charlottesville is in the Culpeper district) is $0.38 per linear foot (Virginia Department of Transportation). The average of these costs will be taken.

($0.33 + $0.38) / 2 = $0.355

Therefore, the assumption is the average road marking costs $0.36 per linear foot. With 16,000 feet of road markings needed, then the cost is:

16,000 feet * $0.36/foot = **$5,760***(round to $6,000)*

Sidewalk Expansion (for the one-way and no parking designs only)

The city plans did not include a sidewalk expansion, so the costs for that design are $0.

For a curb-abutted sidewalk with no buffer space, the low and high projections for one linear foot of sidewalk are $63 and $75.60, respectively. These estimates are according to VDOT's Planning Level Cost Estimates (Virginia Department of Transportation). The average of these costs will be taken.

($63 + $75.60) / 2 = $69.30

Therefore, the average linear foot of sidewalk costs $69.30. The current sidewalks are 7 feet wide. The designs add 2 feet of sidewalk so that the sidewalk is expanded to 9 feet. Therefore,

$69.30/linear foot * 2 feet = $138.60 / linear foot

As previously mentioned, the length of the Water Street corridor is 0.3 miles.

0.3 miles * 5,280 feet/mile = 1,600 feet

There are 5 intersections in the area of study. Each intersection is approximately 15 feet in length where there will be no added sidewalk, therefore

1,600 feet - 5(15 feet) = 1,525 feet

However, because there is sidewalk on both sides of the street, this number is multiplied by two.

2 * 1,525 feet = 3,050 feet

Therefore, 3,050 feet of sidewalk will be added to the corridor. Again, assuming $138.60 per linear foot of sidewalk,

3,050 feet * 138.60 per foot = **$422,730***(round to $422,000)*

Milling and Overlay

According to VDOT's Planning Level Cost Estimates, the low and high projections for one square foot of milling and overlay is $441 and $529, respectively (Virginia Department of Transportation). Taking the average of these costs:

($441 + $529) / 2 = $486

Therefore, it will cost $486 per square foot of milling and overlay. 1.5 inches (0.125 feet) in surface milling is assumed, and the corridor is 0.3 miles long (1,600 feet). Therefore,

$486 per square foot * 1600 feet * 0.125 feet = **$97,200***(round to $97,000)*

Additional Signage

The city plans had 7 new signs being added to the corridor. It is assumed that 7 new signs would also need to be added to the one-way and no parking designs.

The estimates below come from a VDOT bid of three bidding firms: Corman Kokosing Construction Company, Shirley Contracting Company, LLC, and Abernathy Construction Corporation (Virginia Department of Transportation). The average of each bid is taken as the best estimate per unit.

- Sign $75
- Sign post $500
- Sign foundation $4,000
- *Total* $4,575

Therefore, the estimate of the total cost of adding a new sign is $4,575. Adding 7 new signs to the corridor the cost is:

7 signs * $4,575/sign = <u>**$32,025**</u>*(round to $32,000)*

ADA Considerations

In each of the design alternatives, ADA-compliant sidewalks must be implemented. This means installing ADA-compliant ramps at sidewalk crossings. Because the city plans do not include the expansion of the sidewalk, only ramps that do not already exist will be considered. However, the one-way and no parking alternatives require sidewalk expansion and would therefore need each intersection to have new ADA-compliant ramps.

According to VDOT's Planning Level Cost Estimates, the cost estimates for replacing an existing curb ramp in Fairfax County with the latest ADA-compliant curb ramp has a cost range of $12,028 to $15,513 (Virginia Department of Transportation). Averaging these costs:

($12,028 + $15,513) / 2 = $14,000

Therefore, it is estimated that installing one ADA-compliant curb ramp costs $14,000.

For the city plans, there are only 5 new ramps that need to be installed. These ramps would be installed at the following locations:

- 3 new ramps at the intersection of Water Street & 4th Street SE
- 1 new ramp at the intersection of Water Street & 1st Street S
- 1 new ramp at the intersection of Water Street & 2nd Street SW

5 new ramps = 5 * $14,000 = **$70,000**

For the one-way and no parking alternatives, the sidewalk would be expanded and new ramps would be needed at the following locations:

- 4 ramps at the intersection of Water Street & 2nd Street SW
- 4 ramps at the intersection of Water Street & 1st Street S
- 2 ramps at the intersection of Water Street & 2nd St SE
- 2 ramps at the intersection of Water Street & 3rd St SE
- 4 ramps at the intersection of Water Street & 4th St SE

16 new ramps = 16 * $14,000 = **$224,000**

Rectangular Rapid Flashing Beacons (RRFB)

According to the Pedestrian Safety Guide and Countermeasure Selection System, installing one RRFB can range from $4,520 to $52,310 (Rectangular Rapid-Flashing Beacon (RRFB)). The cost to furnish and install a flashing beacon can vary widely based on site conditions and the type of device that is used. It is assumed that the cost of one RRFB to be the median value, which is $14,000.

For each design alternative, 4 new flashing beacons plan to be implemented, with 2 at *each* the 1st Street S and 4th Street SE intersections.

4 * $14,000 = **$56,000**

Summary of Cost Analysis

Below, Table 1 shows a summary of the estimated costs for each of the anticipated construction components for the three preliminary design alternatives.

Table 1: Cost Estimates for Preliminary Design Alternatives

	City Plans	**1-Way**	**No Parking**
Pavement Markings	$6,000	$6,000	$6,000
Sidewalk	$0	$422,000	$422,000
Milling and Overlay	$97,000	$97,000	$97,000
New Signage	$32,000	$32,000	$32,000
New ADA Ramps	$70,000	$224,000	$224,000
Rapid Flashing Beacons	$56,000	$56,000	$56,000
TOTAL	**$261,000**	**$837,000**	**$837,000**

Preliminary Multi-Criteria Analysis

In order to choose one conceptual design out of the three described above, a preliminary multi-criteria analysis (MCA) was performed. Evaluative factors were created, weights for those factors were calculated, and a final score for each design concept was determined.

First, the team created different factors to evaluate the three conceptual designs. These factors were generated and finalized with the assistance of the faculty supervisors and industry mentors. The factors are shown in the left column of Table 2.

The team then evaluated these factors in respect to each design concept, as shown on the right-hand side of Table 2. These factors were evaluated on a scale of one to five – one meant that the design concept met the factor the least, and five meant that the design concept met the factor the most. These values were determined based on careful analysis and comparisons.

To calculate the weights for each factor, the team released a survey to users of Water Street who have bicycled, drove, or walked through the corridor, as well as to the faculty supervisors and industry mentors. The survey asked participants to rank the importance (one being least important, and five being most important) of each factor in the context of a roadway improvement project. From the 29 responses received, the weight for each factor was calculated following the following formula.

$$w_i = \frac{\text{average of the responses from factor } i}{\text{sum of the average responses of all factors}} = \frac{\bar{x}_i}{\sum_{1}^{8} \bar{x}_i}$$

where:

- x = factor
- i = 1,2, …,8 (represents each of the 8 factors)
- w_i = weight for factor i

Table 2: Values for Preliminary MCA

Factors		Design Concepts			
		No-Build	City Plan	One-Way	No Parking
Safety	Bicyclist	1	3	4	4
	Pedestrian	2	4	5	4
	Driver	3	3	5	4
Comfort	Bicyclist	1	3	4	3
	Pedestrian	2	3	5	4
	Driver	3	3	5	4
Cost		5	4	1	2
Time of Construction		5	4	1	1
Maintenance of Traffic During Construction		5	3	1	3
Maintenance of On-Street Parking		5	4	5	1
Environmental Impact		5	4	3	3
Constructability/Feasibility		5	4	2	3

Table 3: Results for Preliminary MCA

Factors		Weights	Design Concepts			
			No-Build	City Plan	One-Way	No Parking
Safety	Bicyclist	0.15	0.15	0.45	0.60	0.60
	Pedestrian		0.30	0.60	0.75	0.60
	Driver		0.45	0.45	0.75	0.60
Comfort	Bicyclist	0.12	0.12	0.36	0.48	0.36
	Pedestrian		0.24	0.36	0.60	0.48
	Driver		0.36	0.36	0.60	0.48
Cost		0.11	0.55	0.44	0.11	0.22
Time of Construction		0.12	0.60	0.48	0.12	0.12
Maintenance of Traffic During Construction		0.13	0.65	0.39	0.13	0.39
Maintenance of On-Street Parking		0.09	0.45	0.36	0.39	0.09
Environmental Impact		0.13	0.65	0.52	0.39	0.39
Constructability/Feasibility		0.15	0.75	0.60	0.30	0.45
SUM		1.00	***5.27***	***5.37***	***5.22***	***4.78***

Final Design Alternatives

From the analysis in Table 3, the modified city plan design concept was chosen. However, this single design was then extrapolated out to two new designs to test different changes to the roadway in VR. Experimental design processes call for a change to only one element of the design for the best comparison (Twist). In this experiment, the one element that changed across all designs was the level of the bicycle lane buffer. There was either 1) no buffer, 2) a striped buffer, or 3) barrier posts. These final design alternatives are shown using typical section views in Fig. 7, 8, and 9, and are presented in a plan set format in Appendix C.

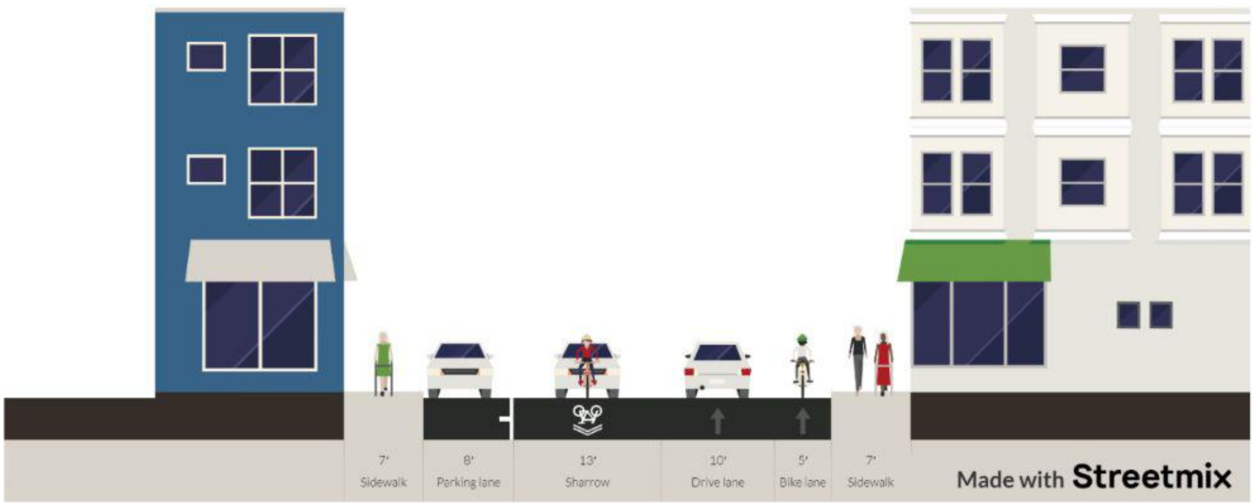

Figure 7: The modified city plan with no bicycle barrier

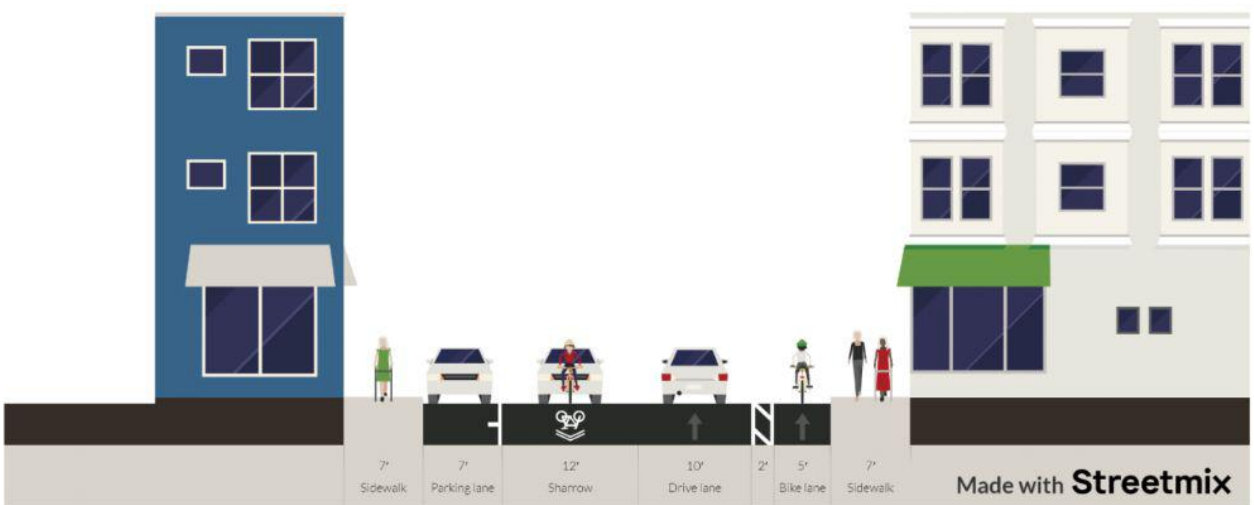

Figure 8: The modified city plan with a striped bicycle barrier

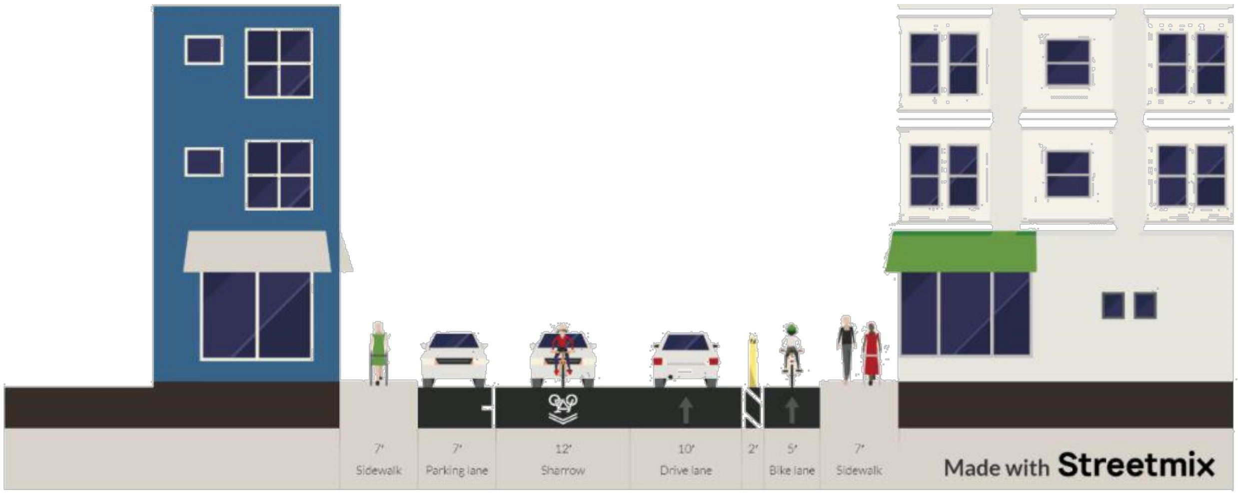

Figure 9: The modified city plan with a bicycle barrier post

To recap, three majorly different design concepts (modified city plan, one-way, and no parking) were narrowed-down to one concept (modified city plan) based on MCA. This one concept was then expanded out to two new alternatives (three total) to determine which level of bicycle lane buffer is best. All of the finalized designs include the additional following recommendations that cover the other general design requirements. These include

- Adding additional signage and lighting to alert vehicular traffic of bicyclist and pedestrian right-of-way
- Installing ADA-compliant ramps at all intersections that do not already have ADA-compliant ramps
- Implementing RRFBs at the two major intersections of Water Street: the 1st Street S and 4th Street SE intersections

Final Solution and Recommendations

Consistent with guidance from the Centers for Disease Control and Prevention (CDC), the United States Department of State, and the Virginia Department of Health, the University of Virginia (UVA) moved all classes online beginning March 19, 2020 due to the COVID-19 coronavirus outbreak. Because students were also asked to leave UVA Grounds, the team was in a situation to continue the work of this project on an online basis. Consequently, the user testing in the VR environment was not carried-out. However, the original testing plan is explained in Appendix B, and the team instead wrote a white paper (Appendix D) regarding how user data would have been evaluated for the final design alternatives (Fig. 7, 8, and 9).

User testing was originally planned to take place in mid- to late-March 2020 in the Omni-Reality and Cognition Lab (ORCL) in UVA's engineering school (see Appendix B for more detailed information). Users would wear a VR headset and ride a stationary bicycle that is connected to the VR environment in order to assess the three final alternative bike infrastructure designs. Users would begin the testing with a baseline VR environment to get their heart rate up to a steady pace using a smartwatch that collects physiological data. They would then ride through the no-build condition and the three finalized designs (i.e. city plans with no buffer, striped buffer, and barrier posts). After each test, users would answer feedback questions that analyze the users' safety and comfort on a one to five scale (one being the least safe/comfortable, and five being the most safe/comfortable). This likert-scale data would be combined with the physiological data to determine a final score for each alternative design. The alternative with the best score would then be recommended to the City of Charlottesville. The white paper that addresses how the final score would have been calculated *with user testing data*can be found in Appendix D. A final multi-criteria analysis using the available data to recommend the best design alternative *without user testing data* is presented below.

Final Multi-Criteria Analysis

In order to select a final design out of the three proposed alternatives, a final multi-criteria analysis (MCA) was performed. Evaluative factors were created, weights for those factors were calculated, and a final score for each design concept was determined. The team used the same factors as in the preliminary MCA in order to select the best alternative out of the three proposed designs (see Table 4: Values for Final MCA). The values that were determined for each alternative were based on careful analysis and comparisons. The weights used for each factor were also the same as what was used for the preliminary MCA, which were determined based on a survey of users of Water Street (see Table 5: Results for Final MCA). From the results in Table 5, alternative 3, the buffer and post design, was chosen as the final recommended design alternative.

