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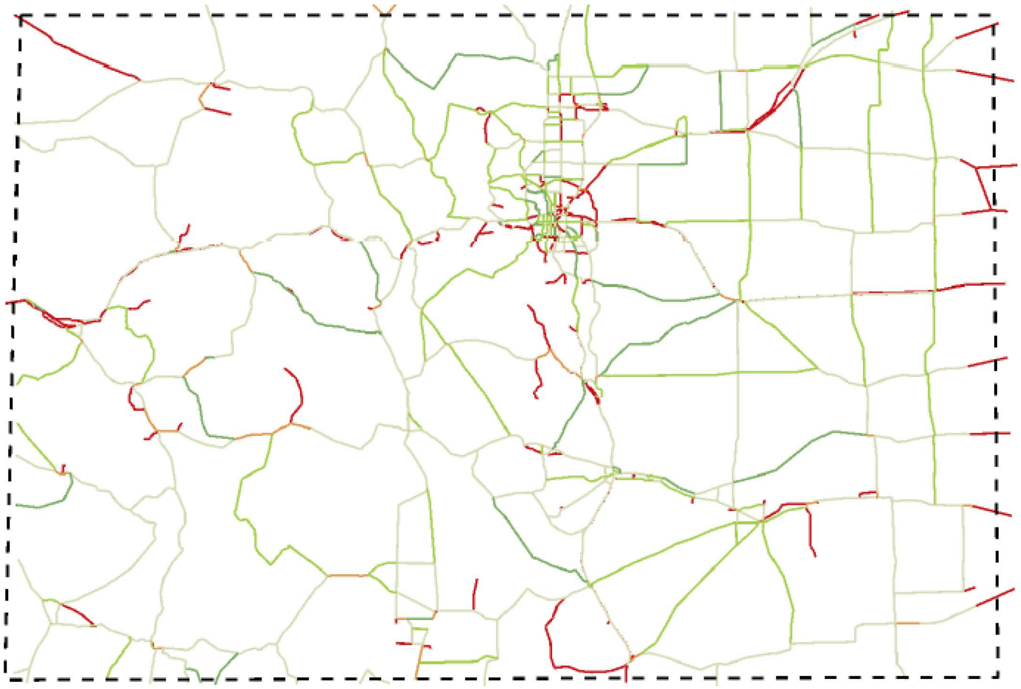

Development of Improved Redundancy Measure for the Colorado State Highway System

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16. Abstract

The Colorado Department of Transportation (CDOT) has been working to improve the resiliency of its transportation system and facilities. A vital attribute of a resilient transportation system is whether the system has redundancies built into it. For example, if a roadway is closed to traffic, but there are alternative routes for the drivers to take, then the closed roadway could be considered to have redundancy. The current redundancy measure that CDOT uses is based on the number of other state highways that connect to a particular highway. The redundancy measure needs refinement because it does not consider the additional travel time and distance from the alternative routes.

This research developed an improved method for measuring the redundancy of state highway facilities in Colorado. To establish information on the number of detours (i.e., alternative routes) for a specific road segment and the additional travel time and distance on each of the detours, detour analyses are carried out to identify (if any) the first, second, and third best alternative detours for all the highway segments in the state highway system. This is realized by closing the corresponding segment or alternative routes, updating the transportation network, and rerunning the traffic analysis on the updated transportation network. For more accurate analysis, the combined distribution and assignment model is used to consider the effects of congestion on the traffic flow. Because the full transportation network in CDOT's statewide model has large number of nodes and links, to reduce the computational effort for the detour analysis (which needs to be repeated for all road segments), an aggregated network based on the full network is developed and used for detour analysis for cars. Separate detour analyses are also carried out for the freight vehicles since they use a separate freight network, which is a subnetwork of the aggregated network. In the end, using the information from the detour analyses, a new improved redundancy metric is developed that considers not only the number of alternative routes for a road segment but also the additional time and distance on the alternative routes. The new redundancy metric also incorporates a weight for each best detour (e.g., the first, second, and third best detours are weighted differently). The detour information will be used to update the existing CDOT Detour Identification Tool. The redundancy metric can be further used to calculate and update CDOT's criticality score to determine resiliency of the Colorado State Highway System and guide activities to enhance its resilience.

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Abstract

The Colorado Department of Transportation (CDOT) has been working to improve the resiliency of its transportation system and facilities. A vital attribute of a resilient transportation system is whether or not the system has redundancies built into it. For example, if a roadway is closed to traffic, but there are alternative routes for the drivers to take, then the closed roadway could be considered to have redundancy. The current redundancy measure that CDOT uses is based on the number of other state highways that connect to a particular highway. The redundancy measure needs refinement because it does not consider the additional travel time and distance from the alternative routes.

This research aims to develop an improved method for measuring the redundancy of state highway facilities in Colorado. To establish information on the number of detours (i.e., alternative routes) for a specific road segment and the additional travel time and distance on each of the detours, detour analyses are carried out to identify (if any) the first, second, and third best alternative detours for all the highway segments in the state highway system. This is realized by closing the corresponding road segment or alternative routes, updating the transportation network, and rerunning the traffic analysis on the updated transportation network. For more accurate traffic analysis, the combined distribution and assignment model is used to take into account the effects of congestion on the traffic flow. Because the full transportation network in CDOT's state-wide model has large number of nodes and links, to reduce the computational effort for the detour analysis (which needs to be repeated for all road segments), an aggregated network based on the full network is developed and used for detour analysis for cars. Separate detour analyses are also carried out for the freight vehicles since they use a separate freight network, which is a subnetwork of the aggregated network. In the end, using the information from the detour analyses, a

new improved redundancy metric is developed that takes into account not only the number of alternative routes for a road segment but also the additional time and distance on the alternative routes. The new redundancy metric also incorporates a weight for each best detour (e.g., the first, second, and third best detours are weighted differently). The detour information will be used to update the existing CDOT Detour Identification Tool. The redundancy metric can be further used to calculate and update CDOT's criticality score to determine the resiliency of the Colorado State Highway System and guide activities to enhance its resilience.

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Chapter 1:

Introduction

1.1 Background

The American Association of State Highway and Transportation Officials (AASHTO) defines the term Resilience as the ability to prepare and plan for, absorb, recover from, or more successfully adapt to adverse events. For the past few years, Colorado Department of Transportation (CDOT) has been working to improve the resiliency of its transportation system. One attribute of a resilience transportation system is whether the system has redundancies built into it. Redundancy is the measure of the inherent substitutability. For example, if a roadway is closed to traffic, but there are alternative routes for the drivers to take, then the closed roadway could be considered to have redundancy. CDOT developed their first ever "Roadway Redundancy Measure" in 2015. The measure relies on the amount of connections a roadway has to other State Highways. The redundancy measure is one of the six criteria used in CDOT's asset criticality model for system resilience to calculate the criticality scores (see Fig. 1.1).