Table 4: Values for Final MCA

Factors		Design Concepts			
		No-Build	Alternative 1 (City Plan - No Buffer)	Alternative 2 (Buffer)	Alternative 3 (Buffer and Posts)
Safety	Bicyclist	1	2	3	4
	Pedestrian	2	4	4	4
	Driver	3	4	3	3
Comfort	Bicyclist	1	2	3	4
	Pedestrian	2	4	4	4
	Driver	3	3	4	4
Cost		5	4	4	3
Time of Construction		5	4	4	4
Maintenance of Traffic During Construction		5	3	3	3
Maintenance of On-Street Parking		5	4	3	3
Environmental Impact		5	4	4	4
Constructability/Feasibility		5	4	4	4

Table 5: Results for Final MCA

Factors		Weights	Design Concepts			
			No-Build	Alternative 1 (City Plan - No Buffer)	Alternative 2 (Buffer)	Alternative 3 (Buffer and Posts)
Safety	Bicyclist	0.15	0.15	0.3	0.45	0.6
	Pedestrian		0.3	0.6	0.6	0.6
	Driver		0.45	0.6	0.45	0.45
Comfort	Bicyclist	0.12	0.12	0.24	0.36	0.48
	Pedestrian		0.24	0.48	0.48	0.48
	Driver		0.36	0.36	0.48	0.48
Cost		0.11	0.55	0.44	0.44	0.33
Time of Construction		0.12	0.6	0.48	0.48	0.48
Maintenance of Traffic During Construction		0.13	0.65	0.39	0.39	0.39
Maintenance of On-Street Parking		0.09	0.45	0.36	0.27	0.27
Environmental Impact		0.13	0.65	0.52	0.52	0.52
Constructability/Feasibility		0.15	0.75	0.6	0.6	0.6
SUM		1.00	***5.27***	***5.37***	***5.52***	***5.68***

Conclusion

Project Outcomes

In this project, the design team created and designed three different preliminary alternatives, and then three final alternatives to be used for the Water Street Corridor. Once the final alternative designs were created and drawn in CAD, VR environments for each of the designs were created in Unity in order to complete user testing for these designs. The designs were analyzed using a multi criteria analysis, in conjunction with the no-build situation, in order to choose the best alternative design to be used on the Water Street Corridor. *The final recommended design is the modified city plan with 7' sidewalks, a 12' westbound sharrow, and a 5' eastbound bicycle lane with a 2' striped buffer and protective barrier posts (see Fig. 9).* This design provides a high level of safety and comfort for pedestrians and cyclists, while retaining on-street parking and bi-directional vehicle travel.

From a regulatory standpoint, one constraint was the City's desire to maintain the existing westbound on-street parking spaces if possible, since Water Street is parallel to the Downtown Mall where vehicles are not allowed to access. On-street parking would allow for freight and delivery vehicles to have better access to the Downtown Mall, improving economic development. This was kept in mind throughout the project's design phases.

However, one objective that the design team could not satisfy, and one key constraint that arose, was the actual testing of the designs in the VR environment. Due to extenuating circumstances and school being moved virtually, the design team could not gather participants to test the different designs in Unity. But, in order to work around this constraint, the design team conducted a final MCA of the three final design alternatives in order to choose the recommended design for the Water Street Corridor. Likewise, the design team wrote a white paper analyzing user comfort and safety along similar streets as an alternative conclusion for the project.

In order to understand the problem presented in the project and develop a solution, the design team conducted in-depth analyses of bike lanes and the different measurements and safety features that are instituted. The design team also researched the effectiveness and ineffectiveness of different types of designs for bike lanes in other cities. This allowed for the team to make an informed, rational decision when creating alternatives for the Water Street Corridor.

Because the user testing phase was never completed, the key types of data that the team focused on were street measurements (lane width, parking length, number of lanes, length of sidewalk) and survey responses in order to complete the MCA. for the street measurement data, the team was able to reference an established plan for the redesign of the Water Street Corridor, as well as as-built plans for the street. When creating the final alternative designs, data from these sources were referenced, and assumptions from the design team were also made.

Physiological and survey data were going to be gathered from the user testing phase, but could not be attained due to the lack of user testing.

Design Complexity

While designing the solution to the project, the complexities included: conflicting technical issues, no obvious solution, conflicting constraints, diverse stakeholders, multiple disciplines, challenges that are not addressed in current codes or standard practice, and other lab-related hindrances like funding.

Diverse stakeholders was the greatest complexity the team faced, and it was faced on two fronts. First, is that the team was unable to provide plans for a design that would perfectly cater to all travelers since cars, bikes, buses, scooters, and walkers since there would be conflict in the narrow stretches of Water Street. The goal was to find a best-case solution that balances the needs of all travelers as well as other stakeholders such as residents, businesses, and people who rely upon on-street parking. This enormous list of stakeholders created a central problem, which resulted in other complexities (no obvious solutions, conflicting constraints, etc.). Any inch of pavement allocated to a bike lane would impact motorized traffic, and any parking spot removed would surely disappoint local residents and businesses. Meeting all of the needs of these stakeholders took a well-thought-out design process.

In a semester where user-testing could have been conducted, the second way in which the presence of multitude of stakeholders would have added complexity to the project would have been in the virtual reality user testing component. An underlying problem with current design practices is the lack of user input in the design process. Furthermore, the comfort of differing skill levels of bicyclists was understudied, leaving gaps of knowledge about how to properly implement bicycle infrastructure. This project hoped to fill these gaps through the use of virtual reality comfort testing. The problem with having such diverse stakeholders is that it would have forced the team to find a wide variety of test subjects in order to have a proportional sample size of users.

In a complex problem such as multi-modal transportation design, it was very beneficial to start with goals. The team worked towards and stayed within these goals in order to actually improve the conditions of Water Street. It would have been easy to become sidetracked and stray away from the task at hand since this was a long-term and complex project, but the team successfully alotted time to scope the project and consider the goals and limits before jumping right in to finding a solution. A handful of goals the team used to guide the project include:

- Maintaining current turn lanes and signal timing for ease of motorist travel
- Increasing pedestrian visibility and access
- Creating bike lanes that improve comfort level of riders
- Removing on-street parking only when necessary

- Limiting changes to existing conditions in order to reduce taxpayer burden and speed construction process (no new pavement just new pavement markings)

Problems of this complexity required a level of creativity to solve since there was not an obvious solution. The team began this project with a few rounds of brainstorming in an attempt to find a creative solution and reached out to the industry mentors to help generate more ideas. The result of this was a wide variety of design ideas from which to choose, and it was often possible to combine ideas. As time progressed, the team refined these ideas and chose a base design using a multi-criteria analysis. This analysis was done with input from a survey sent to potential users in order to hear from various stakeholders. Some of the more out-there solutions went against the team's original goals, and created problems that were unexpected. Once the final design alternatives were completed, the team had planned on doing user-testing through a VR environment. This became no longer possible with the circumstances of COVID-19. Instead, a white paper was written to describe how user-testing would have been conducted and a final alternative design was selected by completing another multi-criteria analysis.

If user-testing had been possible, an issue would have been collecting a representative sample group for user testing, which is a result from having many diverse stakeholders. In order to prevent volunteer or convenience biases from skewing the testing results, the team planned to carefully pick the test subjects and to provide an incentive for those who chose to participate in the study.

Factors Considered in Recommendations

<u>Public Health</u>

The purpose of this project was to design infrastructure changes to help to reduce the rate of accidents that occured on the Water Street corridor in order to protect the health and safety of the public. As a whole, more pedestrians and bicyclists would be and feel safer from the results of the design.

<u>Safety</u>

Safety is the number one consideration that this project is taking into account. Water Street has been identified as an area of focus in the state of Virginia because of the lack of safety the corridor currently provides. Through research and creative ideas, this team has designed a corridor that provides protection for all pedestrians and bicyclists. Some changes that have been included to increase safety include protected bike lanes, signage, and marked crosswalks.

<u>Welfare</u>

The welfare of the public has been an important consideration throughout the lifetime of this project. The alternative designs were to be tested in a virtual reality environment where subjects would be monitored for their reactions to each design. This would have allowed the team to consider their comfort and whether or not they feel safe with each proposed design.

Global Factors

There are not many global factors to consider for this project. However, research on pedestrian and bicycle infrastructure from other locations has been collected to help inspire the design alternatives for the Water Street Corridor. The results from this study can be used to help inspire other pedestrian and bicycle friendly designs at a global level.

Cultural Factors

The problem of safe bicycle and pedestrian infrastructure may influence cultural factors. In some cities, there is a built in culture of public transport in order to help environmental causes, as well as increase the health of an individual. Thus, there could be a culture of environmental and health conscious people. However, this factor has not been highly influential on influencing the final proposed design. The design would help the community in terms of safety, but cultural factors are secondary.

Social Factors

Similar to the cultural factors, if people are more environmentally or health conscious, then there will be this social stigma of wanting to ride bikes or walk more to work or other places. This is important to the project because there is a decent amount of bicycle and pedestrian traffic along the Water Street corridor. Many of these riders and walkers could be trying to be more socially aware of what others are doing around them to support these different environmental or health issues.

Environmental Factors

Many people are very conscious of how vehicles and public transport can affect the environment. This is why a lot of people consider the alternative options, walking and biking, when thinking about how to get to work or class or to a restaurant. This factor was considered in the redesign of the Water Street corridor. Environmental constraints and effects were integrated into the designs and the selection of the final alternative.

Economic Factors

It is certainly cheaper to own a bicycle or to simply walk wherever one is going instead of taking some mode of vehicular transportation. This is one reason why people choose to bike and walk to places instead of buying a car or paying for a public transport service. However, this is not a factor that the project team took into consideration when planning and redesigning the Water Street corridor.

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APPENDIX

Appendix A: Analysis and Supporting Information

This section is divided into subsections, as listed below.

- Background Information
- Basic Dimension Information
- Supporting Information Concerning All Design Alternatives
    - Bicycle lanes
    - Separated bicycle lanes
    - Sidewalks
    - Curb ramps
    - Marked crosswalks
    - Pedestrian signals and pushbuttons
    - Roadway signage
    - “Safe Systems” best practices
- Supporting Information Specific to the City Plans Alternative
    - Shared roadways
    - On-street parking
- Supporting Information Specific to the One-Way Alternative
    - Contraflow bicycle lanes
- Supporting Information Specific to the No Parking Alternative

Background Information

In Charlottesville, there is strong, existing community support and enthusiasm for walking and bicycling. The Charlottesville Bicycle & Pedestrian Master Plan Update of 2015 aims to build upon that existing culture (City of Charlottesville, 2015). The plan was developed over a 12 month period in 2014/15 and was overseen by City staff as well as the Bicycle and Pedestrian Master Plan Update Steering Committee. The City and the Bicycle and Pedestrian Steering Committee used a multi-faceted approach to gather the baseline data and input needed to develop their recommendations. That approach included four key steps:

- Inventory of existing bicycle and pedestrian facilities
- Public and stakeholder input
- Bicycle and pedestrian demand analysis
- Bicyclist level of traffic stress analysis

To help identify where bicycle and pedestrian facilities are most needed, the City measured demand for walking and biking. This analysis helps locate the roads where the greatest number of people are expected to walk and bike, which influences where active transportation infrastructure will be most needed. From this analysis, Water Street was identified as having a “high” generalized bicyclist and pedestrian demand. See Fig. 10, below.

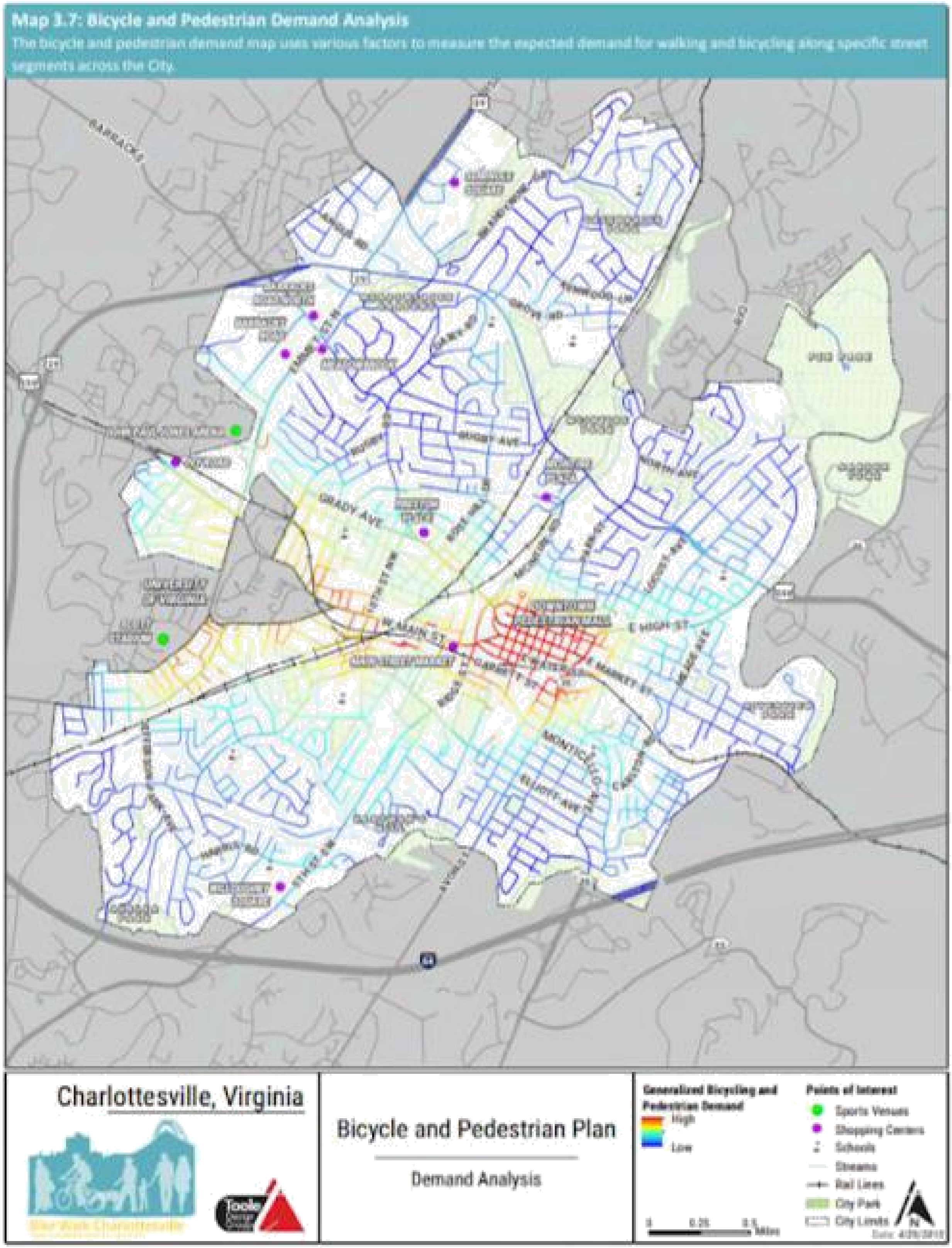


Figure 10: Demand analysis for walking and cycling (City of Charlottesville)

Based on the above research, the City of Charlottesville created recommended bicycle and pedestrian infrastructure projects for the city to build as part of their active transportation vision. The plan is divided into a few parts, including bicycle recommendations and pedestrian recommendations. Supporting information for these recommendations are described below.

Basic Dimension Information

To create the design requirements, basic information concerning bicycle and travel lane widths was research. Below is information that was gathered regarding these two entities.

According to VDOT's Bicycle and Pedestrian Facility Guidelines, the width of a bike lane is 5 feet minimum from the face of a curb to the bike lane stripe on roadways without a gutter pan (Virginia Department of Transportation). The width of a bike lane is 4 feet minimum from the edge of pavement (face of gutter pan) to the bike lane stripe on curb and gutter roadways. Greater bike lane widths (5 feet minimum) are required where substantial truck traffic is present, transit buses are present, or where posted speeds exceed 40 mph. Therefore, there will be a minimum of 5 feet for bike lanes.

From VDOT's same guidelines, residential and mixed-use local streets should have a minimum width of 7 feet (measured from the face of curb) for parking lanes. These guidelines also note that there should be no parking within 20 feet of any intersection measured from the curb return of the intersection.

Supporting Information Concerning All Design Alternatives

All of the design alternatives described above have the following elements.

- Bicycle lanes
- Separated bicycle lanes
- Sidewalks
- Curb ramps
- Marked crosswalks
- Pedestrian signals and pushbuttons
- Roadway signage
- "Safe Systems" best practices

Each of these elements is supported with research, as described below.

Bicycle Lanes

From the Charlottesville Bicycle & Pedestrian Master Plan Update of 2015, bicycle lanes are one-way, on-road bike facilities that provide a dedicated space for people bicycling parallel to motor vehicle traffic (City of Charlottesville, 2015). Bicycle lanes are often delineated with pavement marking stripes and, in some cases, may be fully colored for higher visibility, especially at intersections. Additional striping or hatching between a bicycle lane and vehicular travel lane is recommended to provide a buffer between the person bicycling and the person driving, where roadway widths allow. Bicycle lanes without a buffer require a minimum width of 5-6 feet and bicycle lanes with a buffer require 7-8 feet.

From this information, the project's design alternatives incorporate bike lanes that are at least 5 feet wide. Different levels of bike lane protection were to be tested, as it is recommended to provide a bike buffer between the bike and travel lanes.

Separated Bicycle Lanes

From the Charlottesville Bicycle & Pedestrian Master Plan Update of 2015, separated bicycle lanes are on-road facilities that have separation from motor vehicle traffic (City of Charlottesville, 2015). Vertical separation can provide visual separation or provide physical protection from motor vehicles, using features such as curbs, planters or parked vehicles. The separation increases the perceived sense of safety and can make bicycle routes less stressful. These bicycle lanes can be one-directional on each side of the road, or bi-directional on one side of the road. Separated bicycle lanes require a minimum width of 8-12 feet for a two-way configuration and 5-7 feet for a one-way configuration.

Based on this analysis, the design alternatives incorporate separated bike lanes using bike post barriers. The one-way alternative has a bi-directional separated bike lane on one side of the road, and the city and no parking alternatives have one-directional bike lanes on each side of the road. The recommended widths of 8-12 feet and 5-7 feet have also been incorporated into the design alternatives.

Sidewalks

From the Charlottesville Bicycle & Pedestrian Master Plan Update of 2015, sidewalks are separated, paved pedestrian routes that make up the spine of the pedestrian network (City of Charlottesville, 2015). New sidewalks are required to meet ADA guidelines for width and cross slope. The sidewalk minimum in a residential area is 5 feet and in commercial areas, sidewalks can range from 10 to 20 feet. Optimum sidewalk width will vary depending on pedestrian volumes, land use and desired streetscape elements.

All of the design alternatives incorporate sidewalks that are at least 5 feet wide. Designs that include expansion of the sidewalk also include ADA-compliant ramps. More information about ADA curb ramps is described below.

Curb Ramps

From the Charlottesville Bicycle & Pedestrian Master Plan Update of 2015, ADA-compliant curb ramps are necessary at corners and crosswalks to provide a smooth transition from the sidewalk to the roadway (City of Charlottesville, 2015). Ramps should be made as wide as the approaching sidewalk or path to accommodate more than one user at a time. Two perpendicular ramps on each corner are preferred over one diagonal ramp where physical conditions permit.

The city plans do not require the addition of sidewalks but ADA-compliant ramps will be added where existing ones are not in-place. The one-way and no parking alternatives, on the other hand, do require the addition of sidewalks and will therefore implement ADA-compliant ramps at each intersection.

Marked Crosswalks

From the Charlottesville Bicycle & Pedestrian Master Plan Update of 2015 marked crosswalks indicate optimal or preferred locations for pedestrians to cross and help designate right-of-way for motorists to yield to pedestrians (City of Charlottesville, 2015). Reasonable accommodations should be made to ensure pedestrians do not have to travel too far out of their way to use a marked crosswalk. Crosswalks should be marked with high visibility, use patterns, retroreflective pavement markings and may require additional signage or pedestrian activated signals depending on their context.

To accomodate marked crosswalks, additional signage will be added at pedestrian traffic-heavy intersections. A rectangular rapid flashing beacon (RRFB) will be added on each side of the road at two different intersections along the Water Street corridor. These RRFBs will add higher visibility and signage to the intersections.

In addition, there is a consideration of reducing crosswalk lengths, as suggested by industry mentor Karen King. Ms. King is a Highway Safety Engineer in the Virginia Division of the Federal Highway Administration.

Pedestrian Signals and Pushbuttons

From the Charlottesville Bicycle & Pedestrian Master Plan Update of 2015, pedestrian signals provide important information for pedestrians crossing the street (City of Charlottesville, 2015). The signals must be clearly visible to pedestrians in the crosswalk or those waiting on the opposite side of the street. The Manual on Uniform Traffic Control Devices (MUTCD) requires signals with countdown timers to discourage pedestrian crossings toward the end of the cycle when only a few seconds remain. In general, shorter overall cycle lengths and longer walk intervals concurrent with the flow of parallel traffic provide the highest level of pedestrian service.

Pedestrian push buttons must be located where they are accessible to all pedestrians. Buttons placed on existing signal poles may require relocation or extensions to be accessible for pedestrians with mobility impairments. Audible pedestrian push buttons emit sounds and instructions for pedestrians with vision impairments and can help simplify crossings in locations with limited non-visual clues or complex intersection geometry.

While not implementable in the VR testing environment (and therefore not included in the design alternatives), these types of pedestrian signals and pushbuttons should be considered by the city when officially deciding what types of improvements to make in the Water Street corridor.

Roadway Signage

According to the article titled '"Bicycles May Use Full Lane" Signage Communicates U.S. Roadway Rules and Increases Perception of Safety, the "Bicycles May Use Full Lane" signage showed notable increases in comprehension among novice bicyclists and private motor vehicle commuters, critical target audiences for efforts to promote bicycling in the USA (Hess, 2015). Although limited in scope, the article's survey results are indicative and suggest that Departments of Transportation consider replacing "Share the Road" with "Bicycles May Use Full Lane" signage, possibly combined with Shared Lane Markings, if the intent is to increase awareness of roadway rights and responsibilities. However, further evaluation through virtual reality simulations and on-road experiments is merited.

"Safe Systems" Best Practices

According to the Institute of Transportation Engineers (ITE), the Safe Systems approach differs from conventional safety practice by being human-centered, i.e. seeking safety through a more aggressive use of vehicle or roadway design and operational changes rather than relying primarily on behavioral changes – and by fully integrating the needs of all users (pedestrians, bicyclists, older, younger, disabled, etc.) of the transportation system (Safe Systems). The design alternatives implement some of the ITE's best practices for Safe Systems, such as

- Separating users in space
- Increasing attentiveness
- Reducing vehicle speeds

Separating users in space is important because it segregates the physical space to provide travelers with a dedicated part of the right-of-way. Typically, travelers moving at different speeds – pedestrians, bicyclists, etc. (e.g. sidewalks, cycle tracks) – or different directions (e.g. turning vehicles in separate turn lanes) are separated in space to minimize conflicts with other users. The design alternatives have a separated bike lane to provide bicyclists with a buffer between the bike and travel lanes.

Increasing attentiveness and awareness is critical. This approach seeks to alert users to potential hazards and/or the presence of other users. These techniques can be vehicle, user or infrastructure-based. One way to increase attentiveness is through rectangular rapid flashing beacons (RRFB) that warn drivers of the presence of crossing pedestrians. The project's design alternatives implement 4 different RRFBs.

Lastly, the laws of physics dictate that greater harm will occur at higher speeds and that, typically, the greater the mass of a vehicle, the more harm it will inflict on others. For vulnerable users, speed is a determining factor in survivability – a human's chance of surviving being struck by a vehicle increases from 20% at 40 mph to 60% at 30 mph to 90% at 20 mph. Reducing speed in the presence of vulnerable users is a key safe systems strategy. One approach to tackle this issue is in physical roadway designs (i.e. width and horizontal alignment) to limit free flow speeds. Some of the preliminary designs had wider roadway widths (12 and 13 feet), but the team decided to reduce those widths to around 11 feet to allocate more space for sidewalk expansion and bike buffers.

Supporting Information Specific to the City Plan Alternative

The city plan alternative has the following unique elements.

- Shared roadways
- On-street parking

Each of these elements is supported with research, as described below.

Shared Roadways

From the Charlottesville Bicycle & Pedestrian Master Plan Update of 2015, shared roadways are bicycle facilities that designate a vehicular travel lane as a shared space for people to drive and bicycle (City of Charlottesville, 2015). This designation is demonstrated to all users through on-road pavement markings, known as "sharrows" or street signage indicating that people bicycling may use the full lane. These facilities do not provide any separation between people driving and bicycling and are best used on neighborhood streets or streets with a low level of bicyclist traffic stress.

This information has helped us implement sharrows into the city plans. Some parts of the corridor are too narrow to include sidewalk, parking lanes, travel lanes, *and*bike lanes. Therefore, a sharrow is an efficient design option.

On-Street Parking

From the Charlottesville Bicycle & Pedestrian Master Plan Update of 2015, on-street parking forms a physical buffer between pedestrians and moving vehicles (City of

Charlottesville, 2015). By visually narrowing the travel way, on-street parking encourages drivers to slow down. Because of these benefits, this design idea has been incorporated into the city plans.

In addition, the National Association of City Transportation Officials (NACTO) released a street design principles guide that supports the city plan alternative. The guide mentions how important it is to create definition in the roadway by using striping and cycle tracks. Striping and cycle tracks will be incorporated into the different levels of bike protection that will be tested in VR. The guide also says that cycle tracks require specific attention at intersection crossings. Conflicts could be highlighted using intersection crossing markings with the application of color optional.

Supporting Information Specific to the One-Way Alternative

The one-way alternative has the following unique elements.

- Contraflow bicycle lanes

This design element is supported with research, as described below.

From the Charlottesville Bicycle & Pedestrian Master Plan Update of 2015, contraflow bicycle lanes are on-road bicycle facilities built on one-way streets that provide dedicated space for bicycling in the opposite direction of motor vehicle travel (City of Charlottesville, 2015). These facilities help provide more direct connections for bicycling by transforming a one-way street for motorists into a two-way street for bicyclists. Contraflow bicycle lanes require a minimum width of 5-6 feet and the ability to add shared lane markings in the direction of travel.

Furthermore, according to the NACTO street design principles guide, bicyclists feel uncomfortable riding between fast-moving traffic and the door zone. Double-parked vehicles may cause bicyclists to weave into traffic unpredictably, creating unsafe conditions for both motorists and bicyclists. Many downtown one-way streets have travel lanes with extra capacity or peak-hour restricted parking lanes. Historically, many two-way downtown streets were converted to one-way streets in the mid 20th century to streamline traffic operations and reduce conflicts.

A raised cycle track, or parking-buffered cycle track applied on the left side of a one-way street, removes cyclists from potential conflict with bus traffic and creates a pedestrian safety island that decreases exposure time for pedestrians. This is exactly what the one-way design consists of. Two-way bike lanes can also function effectively on one-way streets. Lastly, as part of a full reconstruction, widening sidewalks should be taken into consideration, especially when they have previously been narrowed in favor of additional travel lanes. The one-way design implements the widening of sidewalks to improve pedestrian safety and comfort.

Supporting Information Specific to the No Parking Alternative

The findings in the article titled “User Preferences for Bicycle Infrastructure in Communities with Emerging Cycling Cultures” indicate a preference for more separated bicycle infrastructure types along with options that exclude on-street parking (Transportation Research Record). This is where the idea for a design alternative with no parking was initiated. The analysis in the article includes linear regression models built on respondents’ reactions to images of bicycling infrastructure and their perceptions of being comfortable, safe, and willing to try cycling on the displayed roadway type.

In addition, according to the Federal Highway Administration’s Separated Bike Lane Planning and Design Guide, providing one-way separated bike lanes on each side of a two-way street creates a predictable design for managing user expectations (Federal Highway Administration). Typically, each separated bike lane will run to the outside of the travel lanes in a design similar to a one-way separated bike lane on a one-way street. A potential challenge with this design is that it takes up more roadway space compared to the alternatives of providing a two-way separated bike lane or developing alternate corridors for directional travel. However, because parking has been removed from this design alternative, there is room for bike lanes on each side of the road.

Appendix B: Intended User Testing Plan

Logistics

- When will users be tested?
  - User testing will take place in mid- to late-March in the Viz Lab/ORCL Lab.
- How will users be tested?
  - Users will use virtual reality (VR) equipment to assess the alternative bike infrastructure designs.
    - Users will wear a VR headset and ride a stationary bicycle that is connected to the VR environment.
  - Users will begin the testing with a baseline VR environment to get their heart rate up to a steady pace.
    - A smartwatch will be used to collect physiological data.
  - Users will then ride through the no-build condition and three alternative designs.
    - After each alternative design, users will answer feedback questions that analyzes the users' safety and comfort on a 1-5 scale (this piece could change).
- Where will users be tested?
  - Users will be tested in the Viz Lab/ORCL Lab.
- How long will the test be?
  - The test will probably last about an hour.
- Will the users be compensated?
  - No, the users will not be compensated for their time.
- Is there anything a user will have to complete beforehand?
  - Users may have to sign a liability waiver.

Experimental Design

- The capstone team will do trial runs for the experimental design. However, their data won't be part of the final data set (due to bias of being familiar with the environments)
- Number of participants
  - 16, 20, or 24
    - Based on 10:1 recommendation for sample size to variable ratio (Newsom, 2018)
    - 2 variables being studied (presence of buffer, presence of barrier posts)
    - 24 different permutations of alternative order
- Environments each participant will test
  - All 4 environments (order randomized)
    - No-build
    - Bike lane with no buffer
    - Bike lane with 2' buffer
    - Bike lane with 2' buffer and barrier posts
  - Consider not counting first of the 4 environments because of user adjustment and comfortability (will finalize after data collection)

- Physiological data to collect
    - Huawei smartwatch
        - Heart rate variation for calculating stress level
        - Not planning to evaluate eye-tracking data
- Final score for each alternative → white paper
    - 3 factors
        - Safety (user survey response on scale of 1-5)
        - Comfort (user survey response on scale of 1-5)
        - Physiological score (will finalize after data collection)
- Testing procedure
    1. Ask participants to fill out consent form
    2. Read script to participants
    3. Bike in generic road for 2 minutes to get heart rate up to a stable level
    4. Bike in the 4 environments in a random order - this will be predetermined to ensure that all 4 environments are equally tested by order
    5. In each environment, stop the experiment once participant passes the study extents
    6. Ask participant post-experiment survey questions after each of the 4 environments. Fill out Data Collection Spreadsheet for Test Subjects with participants' responses.
        - Survey questions:
            - *Please rank how you feel about the statement: "I felt **safe** riding in this environment," with:*
                - *1 being Strongly disagree*
                - *2 being Disagree*
                - *3 being Neither agree nor disagree*
                - *4 being Agree*
                - *5 being Strongly agree*
            - *Please rank how you feel about the statement: "I felt **comfortable** riding in this environment," with:*
                - *1 being Strongly disagree*
                - *2 being Disagree*
                - *3 being Neither agree nor disagree*
                - *4 being Agree*
                - *5 being Strongly agree*
    7. Ask participant for any comments after entire experiment is complete (record in spreadsheet)

Consent Form

Water St Bicycling VR Study: Consent Form

Please read this consent agreement carefully before you decide to participate in the study.

* Required

Purpose of the research study

Rising rates of non-motorized traveler fatalities are an urgent concern in the transportation research community. Standard state and national level crash data sets are derived from police crash reports and are automobile-centric. Analysis of such automobile-centric crash data sets have led to (generally) improving vehicle occupant safety, while bicyclists and pedestrian fatality rates continue to rise. With limited data available on bicyclist and pedestrian safety, innovative strategies are necessary to improve safety for the most vulnerable road users. The recent advancement of virtual reality technology has opened the door for lower cost and lower risk ways to study bicyclists' and pedestrians' perception of safety and acceptance of safety technology.

Recent studies have shown that VR is an effective tool to replicate realistic environmental settings at a low cost and reduced risk to the user. With VR, we can study human behaviors in settings/scenarios that (1) we have limited or no access to (e.g., design of a new intersection that has not been built yet) or (2) are considered high-risk environments for collecting real-life data (e.g., bicyclist safety or crash rates at an intersection and pedestrian crash rates at mid-block crossings). Additionally, these tools provide us the freedom to control and manipulate different variables of interest, which we might not have access to in real-life environments. By coupling VR tools with biometric sensors (e.g., eye trackers and smartwatches), in addition to behavioral information, users' physiological information can also be collected and analyzed. The anticipated product from this research is an understanding of perceived safety and technological acceptance as it relates to bicyclists, pedestrians, and the road environment. This information can be used by planners and engineers to better design technology and infrastructure for bicyclists and pedestrians.

What you will do in the study

The goal of this study is to place bicyclists in an environment in which they can naturally interact with vehicles without the safety concerns of a real world experiment by utilizing virtual reality (VR) technologies. The participant will be seated on a stationary bike and will be wearing a VR headset and physiological sensing. The instrumented bicycle will allow their actions to be replicated in the virtual environment (speeding up, slowing down, steering). Specifically, this research aims to study how bicyclists behave in scenarios where they are presented with different elements of roadway environments. These may include factors such as different types of bicycle infrastructure, lane widths, traffic volumes or surroundings. You will be given a short questionnaire after each test in which you will respond according to your thoughts and feelings regarding your experience.

Time required

The study will require about 1 hour of your time.

Risks

The physical components of these tasks are not stressful, and include head and body turning, moving, and pointing. Light and sound intensities are well within normal ranges. The only foreseeable physical risks are slight eye strain, dizziness, and mild nausea. There are no known mental risks. Participants will be asked to remove the head mounted display if they experience any eye strain, dizziness, or nausea during the sessions. They will be given rest breaks in between the sessions. Upon request, they will also be allowed to be dismissed from the experiment if they feel uncomfortable or cannot continue the experiment. A loss of confidentiality would not put participants at risk.

Benefits

There are no direct benefits associated with the participation in this study. The proposed experiments are straightforward tests of performance and visual comfort using standard virtual environments displays and trackers.

Confidentiality

The information that you give in the study will be handled confidentially. Your name will not be used in any report.

Voluntary participation

Your participation in the study is completely voluntary.

Right to withdraw from the study

You have the right to withdraw from the study at any time without penalty.

How to withdraw from the study

If you want to withdraw from the study, please contact Emily Chen at ecc7qd@virginia.edu indicating that you would like to withdraw from the study. There is no penalty for withdrawing. You may request that your archived data to be destroyed upon withdrawing from the study.

Payment

You will not receive compensation for participating in this study.

Contact Information

If you have questions about the study, contact:

Emily Chen
Email address: ecc7qd@virginia.edu

Donna Chen
Engineering Systems and Environment
151 Engineer's Way, Room 101G
University of Virginia, Charlottesville, VA 22904
Telephone: (434) 924-6224
Email address: tdchen@virginia.edu

Arsalan Heydarian
Engineering Systems and Environment
151 Engineer's Way, Room 257
University of Virginia, Charlottesville, VA 22904
Telephone: (434) 924-1014
Email address: ah6rx@virginia.edu

To obtain more information about the study, ask questions about the research procedures, express concerns about your participation, or report illness, injury or other problems, please contact:

Tonya R. Moon, Ph.D.
Chair, Institutional Review Board for the Social and Behavioral Sciences
One Morton Dr Suite 500
University of Virginia, P.O. Box 800392
Charlottesville, VA 22908-0392
Telephone: (434) 924-5999
Email: irbsbshelp@virginia.edu
Website: www.virginia.edu/vpr/irb/sbs

Agreement *

☐ I agree to participate in the research study described above.

Submit

Script to Read to Participants

After the participant has filled out the consent form…

Welcome

Welcome to the Omni-Reality and Cognition Laboratory and thank you for this participation in this study. Today, you will be entering a virtual environment modeled after the Water Street corridor parallel to the downtown mall in Charlottesville, VA as a bicyclist. Your task as a bicyclist is to bike in the virtual environment until we manually end the experiment for you.

During this experiment, you will be wearing an HTC VIVE headset. You will also be riding a stationary bicycle with handheld controllers and wear a smartwatch to track your physiological data. Video recording of your actions will be recorded in the virtual environment as well as in the testing room.

Should you have any questions or concerns during the test, please feel free to ask me at any time. Should you experience any motion sickness and wish to exit the virtual environment, please let me know at any moment. All data from this test will be made public, however, none of the data collected will in any way, shape, or form, identify you as having been a test subject. Do you have any questions for me before we begin the calibration and testing?

Familiarization

Before you put on the equipment, I will explain what tests you will encounter today. There are a total of 5 environments you will ride in - an environment for you to get used to the VR equipment and 4 other testing environments. First, you will ride on a generic roadway to get used to the feel of the VR equipment and to get your heart rate up to a steady pace. You will ride here for 2-3 minutes. I will then stop that environment and we will move onto the 4 main testing environments. These environments should take a few minutes each to ride in. We will manually stop each of these experiments for you before the roadway ends, so please keep biking normally until the experiment ends. We will then verbally ask you 2 survey questions at the end of each test so that you don’t have to remove all of the VR equipment. At the end of all 4 experiments, you will remove all of your equipment and there will be one final survey question. Do you have any questions up until this point?