1.2 CDOT's Current Redundancy Metric

A brief review of the CDOT's methodology for creating the redundancy metric is presented here (CDOT Division of Transportation Development 2015). First, some assumptions were made for their redundancy metric:

Criteria	Criticality Score					Weight
	1 Very Low Impact	2 Low Impact	3 Moderate Impact	4 High Impact	5 Very High Impact	
AADT	40 – 720	721 – 1,900	1,901 – 4,600	4,601 – 15,000	15,001+	1/6
AASHTO Roadway Classification	Minor Collectors	Major Collectors	Minor Arterial	Principal Arterial	Interstate Freeway Expressway	1/6
Freight $M (2010)	6,353 – 6,422	6,423 - 6513	6,514 – 6,685	6,686 – 8,806	8,807 – 32,085	1/6
Tourism $M (2016)	13 – 152	153 – 479	480 – 1,050	1,051 – 3,414	3,415 – 41,831	1/6
SoVI	-8.69 - -2.93	-2.92 - -1.24	-1.23 – 0.67	0.68 – 2.51	2.52 – 6.23	1/6
Redundancy (CDOT 2015v)	4.51 – 50.5	3.01 – 4.5	2.01 – 3	1.51 – 2.0	1.0 – 1.5	1/6

Figure 1.1: Final CDOT Asset Criticality Model for System Resilience (Colorado Department of Transportation 2015)

- The redundancy map included both the Colorado State Highway (on system) and off system roadway with a Functional Classification of 2, 3 or 4 . This ensures exclusions of many unpaved low capacity roads.
  - Principal Arterial (Freeways and Expressways)
  - Principal Arterial (Others)
  - Minor Arterial
- All roads are treated equal. There is no weight for different roads with characteristics an classification.
- This was done in ArcGIS, and very little human judgement is involved.

An analysis was done from CDOT for their redundancy metric. They first created a simple network that included both the Colorado State Highway and the off system roadway as mentioned above. The network was comprised of road segments identified with end points that are either dead ends or intersections. Then they had each highway segment analyzed independently, and had a proximity analysis where they determine the number of alternative routes for the entire road segment within a 2,000 meter buffer/radius. This analysis produces an overall score for each segment. The proximity analysis considered three major characteristics of a road segment, i.e., 1) Average concentration alternate routes along entire length of a road segment; 2) Alternative routes concentration at the ends points of the road segment; and 3) Length of the segment. Using the analysis an overall score for each road segment was established.

Finally, the scores were compiled, based on which each road segment was classified into one of the five categories. Table. 1.1 shows the redundancy metric that CDOT created in 2015.

The redundancy metric is broken down into fixed values and it is interesting to note that the category "Very Low Impact" has a score of 4.51 to 50.5, which means that there is a lot of redundancy because if the corresponding road segment were to be closed, then there will be various detours for the drivers to take any such closure would have minimum or very low impact on the drivers. In contrast, "Very High Impact" with a score of 1.0 to 1.5 means if a road segment were to be closed, then there would not be multiple viable detours for the drivers to take.

Table 1.1: CDOT's Redundancy Score and Corresponding Criticality Score.

-	**Criticality Score**				
Criteria	**Very Low Impact (1)**	**Low Impact (2)**	**Moderate Impact (3)**	**High Impact (4)**	**Very High Impact (5)**
Redundancy Score (CDOT 2015)	4.51 - 50.5	3.01 - 4.5	2.01 - 3	1.51 - 2.0	1.0 - 1.5

In addition, CDOT has created a visual representation of the redundancy in the form of a redundancy map, which is shown in Fig. 1.2. Note that central Denver has many road segments with high redundancy but moving outside of Denver there is very little redundancy as it fits under the category of "Very High Impact". In CDOT's methodology there are some outliers in their results, such as short road segments in urban area will naturally have high redundancy scores and parallel routes that are past 2000 meter radius will not be captured.

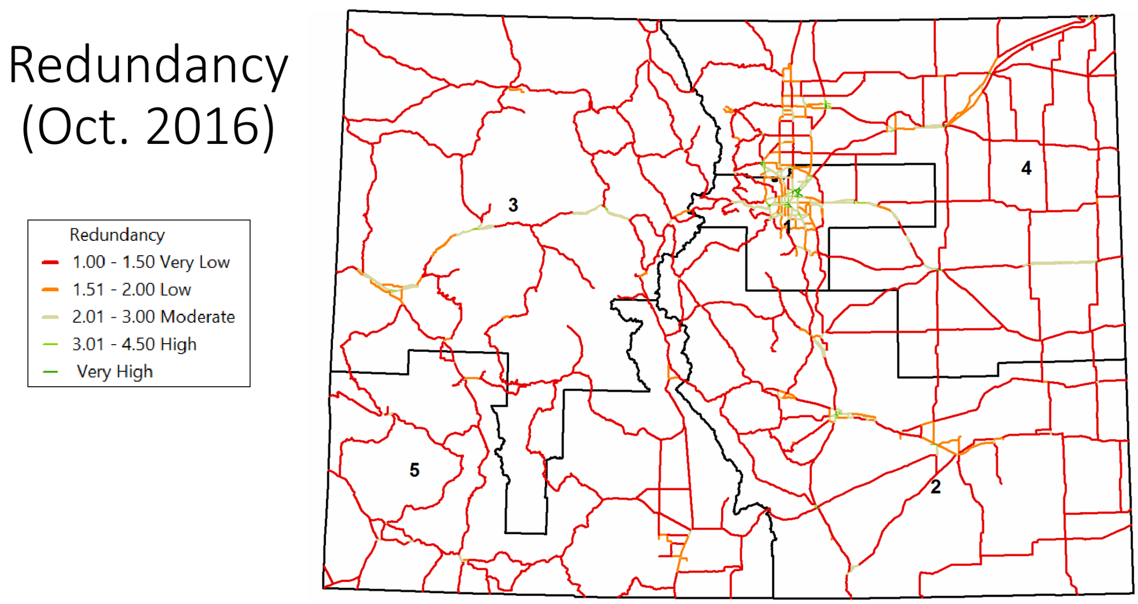

Figure 1.2: CDOT's Redundancy Map (Colorado Department of Transportation 2022).