Please put the smartwatch on your left wrist, snuggly but comfortably. Please mount the stationary bicycle. Place your left hand just to the right of the controller on the handlebar. Place your right hand just to the right of the controller with your thumb wrapped around the controller. Feel the trigger under the controller with your index finger - this is the brake. Please put on the HTC VIVE headset and make any appropriate adjustments so that it fits snug on your head. *(Researcher can help here if necessary)*.

Once the generic road virtual environment has been loaded…

Steering Calibration

Turn the bicycle handle to the left → *calibrate*

Turn the bicycle handle to the right → *calibrate*

Turn the bicycle handle back to the neutral middle position → *calibrate*

Please bike around in this environment to get used to the feel of the stationary bike. Bike at a normal pace according to what feels comfortable to you.

Once the user is calibrated and comfortable...

Now that you have been familiarized with the environment, we will proceed to the next phase of the experiment. Should you wish to spend a bit more time here within the familiarization environment, you are more than welcome to do so. When you feel that you are ready to move forward, let me know.

After experiment 1 is loaded...
CALIBRATE AGAIN

Experiment 1

You will now be placed within the first of four environments *(no-build, bike lane, bike lane with buffer, bike lane with barrier)*. Your task is to bike until we stop the experiment.

Once complete, have the participant answer the questionnaire.

After experiment 2 is loaded...
CALIBRATE AGAIN

Experiment 2

You will now be placed within the second of four environments*(no-build, bike lane, bike lane with buffer, bike lane with barrier)*. Your task is to bike until we stop the experiment.

Once complete, have the participant answer the questionnaire.

After experiment 3 is loaded...
CALIBRATE AGAIN

Experiment 3

You will now be placed within the third of four environments *(no-build, bike lane, bike lane with buffer, bike lane with barrier)*. Your task is to bike until we stop the experiment.

Once complete, have the participant answer the questionnaire.

After experiment 4 is loaded...
CALIBRATE AGAIN

Experiment 4

You will now be placed within the last of four environments *(no-build, bike lane, bike lane with buffer, bike lane with barrier)*. Your task is to bike until we stop the experiment.

Once complete, have the participant answer the questionnaire.

Debrief

You may now dismount the stationary bicycle and remove the headset. Please place it on the designated spot on the ground. Please remove the smartwatch and place it next to the headset. Experimentation within the virtual environment is now complete.

Do you have any comments you'd like to make about your experience in this study?

Thank you for your time.

Data Collection Spreadsheet for Test Subjects

									Familiarization		*No-Build*			
#	**Date**	**Name**	**Age**	**Sex**	**1st Environment**	**2nd Environment**	**3rd Environment**	**4th Environment**	**VR Start Time**	**VR End Time**	**VR Start Time**	**VR End Time**	**Safety**	**Comfort**
1					No-build	Bike no buffer	Bike 2' buffer	Bike 2' w/ poles						
2					Bike 2' w/ poles	No-build	Bike no buffer	Bike 2' buffer						
3					Bike 2' buffer	Bike 2' w/ poles	No-build	Bike no buffer						
4					Bike no buffer	Bike 2' buffer	Bike 2' w/ poles	No-build						
5					Bike 2' w/ poles	Bike 2' buffer	Bike no buffer	No-build						
6					No-build	Bike 2' w/ poles	Bike 2' buffer	Bike no buffer						
7					Bike no buffer	No-build	Bike 2' w/ poles	Bike 2' buffer						
8					Bike 2' buffer	Bike no buffer	No-build	Bike 2' w/ poles						
9					Bike no buffer	Bike 2' w/ poles	No-build	Bike 2' buffer						
10					Bike 2' buffer	Bike no buffer	Bike 2' w/ poles	No-build						
11					No-build	Bike 2' buffer	Bike no buffer	Bike 2' w/ poles						
12					Bike 2' w/ poles	No-build	Bike 2' buffer	Bike no buffer						
13					Bike 2' buffer	No-build	Bike 2' w/ poles	Bike no buffer						
14					Bike no buffer	Bike 2' buffer	No-build	Bike 2' w/ poles						
15					Bike 2' w/ poles	Bike no buffer	Bike 2' buffer	No-build						
16					No-build	Bike 2' w/ poles	Bike no buffer	Bike 2' buffer						
17					No-build	Bike no buffer	Bike 2' w/ poles	Bike 2' buffer						
18					Bike 2' buffer	No-build	Bike no buffer	Bike 2' w/ poles						
19					Bike 2' w/ poles	Bike 2' buffer	No-build	Bike no buffer						
20					Bike no buffer	Bike 2' w/ poles	Bike 2' buffer	No-build						
21					Bike no buffer	No-build	Bike 2' buffer	Bike 2' w/ poles						
22					Bike 2' w/ poles	Bike no buffer	No-build	Bike 2' buffer						
23					Bike 2' buffer	Bike 2' w/ poles	Bike no buffer	No-build						
24					No-build	Bike 2' buffer	Bike 2' w/ poles	Bike no buffer						

Bike Lane w/ No Buffer				*Bike Lane w/ 2' Buffer*				*Bike Lane w/ 2' Buffer and Barriers*				
VR Start Time	**VR End Time**	**Safety**	**Comfort**	**VR Start Time**	**VR End Time**	**Safety**	**Comfort**	**VR Start Time**	**VR End Time**	**Safety**	**Comfort**	**Participant Comments**

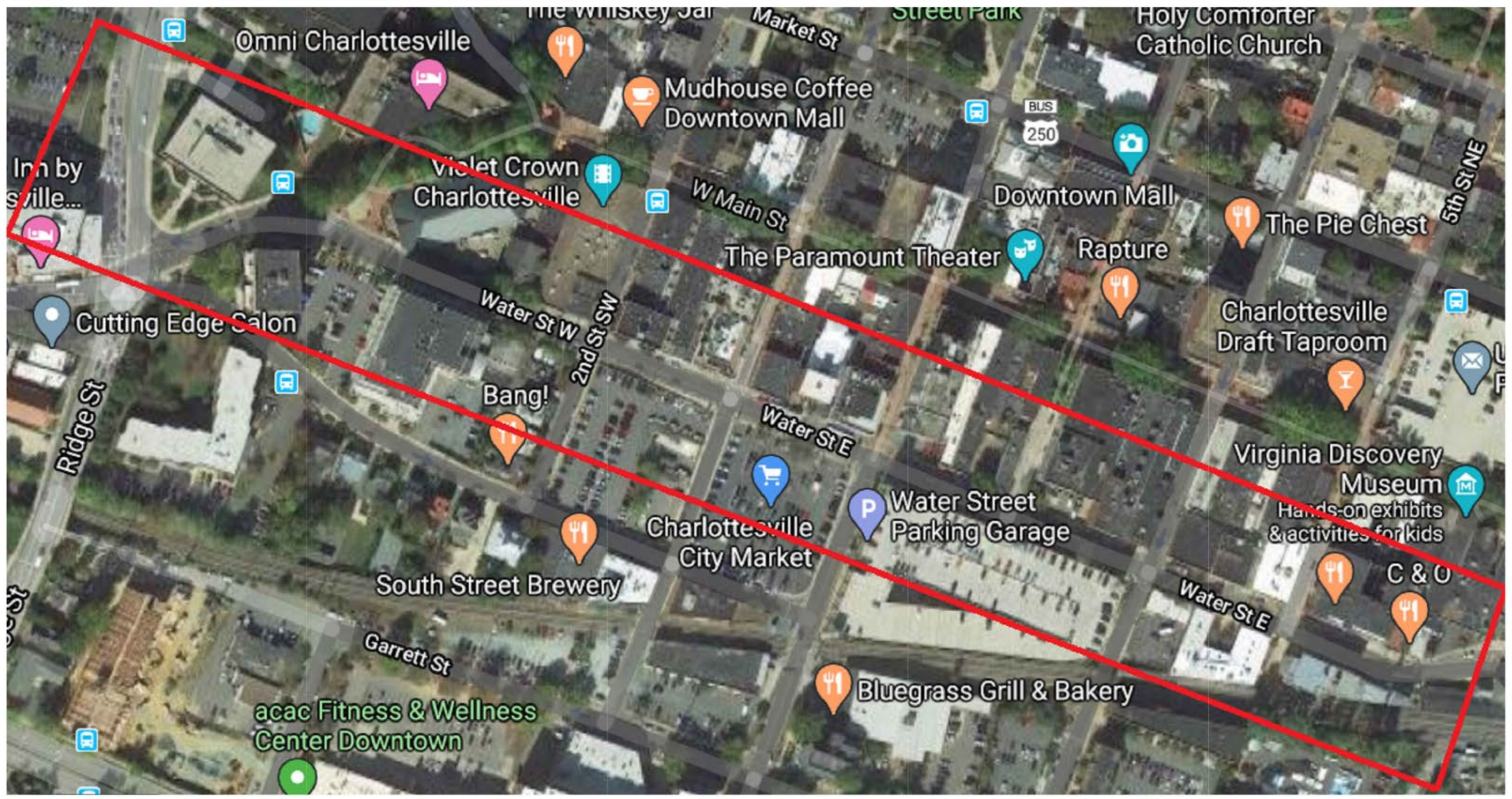
Appendix C: Final Design Alternatives Plan Set

See the following pages

Project Description

Water St Pedestrian and Bicyclist Infrastructure Improvements

CHARLOTTESVILLE, VIRGINIA, USA



Design Alternatives Plan

KEY MAP

N

[redacted] [redacted]

N/A

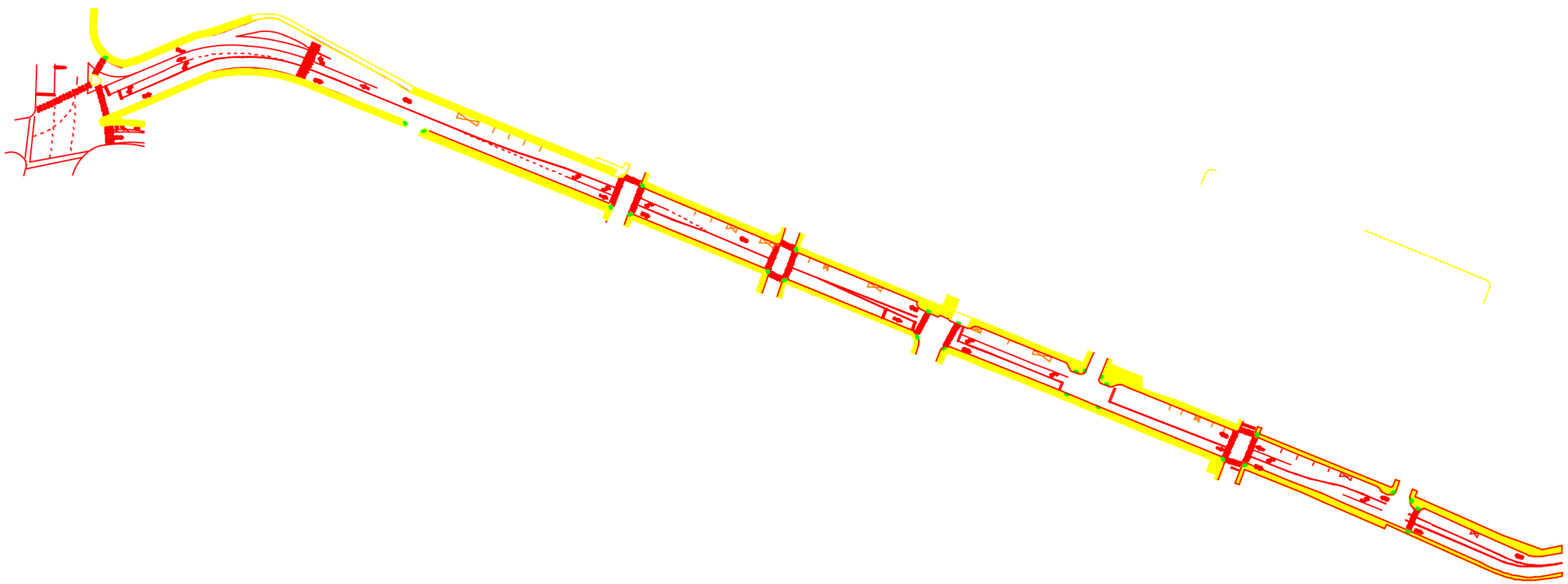
[redacted]

1

3/26/2020

[redacted]

Cover Sheet



LEGEND

- Lane markings
- Sidewalk
- On-street Parking
- Truncated Domes (ADA-compliant)

Project Description

KEY MAP

N

[redacted] [redacted]

1" = 180'

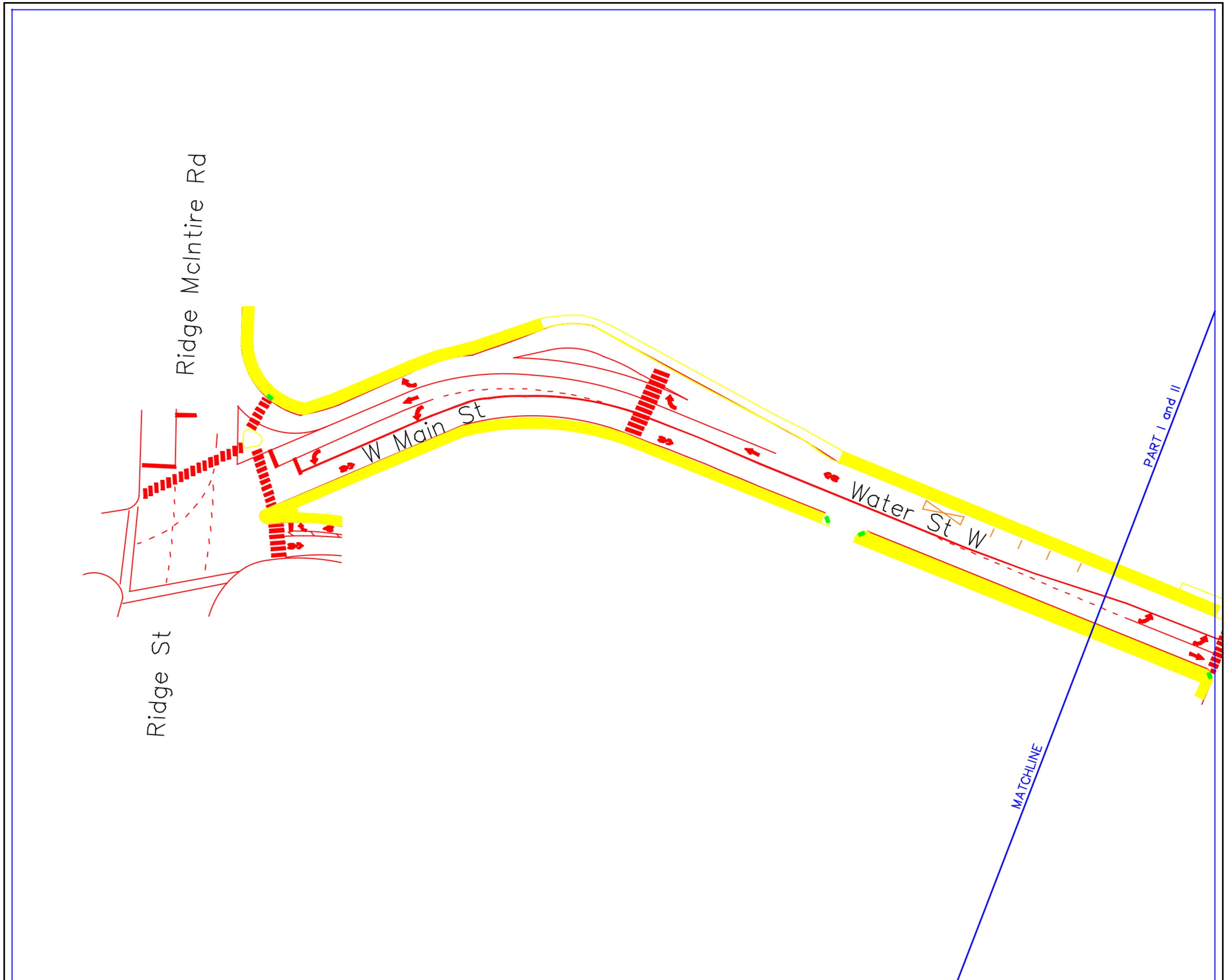
[redacted]

3/26/2020

2

[redacted]

Existing Conditions (Overview)



Project Description

KEY MAP

N

[redacted] [redacted]

1" = 50'