1.3 Objectives and Scope of Research

Motivated by the fact that the redundancy measure can and should be refined, this research aims to develop an improved redundancy measure for the Colorado State Highway System. In particular, the following research objectives will be accomplished.

1. **Refine the current CDOT detour analysis for state highways**

To establish information needed for developing the new redundancy metric, a new refined traffic simulation model will be developed that provides a more practical representation of Colorado's state highway system by incorporating several considerations such as multiple detours, congestion, and heavy vehicle restrictions.

2. **Calculate and document detour times and distances for all state highways**

   Using the refined model, detour analysis will be run for all state highways to calculate the detour times and distances for all the alternative detours. The detour analysis will be run for both standard (passenger) vehicles and commercial vehicles. The information will be used to update the current CDOT Detour Identification Tool.

3. **Develop a new redundancy measure for all state highways**

   Using results from the detour analysis, a new redundancy measure will be developed that takes into account factors such as the availability of multiple detours, and additional travel time and distance for each alternative detour.

4. **Update criticality score based new redundancy measure**

   The criticality score will be updated using the new redundancy measure for all state highways. An updated criticality score will aid CDOT in determining the resiliency of the Colorado State Highway System and guide activities to enhance its resilience.

1.4 Organization of Report

The remainder of the report is to accomplish the above objectives and is organized as follows. Chapter 2 presents the current State-wide Model that CDOT uses for detour analysis, including the transportation network, the traffic data, the traffic analysis model, and the modeling of car (e.g., passenger car) and freight (e.g., heavy vehicles) flow. In addition, this chapter describes CDOT's Detour Identification Tool that will be refined. Chapter 3 discusses the development of the new traffic simulation model for the detour analysis, including aggregation of the network (to reduce computational time) and traffic data, the combined distribution and assignment model for traffic analysis (that takes into account congestion), the improved modeling of car (e.g., passenger car) and freight (e.g., heavy vehicles) flow. Chapter 4 presents the procedure of identifying the first, second, and third best detours for any closed highway segment. This chapter also discusses the procedure of obtaining the nodes and segments for the closed highway segments based on the original network data. Chapter 5 presents the detour analysis results for both car and freight, and the updating of CDOT's Detour Identification Tool (i.e., add information on multiple detours, and the additional travel time and distance for each alternative detour). Chapter 6 presents the proposed new redundancy metric and compares it with current redundancy metric. Chapter 7 presents the products and implementation of what CDOT's study panel will receive upon completion of the report and research. Finally, Chapter 8 concludes the research with the findings and presents several recommendations for future research.

Chapter 2:

Existing Detour Analysis for Colorado State Highway System using State-wide Model without Considering Congestion Effects

2.1 Overview of the State-Wide Model

To develop a new detour analysis that is a more realistic representation of Colorado's state highway system that incorporates multiple detours, congestion, and heavy vehicle restrictions, an understanding of the current detour analysis has been completed to recognize the limitation and conditions of the analysis.

CDOT's state-wide model is based off of a transportation planning software called, "TransCAD", a modeling package that is Geographic Information System (GIS) based and is the most capable travel demand modeling software (Caliper Corporation 2008). TransCAD employs the traditional four-step travel model including trip generation, trip distribution, mode choice, and trip assignment. The network performances (e.g., travel time) are obtained by building the Colorado state highway transportation network in TransCAD and running traffic analysis using the four-step model where there are different trip assignment options that can be used. Next, CDOT's state-wide model is introduced, including model inputs (i.e., transportation network and traffic data), the four-step travel model, and model outputs (i.e., traffic flow and travel time).

2.1.1 Model Inputs - Transportation Network and Traffic Data

The state of Colorado's Highway network is considerably large. The entire full network can be referenced in Table 2.1, notice that the full network has 36,407 nodes, 100,000 links, and 6,880 traffic analyzes zone (TAZ). With so many nodes, links, and TAZs the traffic analysis such as trip distribution and assignment would require significant computational efforts. To reduce the transportation network, the full network's local streets were dropped, and connectors were rebuilt between the isolated centroids of the TAZ and the closest highway node. The full network was reduced to one with 17,082 nodes, and 26,129 links while the number of TAZs will still stay the same. The reduced network then corresponds to the network used in the state-wide model, and here is referred to as the "Original Network". Fig. 2.1 shows the corresponding original network obtained from the full network. The original network contains the node (dark green square), links (purple line), the centroid of the TAZs (bright green square), and centroid connectors (light green line) which are lines that are connected to the centroid of the TAZ by the shortest path. However, using the original network for the detour analysis will still be too large for the traffic analysis and still too computationally expensive. Chapter 3 will discuss another method of simplifying the transportation network.

Table 2.1: Transportation Network in the State-Wide Model.

-	Full	Network: State-Wide Model (Original Network)
# of Nodes	36,407	17,082
# of Links	100,523	26,129
# of TAZs	6,880	6,880