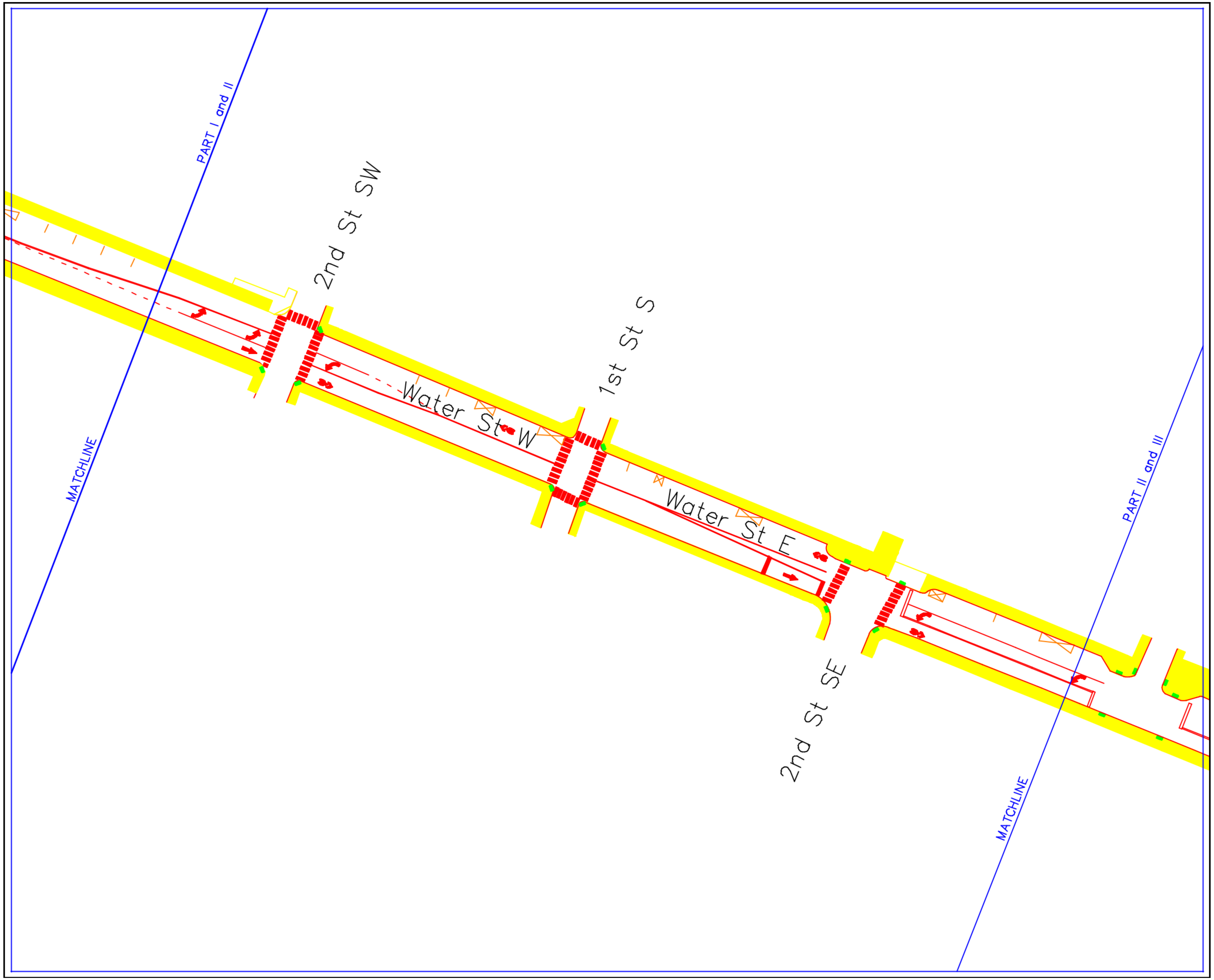
[redacted]

3/26/2020

3

[redacted]

Existing Conditions (Part I)



Project Description

KEY MAP

N

[redacted] [redacted]

1" = 50'

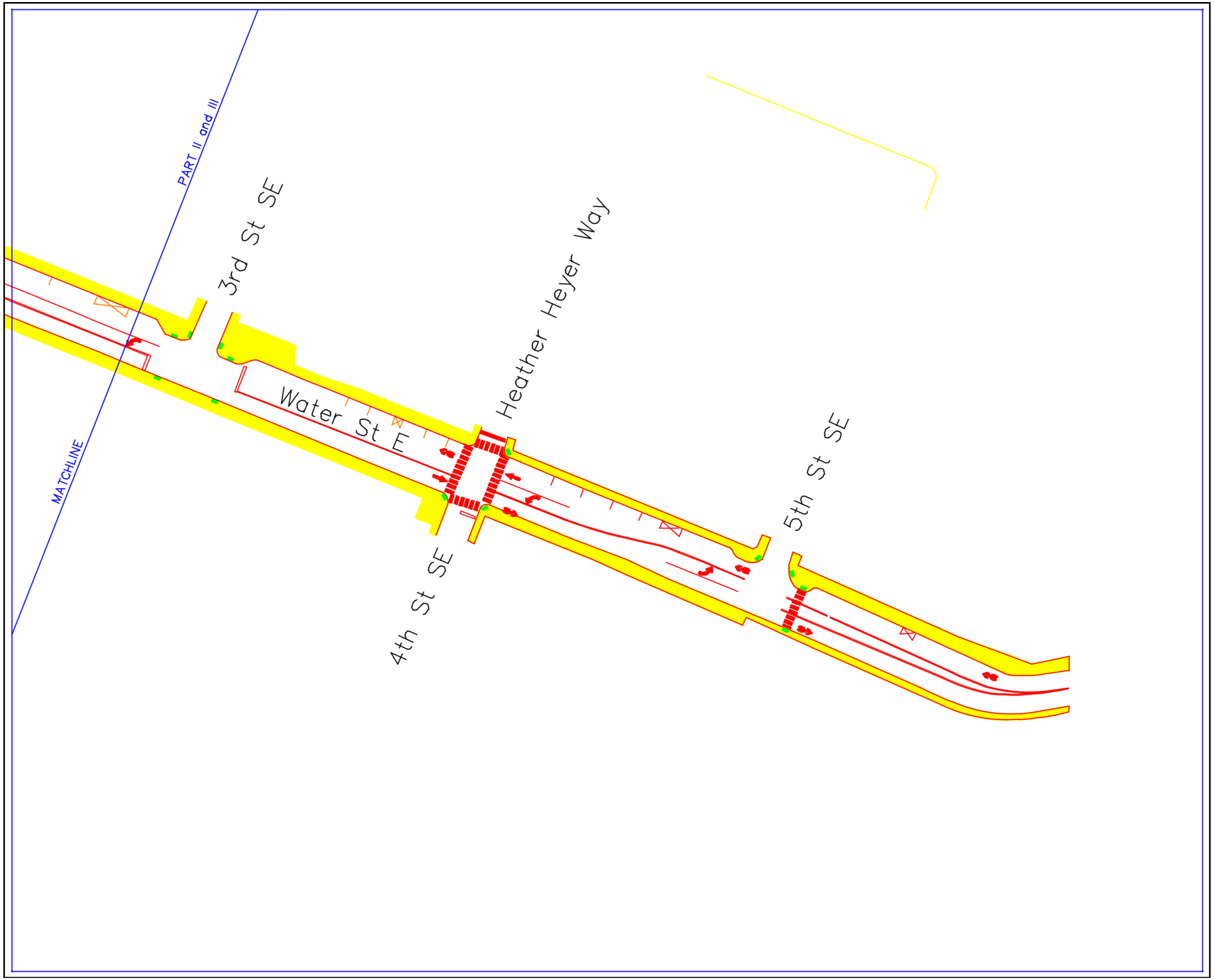
[redacted]

4

3/26/2020

[redacted]

Existing Conditions (Part II)



Project Description

KEY MAP

N

[redacted] [redacted]

1" = 50'

[redacted]

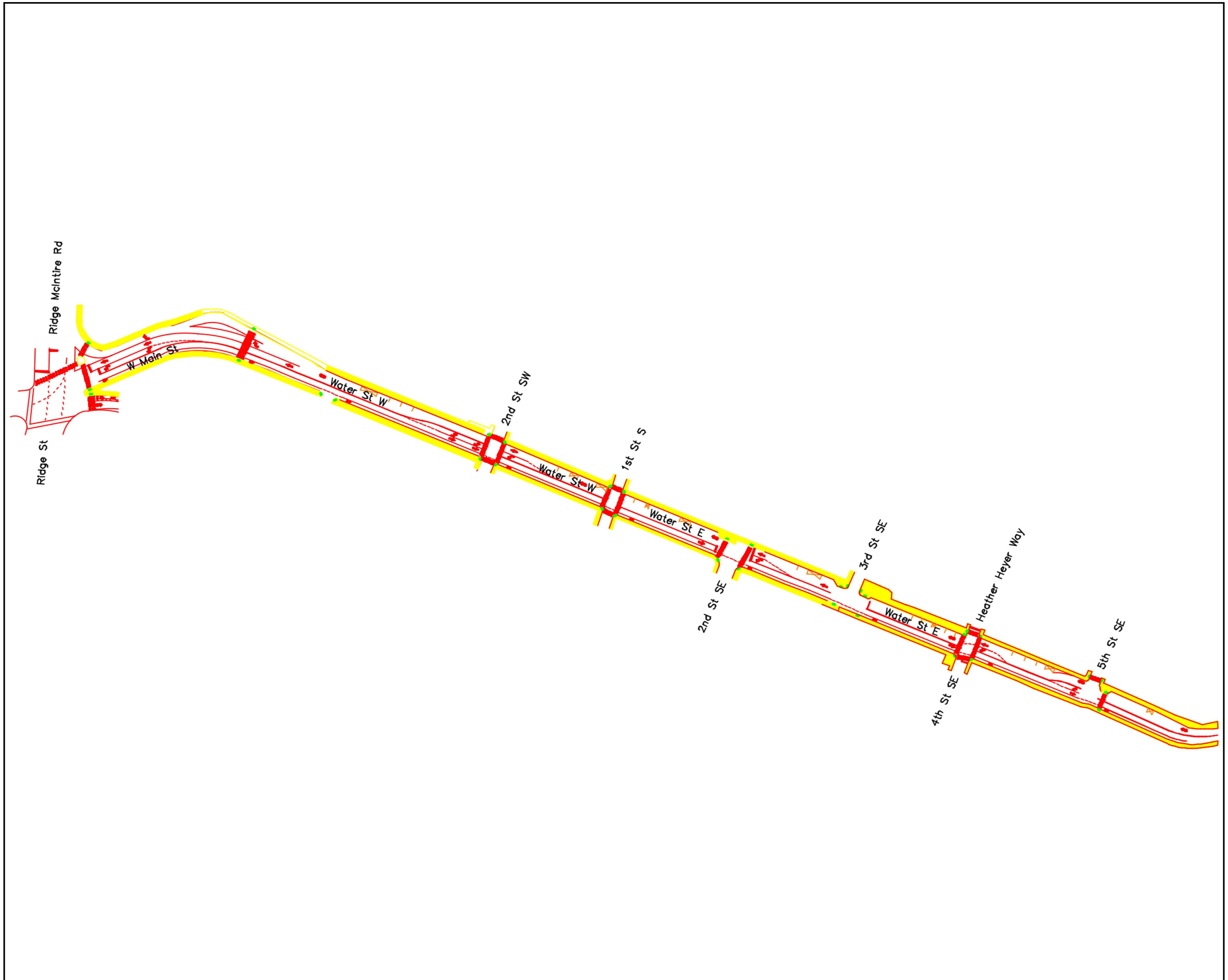
5

3/26/2020

[redacted]

Existing Conditions (Part III)

Project Description



KEY MAP

N

[redacted] [redacted]

1" = 180'

[redacted]

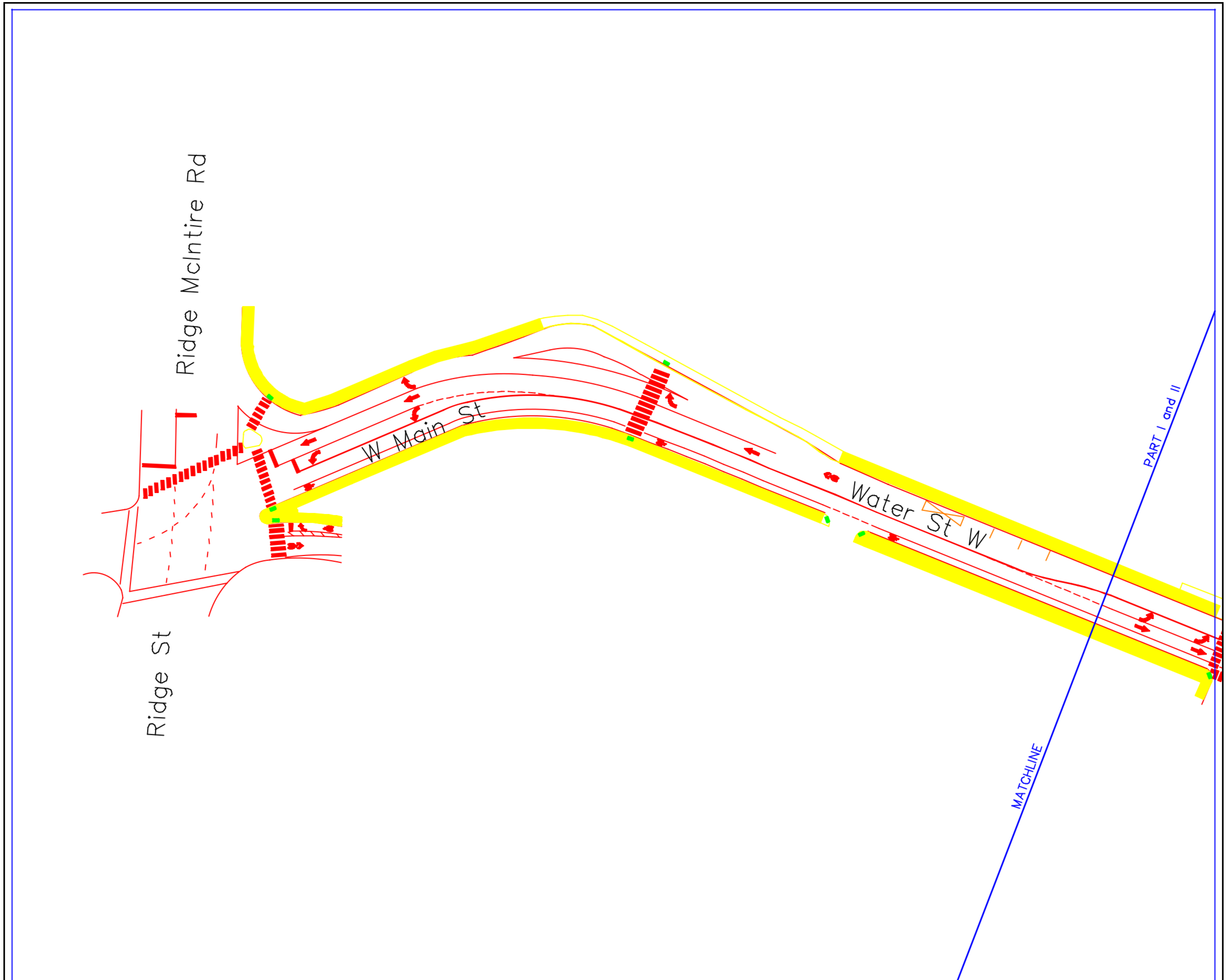
6

3/26/2020

[redacted]

Alternative 1 (Overview)

Project Description



KEY MAP

N

[redacted] [redacted]

1" = 50'

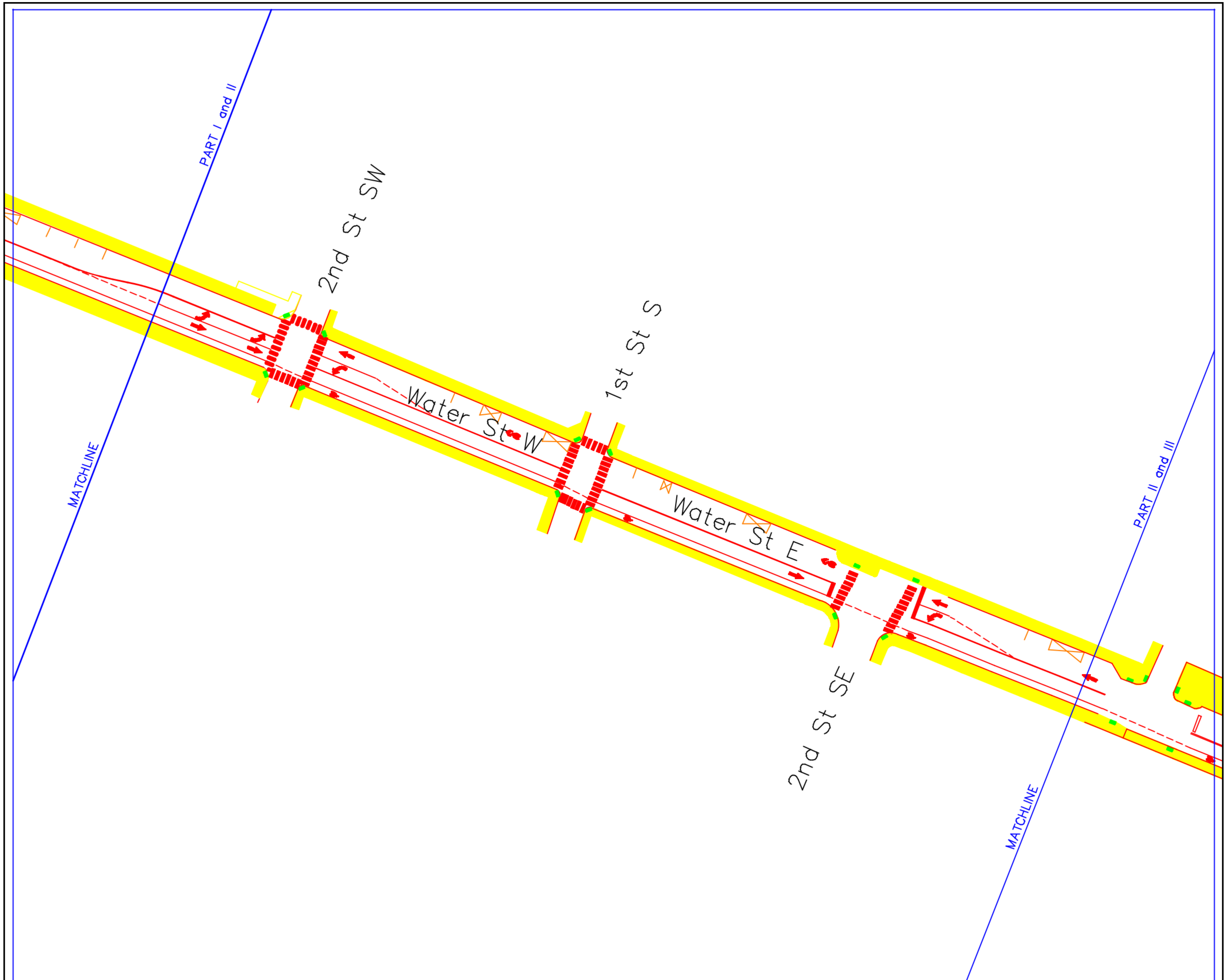
[redacted]

3/26/2020

7

[redacted]

Alternative 1 (Part I)



Project Description

KEY MAP

N

[redacted] [redacted]

1" = 50'

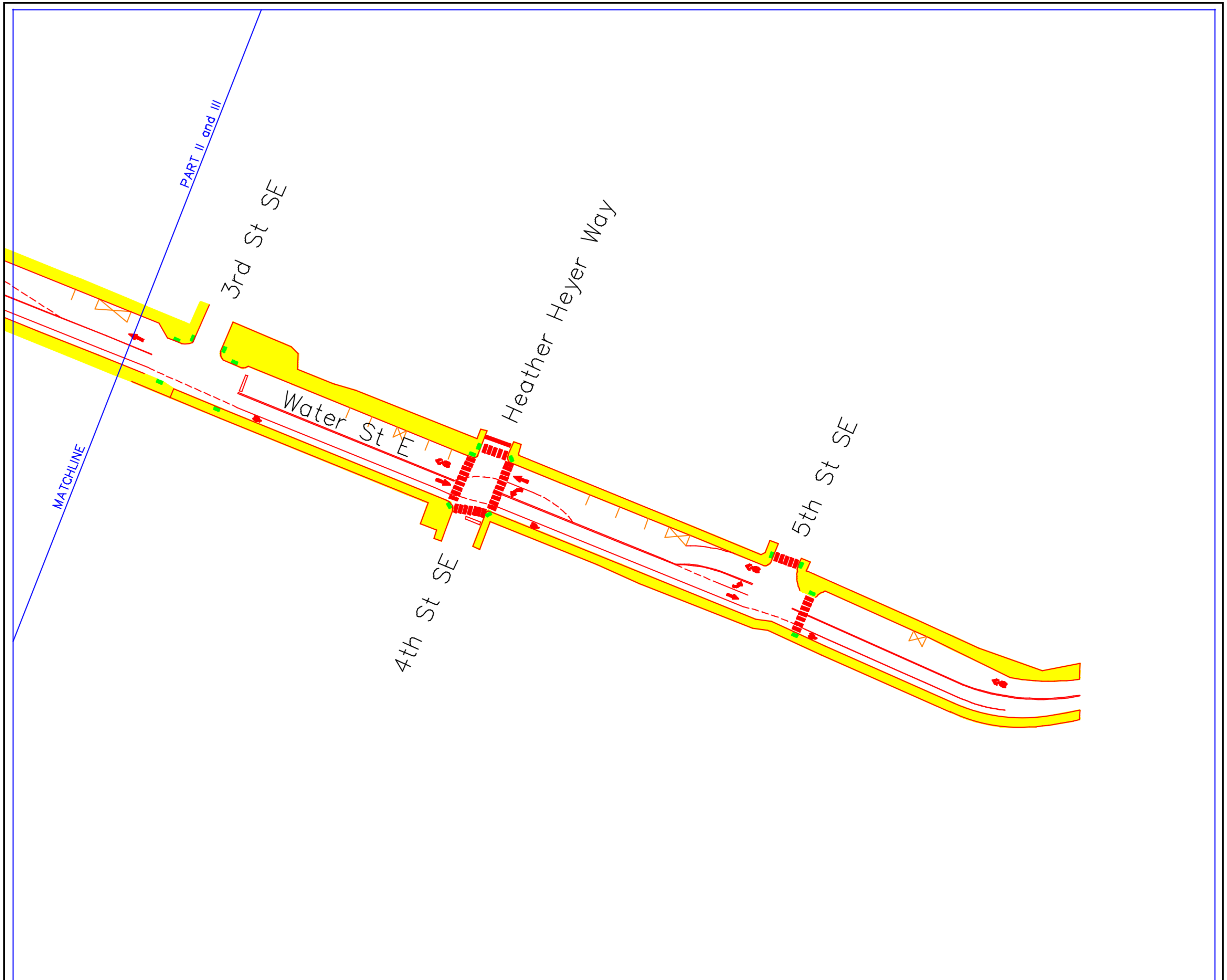
[redacted]

8

3/26/2020

[redacted]

Alternative 1 (Part II)



Project Description

KEY MAP

N

[redacted]

1" = 50'

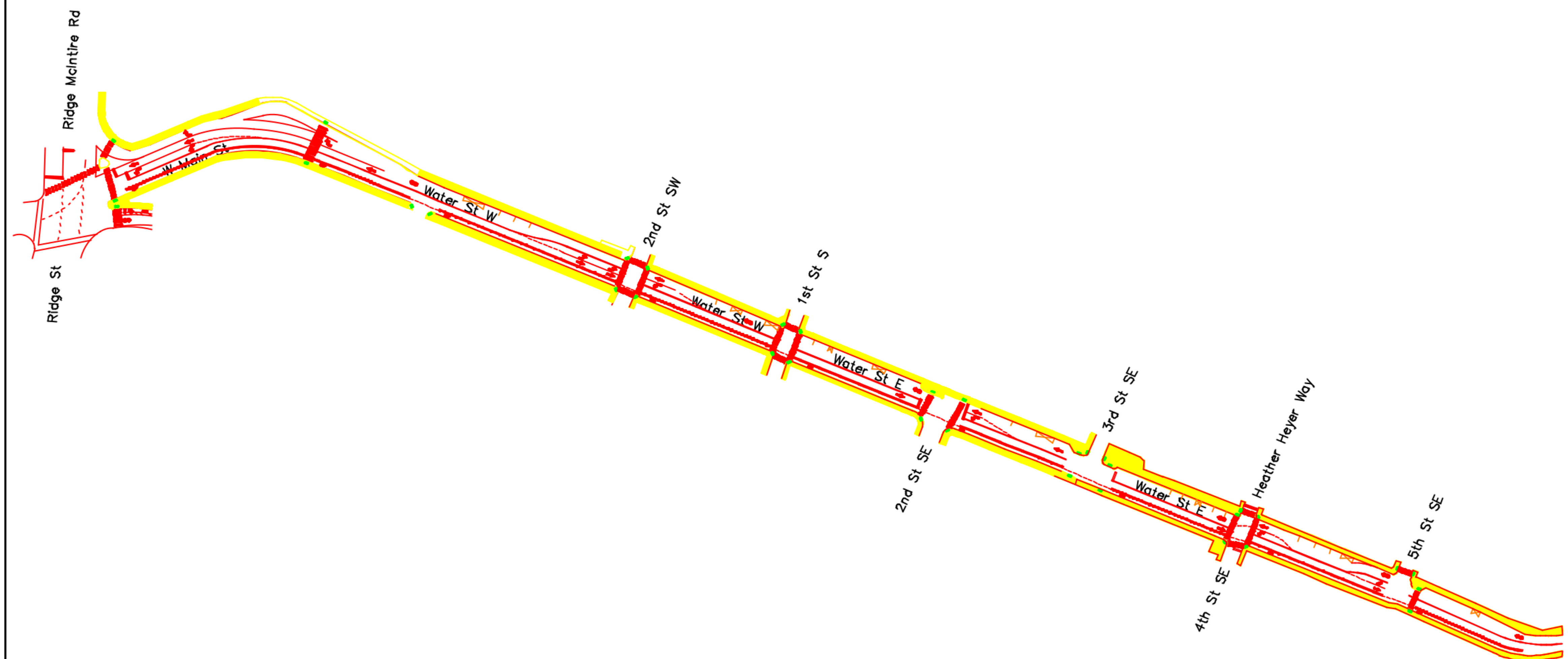
[redacted]

9

3/26/2020

[redacted]

Alternative 1 (Part III)



Project Description

KEY MAP

N

[redacted] [redacted]

1" = 180'

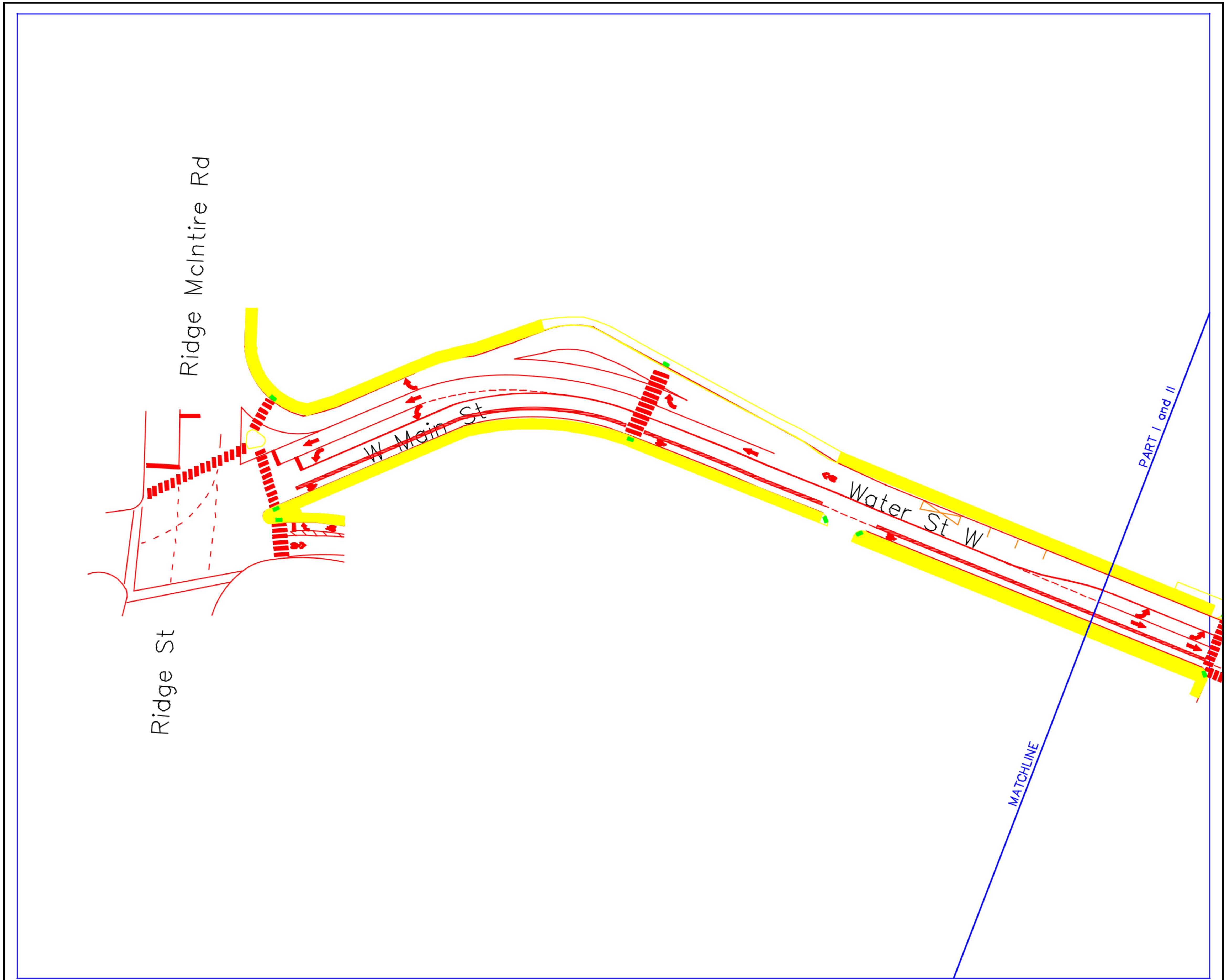
[redacted]

10

3/26/2020

[redacted]

Alternative 2 (Overview)



Project Description

KEY MAP

N

[redacted] [redacted]

1" = 50'

[redacted]

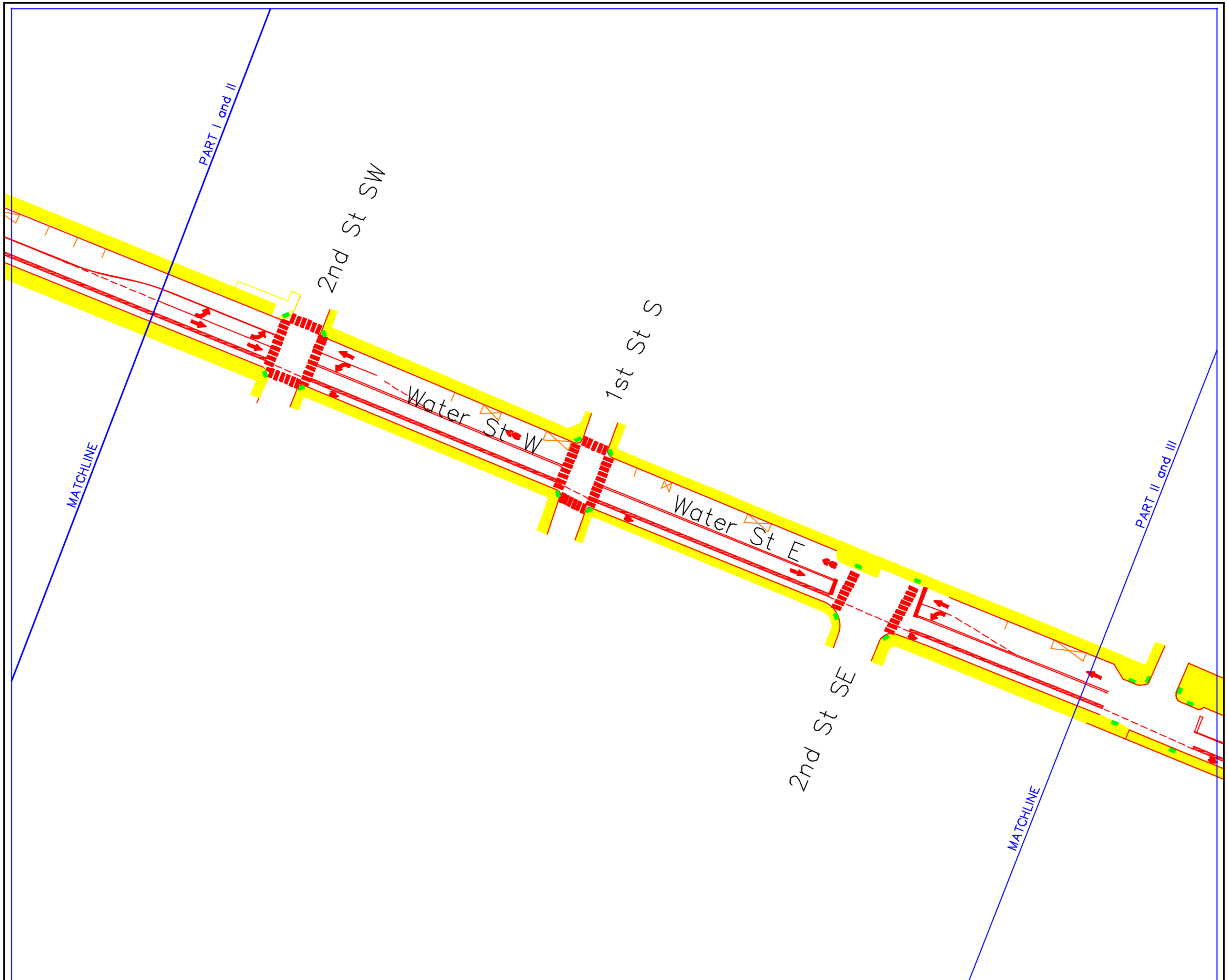
11

3/26/2020

[redacted]

Alternative 2 (Part I)

Project Description



KEY MAP

N

[redacted] [redacted]

1" = 50'

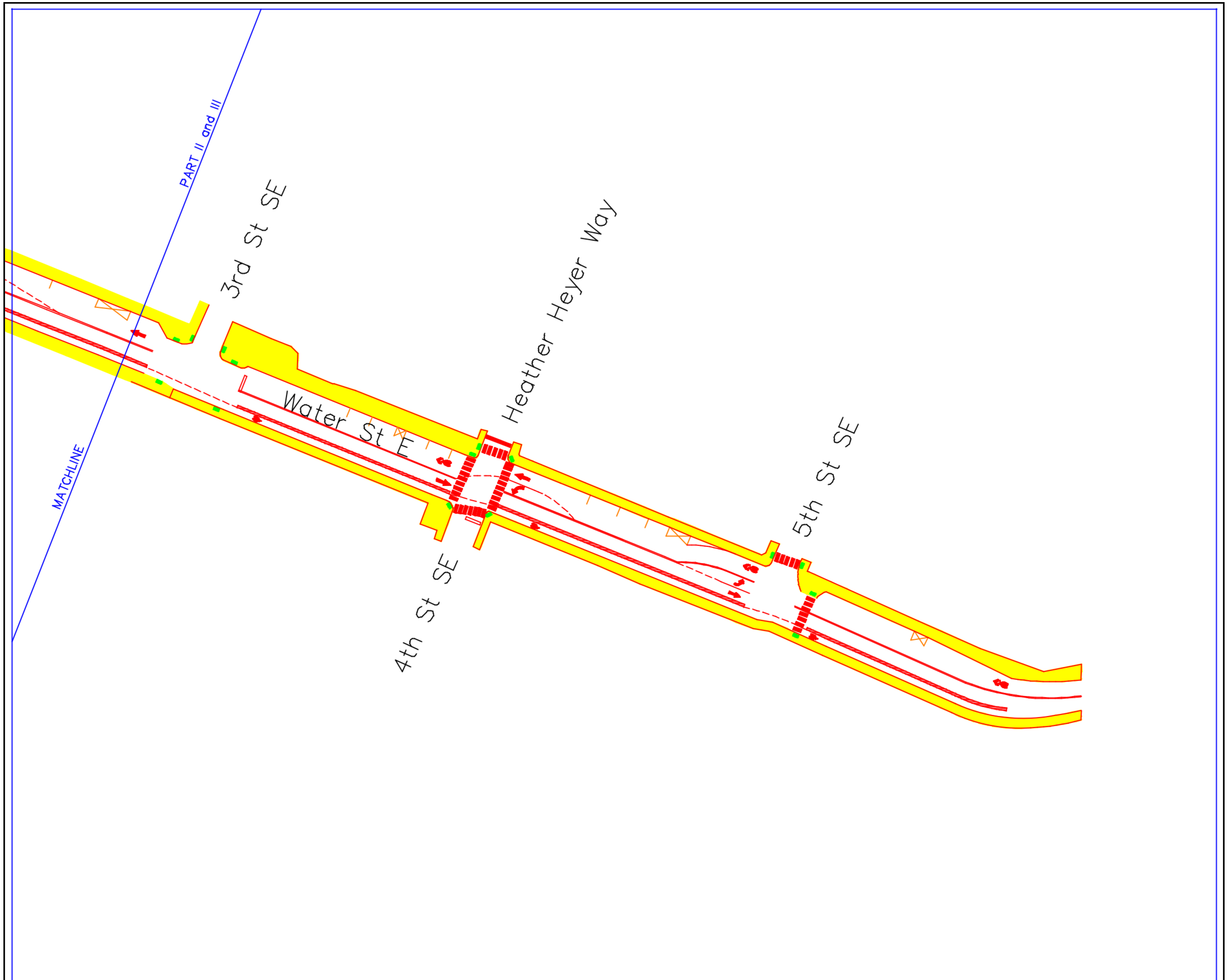
[redacted]

3/26/2020

12

[redacted]

Alternative 2 (Part II)



Project Description

KEY MAP

N

[redacted]