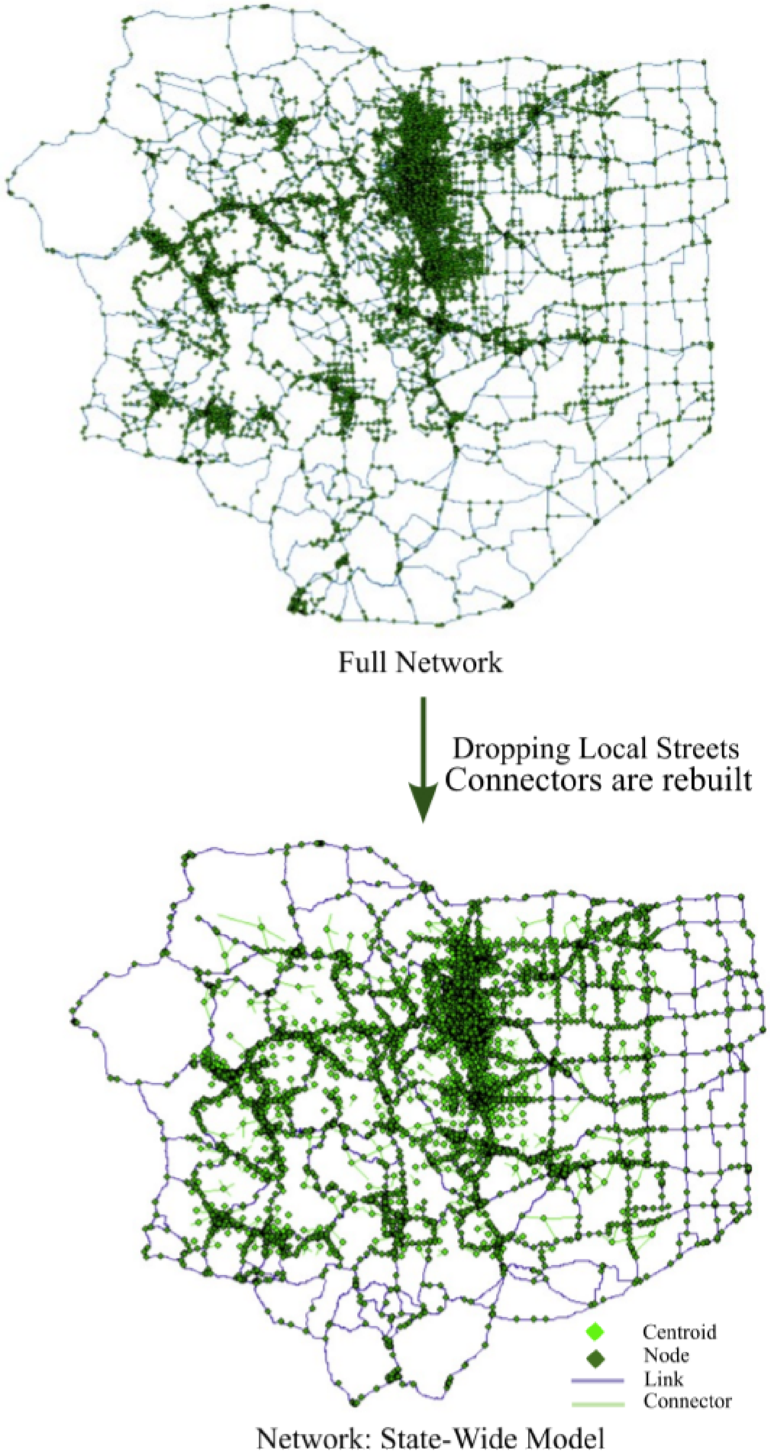

Figure 2.1: Illustration of State-wide Model's Network.

2.1.2 Four-Step Travel Model

The current state-wide model uses the four-step travel model to predict change in travel patterns and the utilization of the Colorado state highway transportation system (Ahmed 2012). Fig. 2.2 is an illustration of the traffic analysis using the four step model. For trip generation, the current statewide model uses TAZs to count the numbers of vehicles coming in and out of a zone, and CDOT will predict the future demand by determining the demand needed. Then both would be interpolated to determine an average value for trips, and then the attraction and productions are converted to origin and destinations. The mode choice (i.e., mode of travel) that the statewide model runs includes the car (passenger car) and freight (heavy vehicle). Then for the trip distribution, the model uses a gravity model, which is an iterative process that operates on the premise of flow between TAZs (Ahmed 2012). The gravity model uses an impedance function ($f(c_{ij})$) which is set to 1 in the state-wide model because the model does not consider congestion. The impedance function is the resistance for transportation such as time or cost. The higher the travel time, the less the travel demand (T_{ij}) is between the origin and destination. The gravity model is calibrated with balancing factors (A and B), and only requires the trip production (O) and attraction (D) for each trip which CDOT already has. After a series of iteration, then an origin-destination (O-D) matrix is created (Ahmed 2012).

In terms of trip assignment, one of the two traffic assignment models is All or Nothing (AoN), which assigns all traffic flow between the origin - destination (O-D matrix) pairs to the shortest path connecting the origins and destinations. This algorithm requires very minimal inputs into TransCAD, as all that is needed is the O-D matrix and a transportation network with information on links travel times. AoN is used as a central component of several other assignments models.

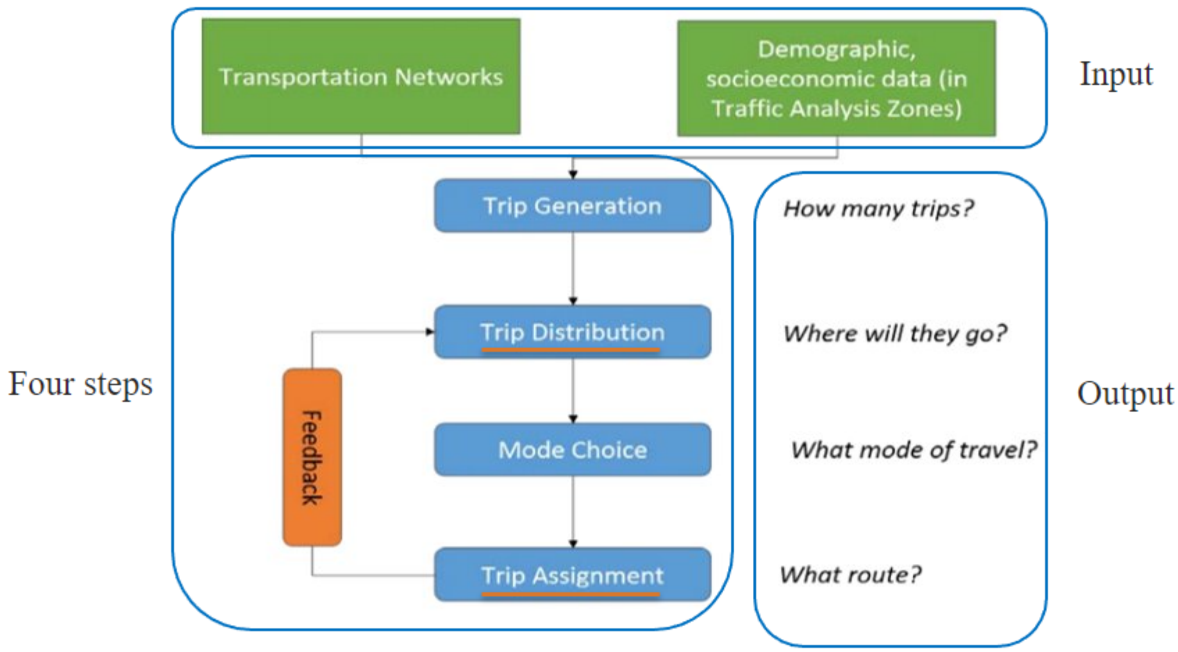

Figure 2.2: Illustration of Traffic Analysis using Four-Step Model (adapted from (Ahmed 2012)).

However, this model, AoN, as a trip assignment model, is typically unrealistic because trips assigned to each link do not have consideration of adequate capacity or (heavy) congestion on the link. Also, AoN neglects multiple routes that are available that could be utilized by people. Overall, this trip assignment model directly assigns all travelers to the shortest route.