1" = 50'

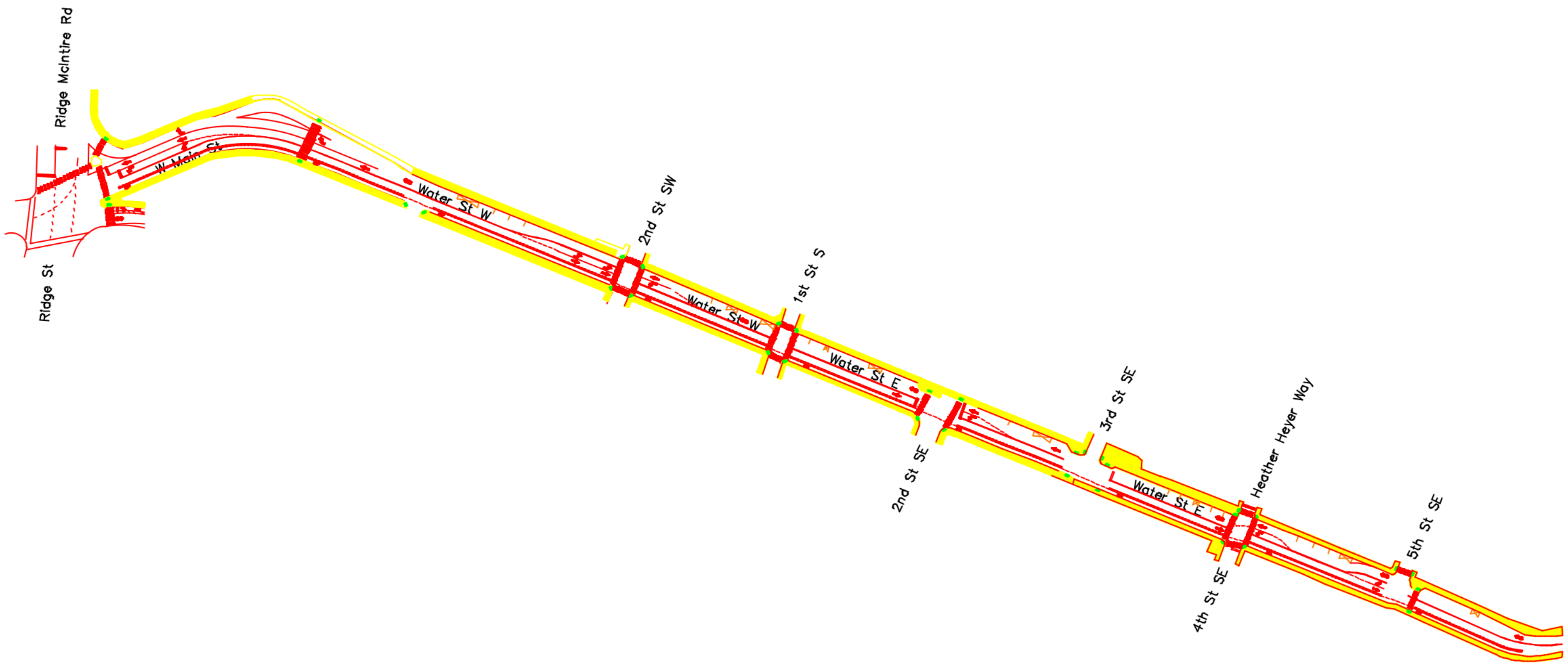
[redacted]

3/26/2020

13

[redacted]

Alternative 2 (Part III)



Project Description

KEY MAP

N

[redacted] [redacted]

1" = 180'

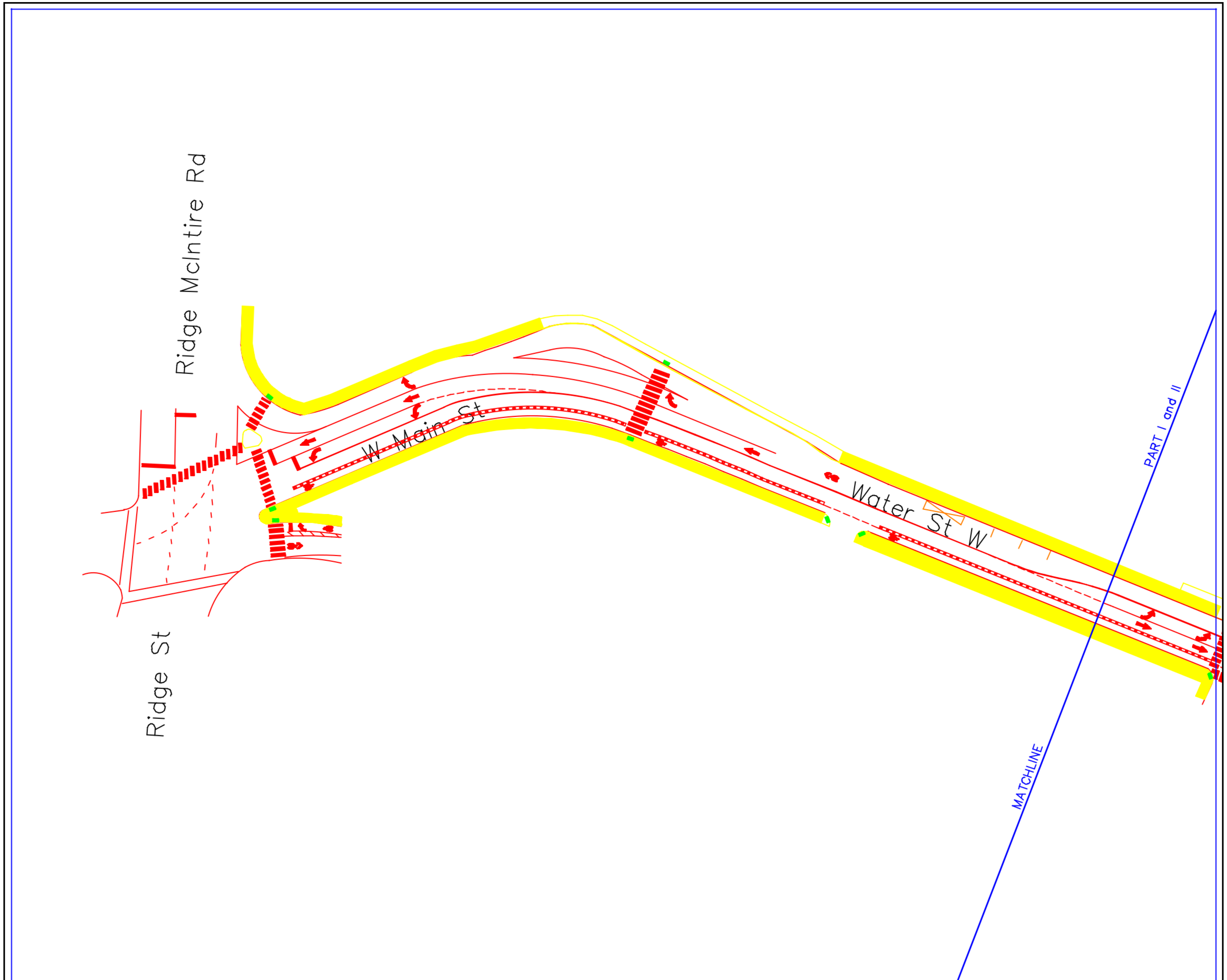
[redacted]

3/26/2020

[redacted]

Alternative 3 (Overview)

14



Project Description

KEY MAP

N

[redacted] [redacted]

1" = 50'

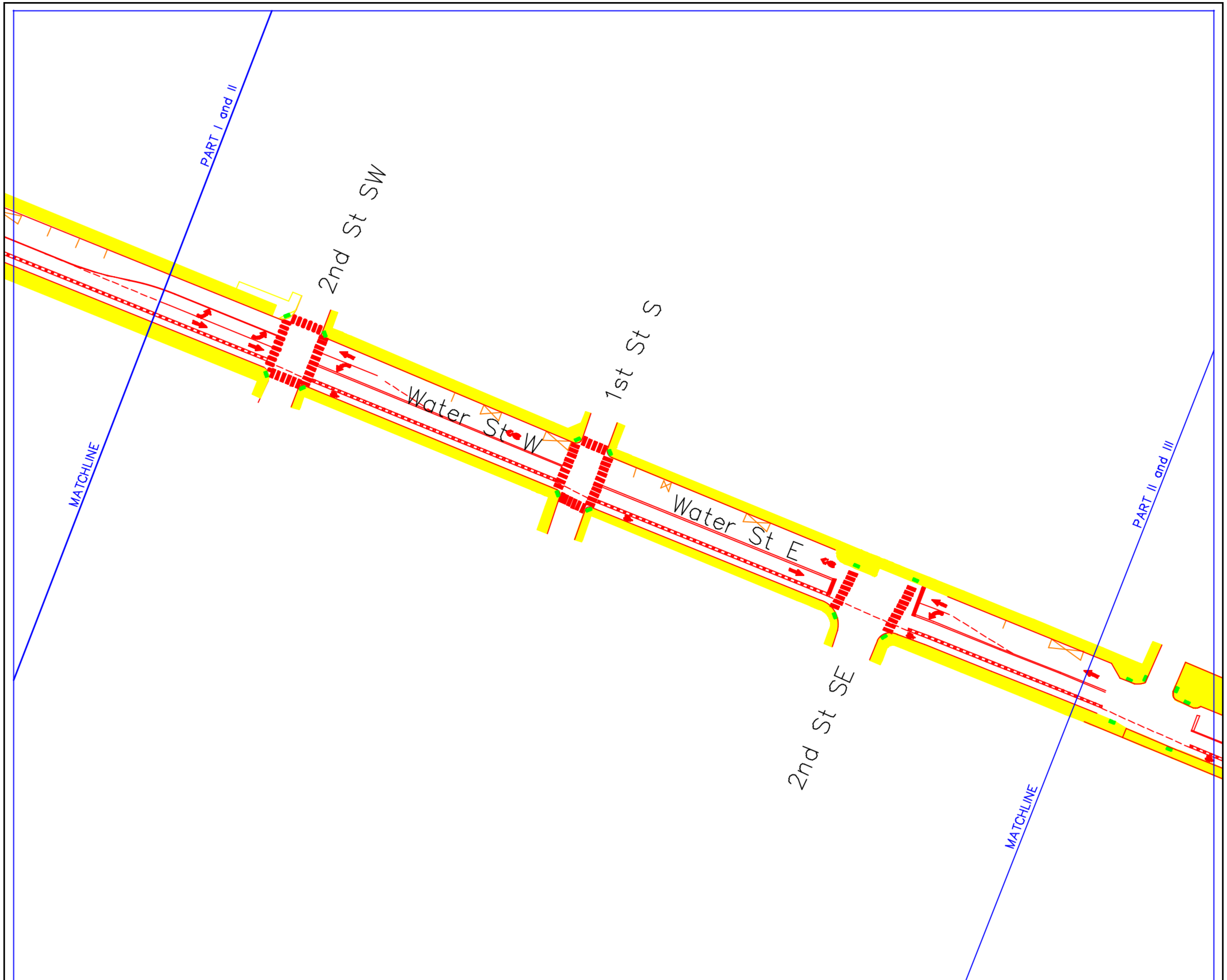
[redacted]

15

3/26/2020

[redacted]

Alternative 3 (Part 1)



Project Description

KEY MAP

N

[redacted]

1" = 50'

[redacted]

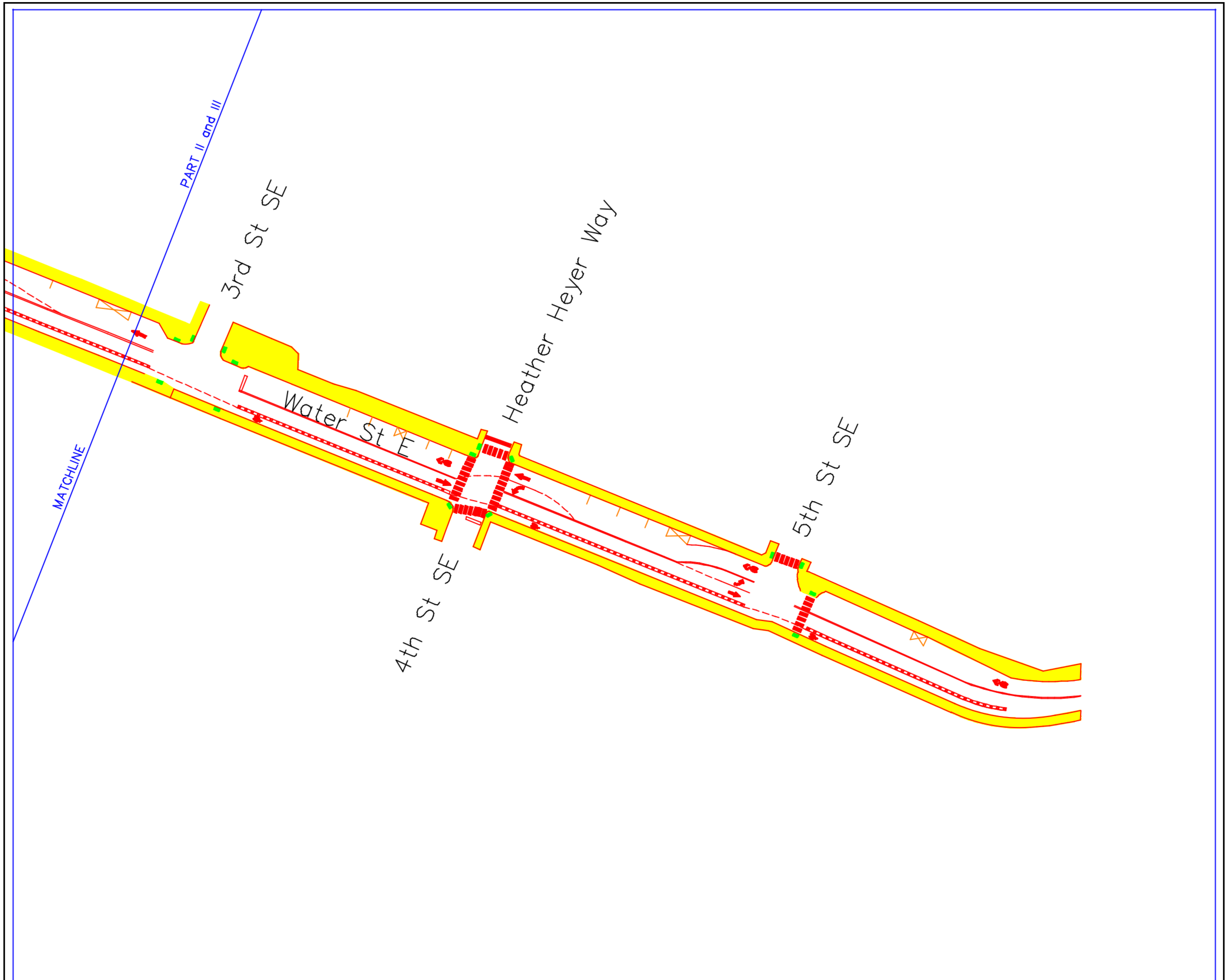
3/26/2020

[redacted]

16

Alternative 3 (Part II)

Project Description



KEY MAP

N

[redacted] [redacted]

1" = 50'

[redacted]

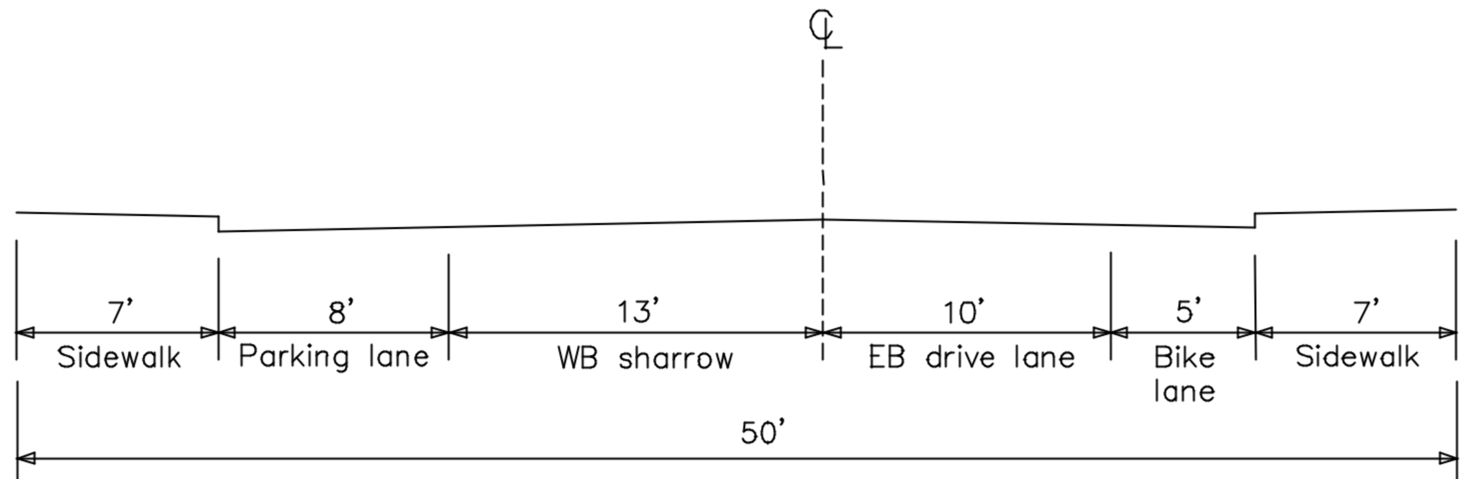
17

3/26/2020

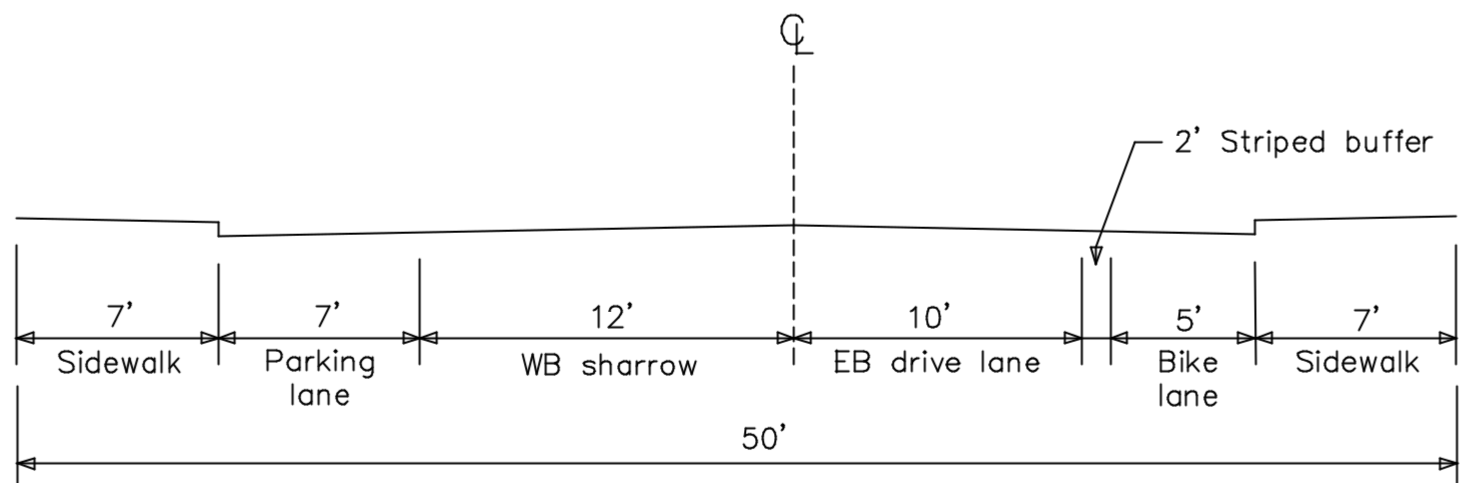
[redacted]