The other traffic assignment model is User Equilibrium (UE). UE assigns trips to a network so that no individual user can reduce their travel time by choosing a different route. UE is an iterative method where the assignment continues until convergence is achieved or maximum iteration has been reached (Haider and Gregoul 2009). This is commonly used since the underlying assumption is that travelers choose the route that minimizes their individual travel time and they will take it. Unfortunately, UE assumes that the users have the perfect information and that they are aware of any possible route at a given time. However, it is difficult that real people will ever travel the routes that the UE model ever predicts. Overall the assignment methodology is to mathematically optimizes the user's travel time by implementing a convergent algorithms that requires an iterative process.

The state-wide model uses the AoN traffic assignment for both car and freight (heavy vehicles). AoN does not consider congestion effect, while UE does consider congestion effects. Ideally, UE would provide the more realistic result for the detour analysis, however, the computation using UE is much more expensive.

In this study the objective is to use User Equilibrium for traffic assignment to consider congestion by developing a combined distributions and assignment model.

2.1.3 Model Outputs - Traffic Flow and Traffic Time

The four-step model in the state-wide model provides data on the travel patterns. The model outputs traffic flow, time, and distance for the entire highway network without considering congestion effects. To calculate the additional travel time and distance, the state-wide model uses the model outputs from the four-step model, specifically using All or Nothing (AoN) for trip assignment. The travel time on detour is calculated by taking the length of the detour and divide that by the free flow speed on the detour, and subtracting this by the closed segment travel time gives the additional time. The additional length was generated by taken the length of the detour subtracting by the length of the closed segment.

2.2 CDOT Detour Identification Tool

One of CDOT's Risk and Resilience Tools is their Detour Identification Tool which is in the form of an excel sheet and allows the users, transportation professionals in CDOT, to know the additional travel time and distance by selecting a location within a highway segment (e.g., route and mile post (MP)) to be closed. This tool allows other departments in CDOT to obtain data needed for other research, program, or work. Fig. 2.3 shows Detour Identification Tool's user interface to selecting a closed location by choosing a desired route and the maximum and minimum MP to close. Then Fig. 2.4 represents the detour information based on the user's closed location shown in part a. If a closure location is chosen then there is the entire detour information for the highway segment will be displayed illustrated in part b. The information provides the routes in the system, and the additional travel time and distance (but without considering congestion effects). Furthermore, based on such information, a map was also generated for the additional time for the detours, which is shown in Fig. 2.5. It is noted that most of central Denver city have blue lines indicated detours only adding up to 15 minutes. In contrast, around Denver there are various detours from 30 minutes detours to even more than 2 hours detours as the time increases the thickness of the line increases.

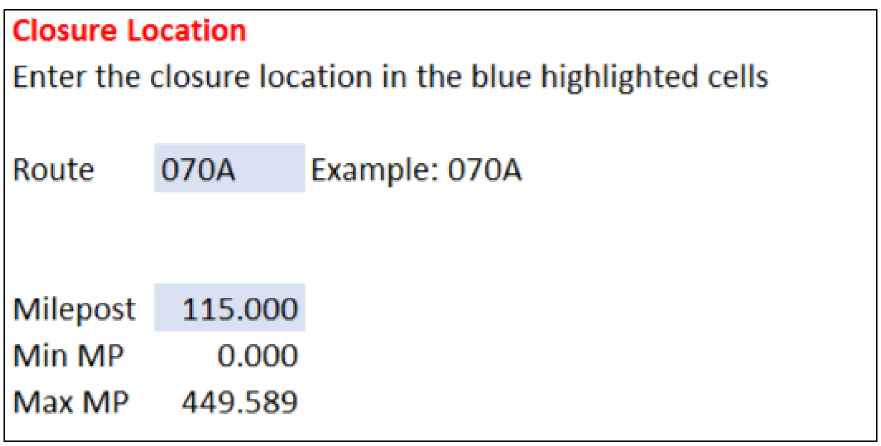

Figure 2.3: Selecting Closure Location in CDOT's Detour Identification Tool (Colorado Department of Transportation 2022).

The detour identification tool will be updated in this study so the user has the ability to identify the additional travel time, distance, and routes used on detour for any selected route considering congestion effects and multiple detours (i.e., not just the first detour).

a)

Route	MPDirection	RoutePlusDir	StartMP	EndMP	AlgSequence	NameInRouteSystem	AddedTime	AddedDist	RoutesUsedOnDetour	MPSort	ClosureMiles
082A	Pri	082A_EB	0.040	11.699	1	082B_EB_002	216.81	195.166	070A, 070B, 141B, 050A, 092A, 133A	0.040	11.659
082A	Sec	082A_WB	11.699	0.040	2	082B_WB_001	216.37	194.865	133A, 092A, 050A, 141B, 070B, 070A	988.301	11.659
550B	Pri	550B_NB	103.702	130.219	2	550B_NB_048	206.36	165.945	160A, 149A, 050A	103.702	26.517
550B	Sec	550B_SB	130.219	103.702	3	550B_SB_001	206.25	165.945	050A, 149A, 160A	869.781	26.517
145A	Pri	145A_NB	84.289	116.879	1	145C_NB_001	205.67	134.324	184A, 491B, 141A	84.289	32.590
145A	Sec	145A_SB	116.879	84.289	2	145C_SB_001	205.64	134.324	141A, 491B, 184A	883.121	32.590

b)

Route	MPDirectio	CardinalDi	RoutePlusDi	StartMP	EndMP	DetourSequenc	NameInRouteSyste	RouteSystemFileBa	AddedTime	AddedDist	RoutesUsedOnDetour
070A	Pri	EB	070A_EB	44.000	116.185	7	070A_EB_034	Detour_OOS01	112.90	53.250	070B, 050A, 092A, 133A, 082A

Figure 2.4: CDOT's Detour Information Interface. a) The Entire Detour Information for Each Highway Segment. b) Detour Information for the Closed Location.

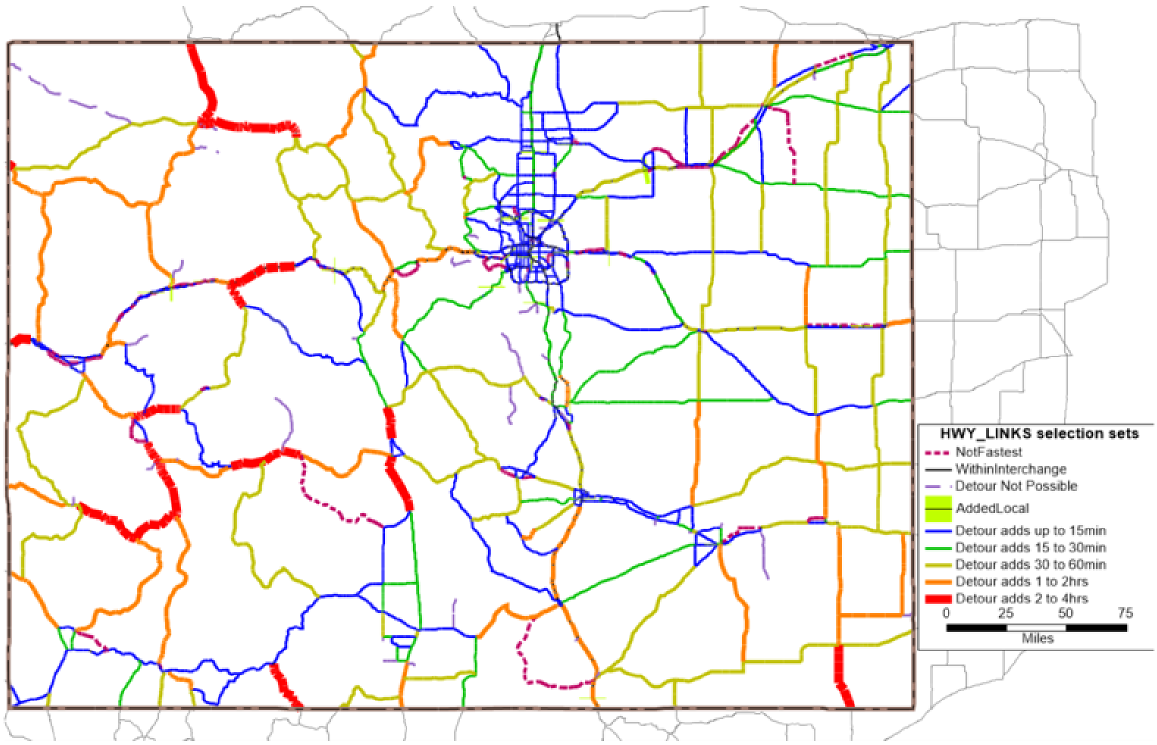

Figure 2.5: CDOT's State Detour Map (Colorado Department of Transportation 2022).

Chapter 3:

New Detour Analysis for Colorado State Highway System Using Combined Distribution and Assignment Model Considering Congestion Effects

3.1 Introduction

The new detour analysis for the state highway system still employs a four-step model similar to the state-wide model. However, the main difference between the two detour analysis is that the new detour analysis considers the congestion effects in the calculation of travel time. In particular, we introduce the combined distribution and assignment model within the four-step model for the new detour analysis (Bocchini and Frangopol 2011). Fig. 3.1 illustrates the analysis process of the four-step model used in the new detour analysis using the trip generation and mode choice from the state-wide outputs, aggregated network, and the combined distribution and assignment model. Next the new traffic simulation model is introduced, including model inputs (i.e., transportation network and traffic data) with focus on how to establish the aggregated network, the four-step travel model with a focus on the combined distribution and assignment model, and procedures on how to run separate car and truck detour analyses.

3.1.1 Model Inputs - Transportation Network and Traffic Data

Here, we propose an aggregated network method for the full network in the car detour analysis to reduce the computational burden in the detour analysis. The freight's network does not need to be

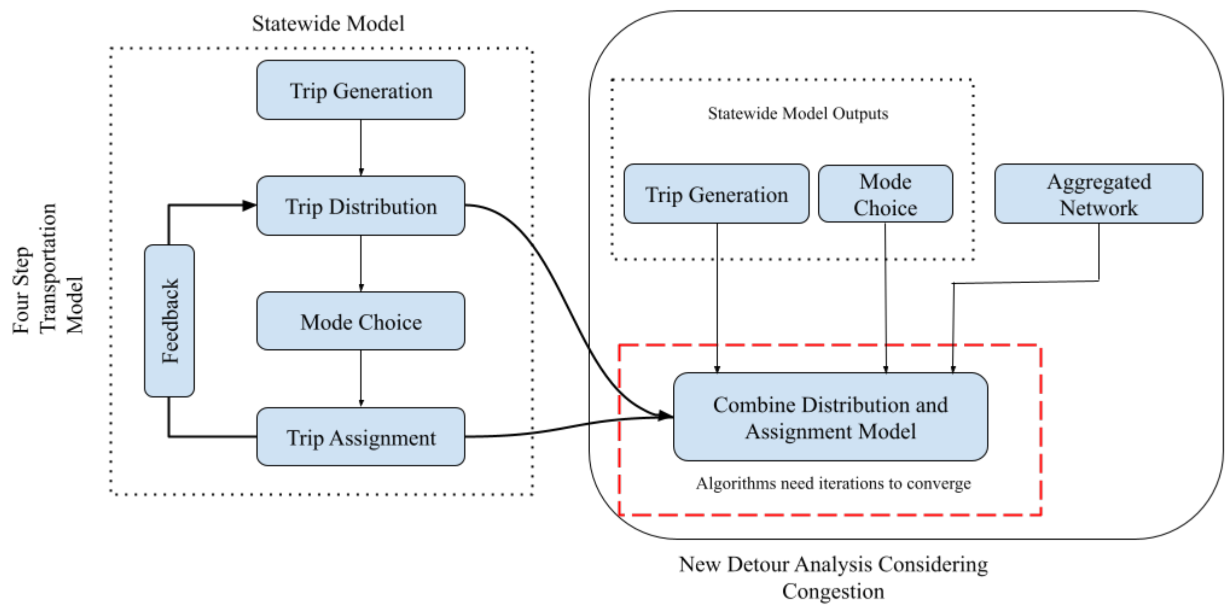

Figure 3.1: Process of the Four-Step Model Used in the New Detour Analysis.

aggregated considering the relatively small scale. The freight network is directly obtained from CDOT which contains fewer highway segments than the car's aggregated network. The proposed aggregated network for cars will significantly reduce the runtime for the detour analysis for cars. This section discusses in detail the process to establish the aggregated network.

Development of Aggregated Network of Colorado's State Highways

Since the original network still has too many nodes and links, running detour analysis using such network would take significant amount of computational effort and time, making it computationally infeasible to be directly used for detour analysis of the entire highway system, since there are many road segments and the analysis needs to be run for each segment. CDOT prefers some model that can be run in a reasonable amount of time which should take weeks rather than months. To reduce the computational time, here we propose to develop an aggregated network of the original network.