Alternative 3 (Part III)

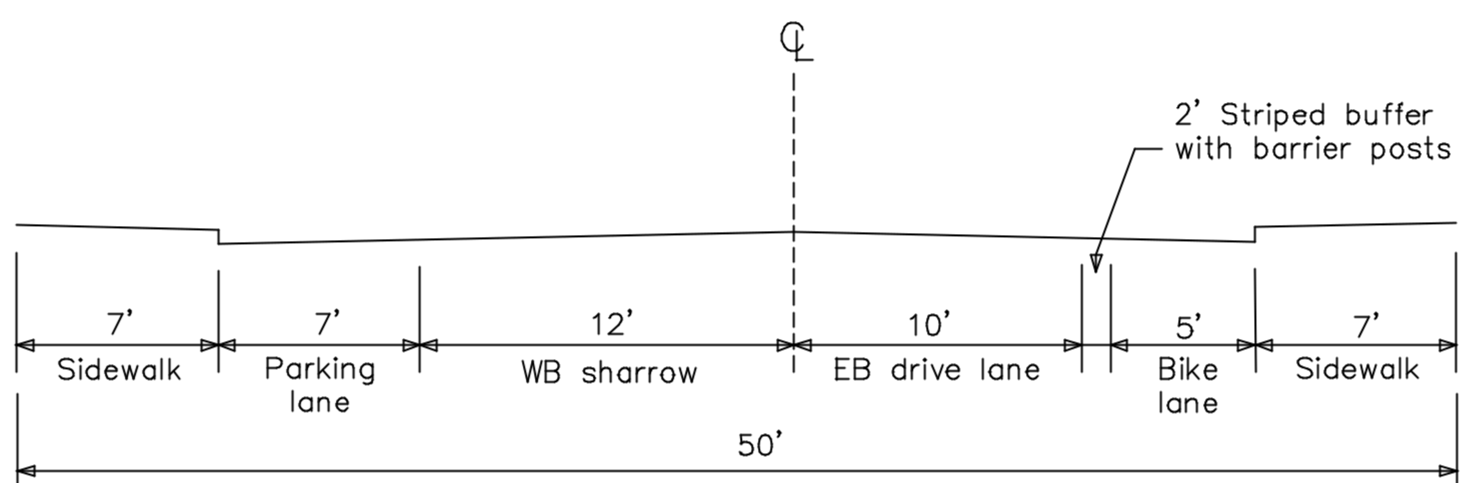
Project Description



Alternative 1: Modified City Plan (with no bicyclist protection)



Alternative 2: Modified City Plan with Buffer



Alternative 3: Modified City Plan with Buffer and Barrier Posts

KEY MAP

N

[redacted] [redacted]

1"=6'

[redacted]

18

3/26/2020

[redacted]

Alternatives 1-3: Typical Sections

Appendix D: Technical White Paper

User Comfort and Safety Data Analysis

Introduction

The purpose of this white paper is to research, analyze, and examine how user experience data has been analyzed in other use cases evaluating preferred alternatives. This information will be useful for ORCL researchers in terms of how to use the data they are collecting. There are three types of data that are being collected: likert scale data (from survey questions), eye tracking data (from the VR headset), and heart rate data (from the wearable smart watch). This paper is organized as follows: previous use cases are examined with respect to each individual type of data (likert, eye tracking, and heart rate). These best practices are then combined to set forth a recommendation on how to analyze data for this study.

Likert Scale Data

Previous examples of evaluating bicycle comfort and safety levels are very detailed and complex. These studies include many factors that, for this project in a VR environment, can be hard to change and/or replicate. For example, below is a list of different factors that have been used in other use cases regarding bicycle safety (Noel, 2003; Pedestrian and Bicyclist Intersection Safety Indices, 2006).

- Slip lane/channelized right-turn lane
- Pavement irregularities (i.e., broken asphalt, trolley tracks, gutters/grates, etc.)
- High crossing pedestrian volume
- Loading/unloading vehicles stopped in bicycle travel space
- Bike lane to the right of an exclusive right-turn lane
- Perpendicular on-street parking
- Bus entering/exiting area where there is potential interaction with bicyclists
- Offset intersection
- Parking dimensions
- Space available to the cyclist
- Shoulder pavement
- Car speed
- Car traffic flow
- Heavy truck traffic flow
- Roadsides with sand, gravel, or abundant vegetation
- Retail/industrial and residential entrances
- Ditches

One way in which these many different factors were analyzed was through statistical analysis. According to a Federal Highway Administration report, linear regression was the model used to calculate the predicted safety index value (Pedestrian and Bicyclist Intersection Safety Indices, 2006). The coefficients were estimated by a weighted least-squares procedure where each observation was weighted by the inverse of its variance. In this specific study, the collection of intersection data and the videotaping of sites were performed with the help of local data collectors. The data collection effort included gathering information on the roadway's physical characteristics, crash data, and behavioral data. This is, therefore, different from the current study that implements VR testing, but the factors analyzed and methods used still provide helpful insight.

Another way in which these factors can be analyzed is a sum of weighted scores (Noel, 2003). This is similar to linear regression, except that a safety index was built from an additive model where each of the elements is weighted according to its importance by a panel of experts. Therefore, the weights can change depending on who is a member of the panel of experts. It is interesting to note that, in this study, cyclists evaluated the comfort of different roadway sections on a scale of 1 to 6 (1 = low risk and 6 = high risk). These evaluation factors included the width of the shoulder, the state of the roadside, and the profile of the road (curves, hilliness). The average of these scores (the rating from 1 to 6) was then used in the final calculation of the safety index.

Additionally, from a report by the Transportation Research Center for Liveable Communities, participants were asked to determine their comfortability (1 = very uncomfortable and 5 = very comfortable) at each different roadway segment after completing the field experiment (Oh, 2017). The average of this likert response data was used to determine the most and least comfortable roadway segment.

Finally, in a Florida Department of Transportation Safety survey on bicycle and pedestrian facilities, likert scales were used to ask residents how they felt about bicycle safety-related topics (Winters, 2005). T-tests and one-way ANOVA tests were run to determine if there are statistically significant differences between bicyclists and non-bicyclists, but the current study has more than two groups under comparison. Additionally, these statistical tests only show whether or not one group's average response is statistically different from another group's. This is not very helpful information when trying to rank different roadway alternatives.

It is interesting, however, that averages were taken for likert data in some of the previous use cases mentioned above. According to the Journal of Extension, there are two types of likert data: likert *type* and likert *scale*(Boone, 2012). With likert type data, there is no attempt by the researcher to combine the responses from the items into a composite scale. Likert scale data, on the other hand, is composed of a series of four or more likert type items that are combined into a single composite score/variable during the data analysis process. The data analysis decision for likert items is usually made at the questionnaire development stage. In the case of the Water Street study, likert type questions are used. This is because the research team phrased the questions (for the Water Street study) as independent:

- Please rank how you feel about the statement: “I felt **safe** riding in this environment,” with:
  - 1 being Strongly disagree
  - 2 being Disagree
  - 3 being Neither agree nor disagree
  - 4 being Agree
  - 5 being Strongly agree
- Please rank how you feel about the statement: “I felt **comfortable** riding in this environment,” with:
  - 1 being Strongly disagree
  - 2 being Disagree
  - 3 being Neither agree nor disagree
  - 4 being Agree
  - 5 being Strongly agree

While you can find an average of the numbers 1, 2, and 3, you can’t find an average of “agree”, “disagree”, and “neutral” (Stephanie, 2016). Therefore, the median or mode is the best way to analyze the likert type data (Boone, 2012). These median or mode values can be easily compared across different roadway designs.

From this information, the team recommends taking the median of the likert type responses and multiplying those values by weights determined by the ORCL researchers, as follows:

- Combined Safety and Comfort Score = $W_x[Med(x)] + W_y[Med(y)]$

  where:

- $Med()$ = median
- x = safety
- W_x = weight of safety
- y = comfort
- W_y = weight of comfort

The types of previous studies mentioned above have gone more in-depth than the scope of this project. However, a recommendation of this project for future work is to, if time allows, segment the evaluation methodology into more categories than just comfort and safety. Inspiration for such categories can be found by using the resources above.

Eye Tracking Data

Eye tracking has become a practical approach to evaluating a design process because it allows researchers to study the cognitive workload of participants (Raschke et al., 2013). In our study, eye tracking, measured with a VR headset, is used to evaluate perception and user comfort in bicycling for each design alternative. Research from the Technical University of Vienna in Austria evaluates the qualitative elements of “bikeability” to analyze perception and emotions of bicyclists from eye tracking data (Berger, 2018). This study develops a methodology on how sensor technology can be evaluated in the data collection process in order to track bicyclists stress levels.

“Bikeability,” refers to the “attractiveness” of bicycling where comfort is seen as a significant factor. Research has indicated that bikeability is correlated with human perception where an increase in perception is correlated with higher satisfaction in the environment. Eye trackers are used to capture the visual perception and stress levels of bicyclists. In fact, emotions of the bicyclists can be quantified through higher eye movements and gaze patterns (Berger, 2018).

Case studies evaluated by Martin Berger and Linda Dorrzapf from the Technical University of Vienna explore whether data from new sensor technologies can be used to determine what makes bicycling stressful. Several integration technologies were used: electrodermal activity (EDA) device (Skin Response), electroencephalography (EEG) device (MindCap), and an eye tracker (TobiiGlasses). One of the case studies, “No trespassing,” evaluates bicyclists’ perception on roadway changes caused by construction sites. Different streets in the city of Vienna with construction sites were chosen based on temporary impairment of a bicycle lane and frequency of bicyclist traffic. In this case study, the eye tracker was essential to detect the viewing direction and route choices of bicyclists. The eye tracking software then creates a heat map from the eye tracking results. Data from eye tracking found that bicyclists’ eyes were focused on the construction site early on, therefore indicating early awareness of a change in the bike lane. This data is evaluated based on a heat map that is created from the eye tracking device. Overall, the study identified that although eye trackers are effective for visualizing eye movement and gaze patterns in bicyclists, the software should take objectivity of the surrounding environment into consideration. Since bicyclists are constantly moving, the eye tracker takes time to record the surrounding which results in inaccurate fixation points on the heatmap (Berger, 2018).

Based on the methodology from the study above, ORCL researchers should use the fixation frequencies and durations of a gaze on a heat map as indicators to evaluate bicyclist behavior. Furthermore, surveys should be used to evaluate if the heat map correlates to how the user perceives comfort.

Heart Rate Data

Introduction

While bicycling as an energy-efficient way of transportation can bring extensive environmental, social and economic benefits, negative perceptions of safety and comfort constitute a major hurdle to the growth of cycling. Understanding these perceptions through the application of novel methodological tools such as heart rate monitoring could provide important insights into bicyclist perception of safety. According to Daniel McDuff - a researcher at Affectiva, a Cambridge, Massachusetts-based company that analyzes emotion from facial expressions - heart rate variability is one of the most robust, noninvasive measures of stress response (Ghose, 2015). Although it is a common perception that heart beats usually have a regular rhythm, in contrast, the interval between heartbeats naturally varies in healthy young adults, to the extent that the heart rhythm during a single breath cycle of one inhalation and one exhalation can change by 10 to 15 beats per minute, as per Frederic Shaffer, the head of the Center for Applied Psychophysiology at Truman State University in Kirksville, Missouri. (Ghose, 2015). According to the study, when someone is undergoing a distressing or fearful situation, the autonomic nervous system activates the fight-or-flight response, which reduces the variability in the interval between heartbeats. A stressed-out heart, for instance, may only vary by two beats per breath cycle, as per the research.

As per research done by Doorley, Ronan; Pakrashi, Vikram; Byrne, Eoin; et al. and published by Elsevierin in Ireland, on "*Analysis of Heart Rate Variability amongst Cyclists under Perceived Variations of Risk Exposure*," there is evidence that the heart rates of bicyclists while cycling in a mixed mode urban network are correlated with their subjective risk perceptions. It has been demonstrated that situations which are perceived by the bicyclists to be high in risk are likely to produce higher heart rate responses than situations which are perceived to be low in risk. The dependency is most significant when comparing the highest risk perceptions to all others but may still exist when comparing lower risk perceptions to one another. Additionally, the research concluded that the confounding effects of risk perceptions on heart rate-based exercise management tools are likely to be greatest when cyclists are in regular interaction with car traffic. This research also indicates that an important step to be taken in improving the perceived safety experience of bicyclists would be the introduction of more dedicated cycling facilities which protect cyclists from motor vehicle traffic, particularly on busy roads and at roundabouts (Doorley et al., 2015).

Building on the results of this comprehensive research study, it may be expected that out of the three design alternatives for the Water Street study (i.e. city plans with no buffer, striped buffer, and barrier posts) along with the no-build condition, the design alternative with barrier posts would have caused the lowest safety and comfort concern for the users, followed with striped buffer and finally no buffer alternatives, as more dedicated cycling facilities would reduce the risk perception. (Doorley et al., 2015)

Methodology and Results

The study conducted by Doorley et al. was comprised of a fully controlled experiment, a partially controlled experiment, and an uncontrolled experiment. In the fully controlled experiment, heart rates of participants were measured while completing various trials in an environment isolated from all forms of traffic where the effects of feelings of insecurity were expected to be negligible. Different course types (slalom course, cornering course and gap course) and difficulties were used with three levels for each course type and difficulty level.

In the partially controlled experiment, participants cycled two fixed routes in the urban environment while exposed to normal traffic conditions. At scheduled locations along each route, participants were instructed to announce a number between 1 and 10 to represent the degree to which they felt at risk, based on the risk rating scale, with 1 denoting "Very Little Risk" and a risk rating of 10 denoting "Risk of Severe Accident". The audio recording of a head mounted camera captured the risk ratings announced by the participants and the video recording allowed the authors to identify the location and context associated with that perceived risk rating. The heart rate is calculated from the Inter Beat Interval (IBI), measured in milliseconds through a heart rate monitor worn by all participants. During both the fully controlled and partially controlled experiments, a lightweight plastic belt, which is worn around the chest, detects heart rate by means of two thin electrode strips making contact with the chest.

In the uncontrolled phase of the experiment, it was observed from the diary entries of 37 users that intersections are a high-risk road element for bicyclists. Over half of the recorded incidents occurred at an intersection. Incidents of type "Car turning right across bicyclist at junction" had the highest frequency and highest risk rating of the study (Doorley et al., 2015).

Discussion

The results of the controlled experiment suggest a complex relationship between type of maneuver, difficulty level, and heart rate. For the gap and slalom tests, median heart rate increases with increasing difficulty. However, for the corner test, the median heart rate decreases with increasing difficulty. It is not clear, however, whether this was due to the fact that a smaller radius effectively makes the maneuver shorter and allows less time for the heart rate to increase.

In order to investigate the relationship between heart rate and risk rating, the heart rate data was divided into groups based on the associated risk ratings. The main finding of the partially controlled experiment is that there is a significant dependency between perceptions of risk among cyclists and heart rate. The frequencies of risk ratings above 5 were too low to make any inferences about the heart rates associated with these risk ratings. However, for risk ratings of 1 to 5, higher risk ratings were generally associated with higher heart rates.

As a limitation of the test, the study group was composed entirely of young males living in Cork City, Ireland. The homogeneity in the study group allowed the study to focus on this particular prominent user group and prevent differences between subjects from dominating the results (Doorley et al., 2015). However, for this reason, it is not known if a similar link between risk rating and heart rate would be observed in a group of different physical or social characteristics. Future studies may remedy this by using a more diversified study group, given that in these studies we believe we have developed and validated a methodology which would make a larger study worthwhile.

Conclusion and Recommendations

In line with the methodology and results of this research study, the VR environment in ORCL can be designed to simulate certain “risk events” with all the design alternatives (Doorley et al., 2015). The users can then be exposed to different “virtual risk events” for various design alternatives (Doorley et al., 2015). Heart rate data collected from the users can then be compared to the risk perception as a proxy for the safety and comfort factor. This data can be used to seek evidence between any statistically meaningful relationship.

Recommendation of Analysis

Based on the above research, we recommend that the eye tracking and heart rate data be used to validate the likert scale data. For example, if a rider is distracted by the moving vehicles in the VR simulation, this would likely be reflected by a higher heart rate and a more focus-gazed eye pattern. This data could then be crosschecked with the user’s responses from the likert scale data in order to see if those responses are either supported or contrasted. A potential limitation with respect to the use of heart rate data to capture the reaction to risk events is associated with the nature of the VR environment itself. As users would know that they are in a VR environment, their reaction to the artificial risk events can be different from the real-life risk events. Eye tracking data has several limitations in the VR environment, as well. Although eye trackers are effective for visualizing eye movement in bicyclists, the eye tracker takes time to record the surrounding environment, resulting in inaccurate fixation points while the user is adjusting to the VR environment. Therefore, the use of likert scale data is more relevant for evaluating the tests in the VR environment. The likert scale data can be used as a numerical, definitive way of assessing user comfort and safety, and the eye tracking and heart rate data can be used as supporting analysis.

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