There are multiple approaches to aggregate a network. An example is the transportation network used in CDOT's state-wide model, i.e., the original network, is obtained by dropping local street and building connections between the isolated centroid of the TAZ and the closest highway node and aggregating the corresponding data through the use of Thiessen polygons to reduce the large number of nodes, links and TAZs.

The other approach is the direct way, which is done by merging road segments with similar characteristics on the same highway or aggregating the TAZs to the closest highway nodes. These aggregated networks are tested and compared for the efficiency of the traffic analysis. Further aggregation of the "original network" is tested in the section with various aggregation rules such as rebuilding centroid connectors, merging highway segments, or aggregating the TAZs to the closest highway node.

Table 3.1 summarizes the three aggregated networks that were built and investigated for their computational efficiencies.

Table 3.1: Summary of Characteristics and Traffic Analysis Using The Three Aggregated Networks.

-	**Full**	**Network: State-Wide Model (Original Network)**	**Agg. Network 1**	**Agg. Network 2**	**Agg. Network 3**
# of Nodes	36,407	17,082	17,082	17,082	10,642
# of Links	100,523	26,129	18,907	15,700	12,467
# of TAZs	6,880	6,880	6,880	6,880	3,160
Detour Analysis Run?	Not Tested	Not Tested	Yes	Yes	Yes
Running Time (Hours)	Not Tested	Not Tested	$\sim$120	$\sim$100	$\sim$6

Fig. 3.2 shows the Aggregated network 1, which was obtained from the original network (state-wide model) by building the centroid connector for the isolated centroid of the TAZ by

connecting the centroid to the closest highway node (if they are not already located on the highway). The original network in Fig. 3.2 shows the light green squares as the centroid of the TAZs with light green lines as connectors. From the original network to Aggregated network 1, rebuilding the connectors (light green lines), the Aggregated Network's connectors (yellow line) is reduced from many connectors to a single connector connecting to the centroid to the closest highway node shown in red nodes on the blue links. This reduces the number of links significantly from 26,129 to 18,907 links, reducing the computational run time from 120 to 100 hours.

Then Aggregated network 2 in Fig. 3.3 below was aggregated from the Aggregated network 1 by merging the road segments with the same characteristics. This merging leads to reduced number of nodes and links, and is illustrated Fig. 3.4 for one of the road segments.

Finally, Aggregated network 3 was aggregated from Aggregated network 1 by combining the TAZs to the nearest highway node shown in Fig. 3.5. Then Fig. 3.6 shows the TAZs in the green lasso being aggregated to the closest highway node to the red dot. To determine the closest highway node, the TAZs are connected to the gold lines, which are the connectors, and whichever connector line is the shortest, the TAZ will go to the highway node. The final network that will be used for the detour analysis is the Aggregated network 3, which has 10,642 nodes, 12,467 links, and 3,160 TAZs. It is dramatically smaller than the full network of 36,407 nodes, 100,523 links, and 6,880 TAZs. The use of the Aggregated network 3 will significantly reduce the computational efforts, as shown in Table 3.1.

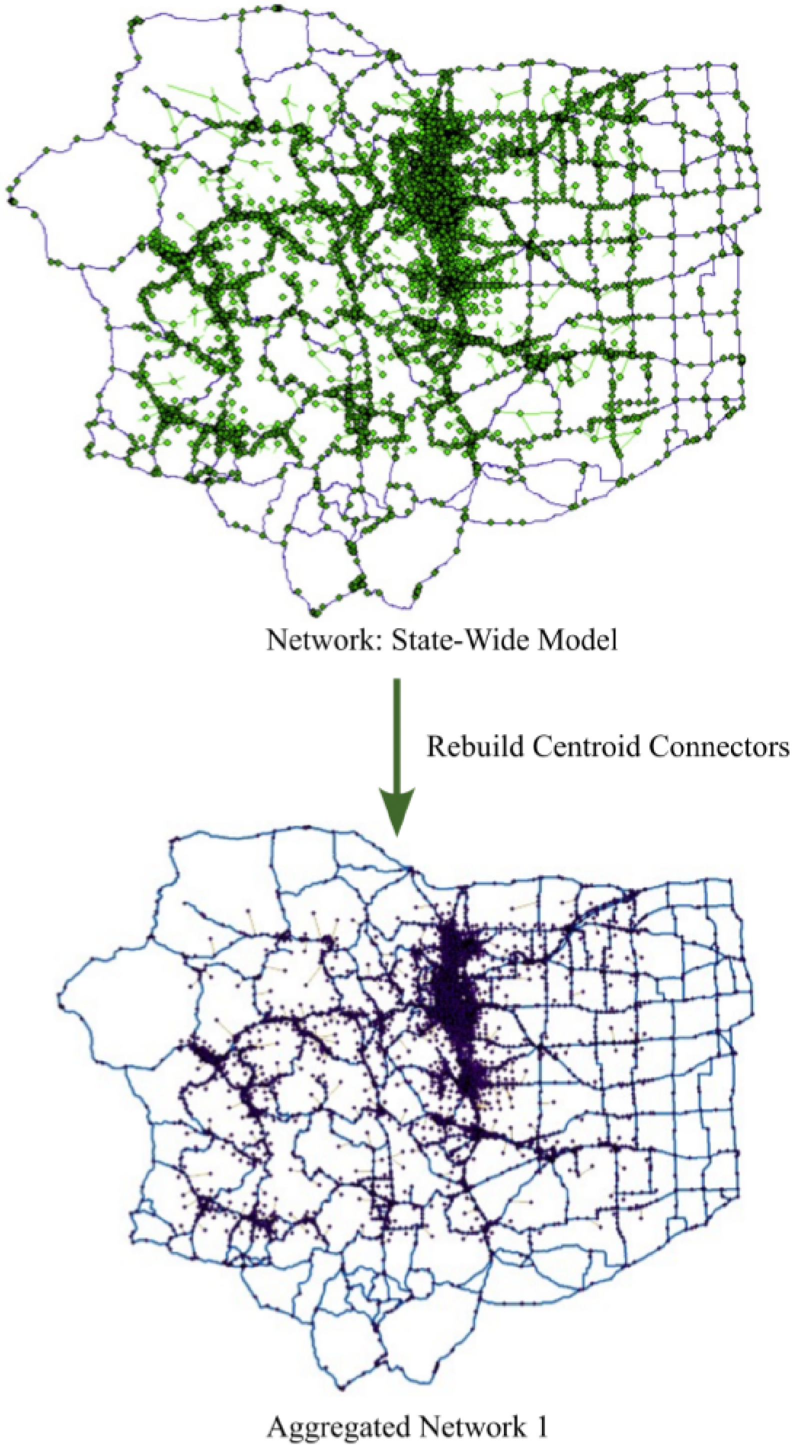

Figure 3.2: Aggregating Original Network to Obtain Aggregated Network 1.

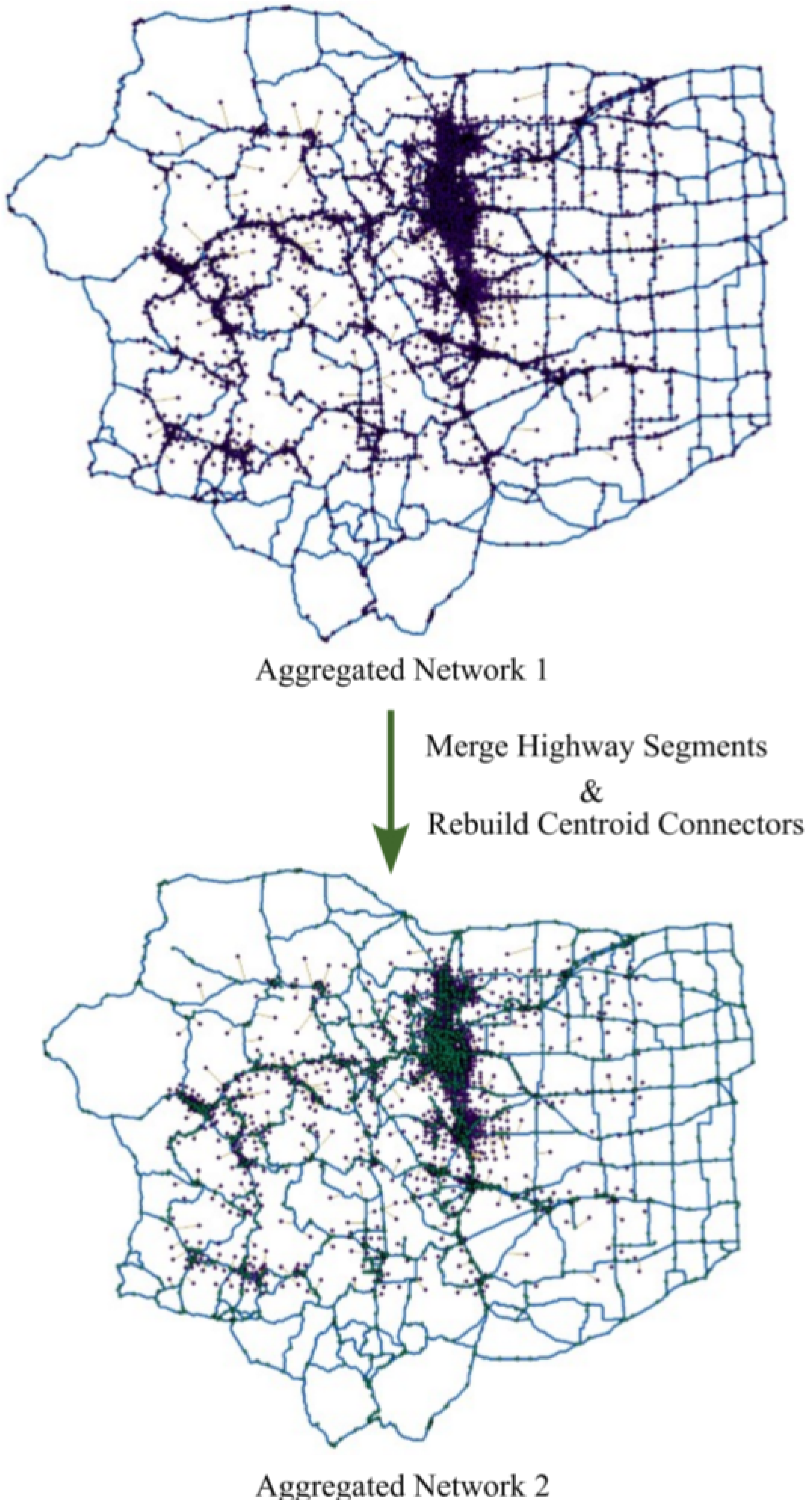

Figure 3.3: Further Aggregation of Network 1 to Obtain Aggregated Network 2.

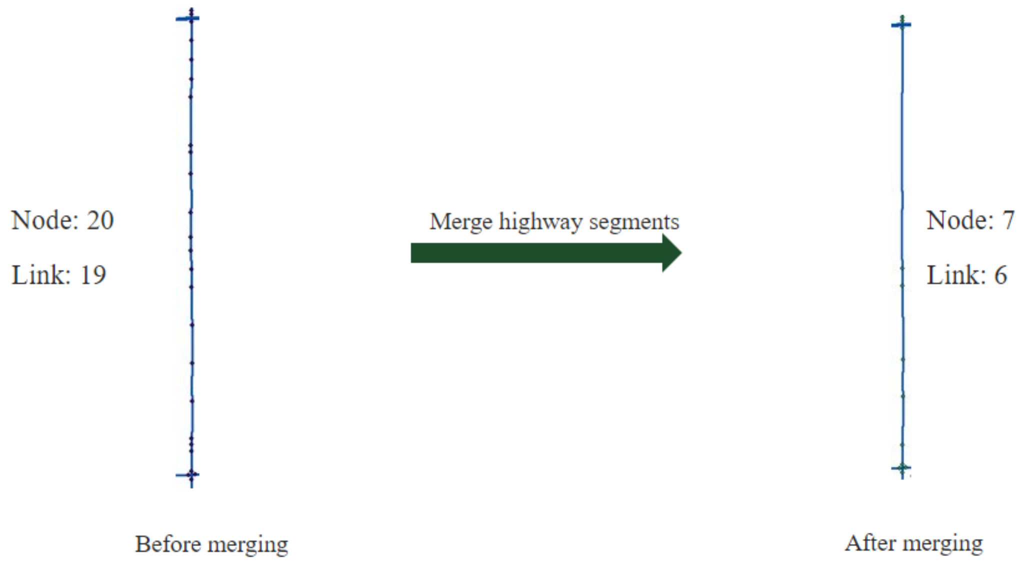

Figure 3.4: Merge Highway Segment with Same Characteristics.

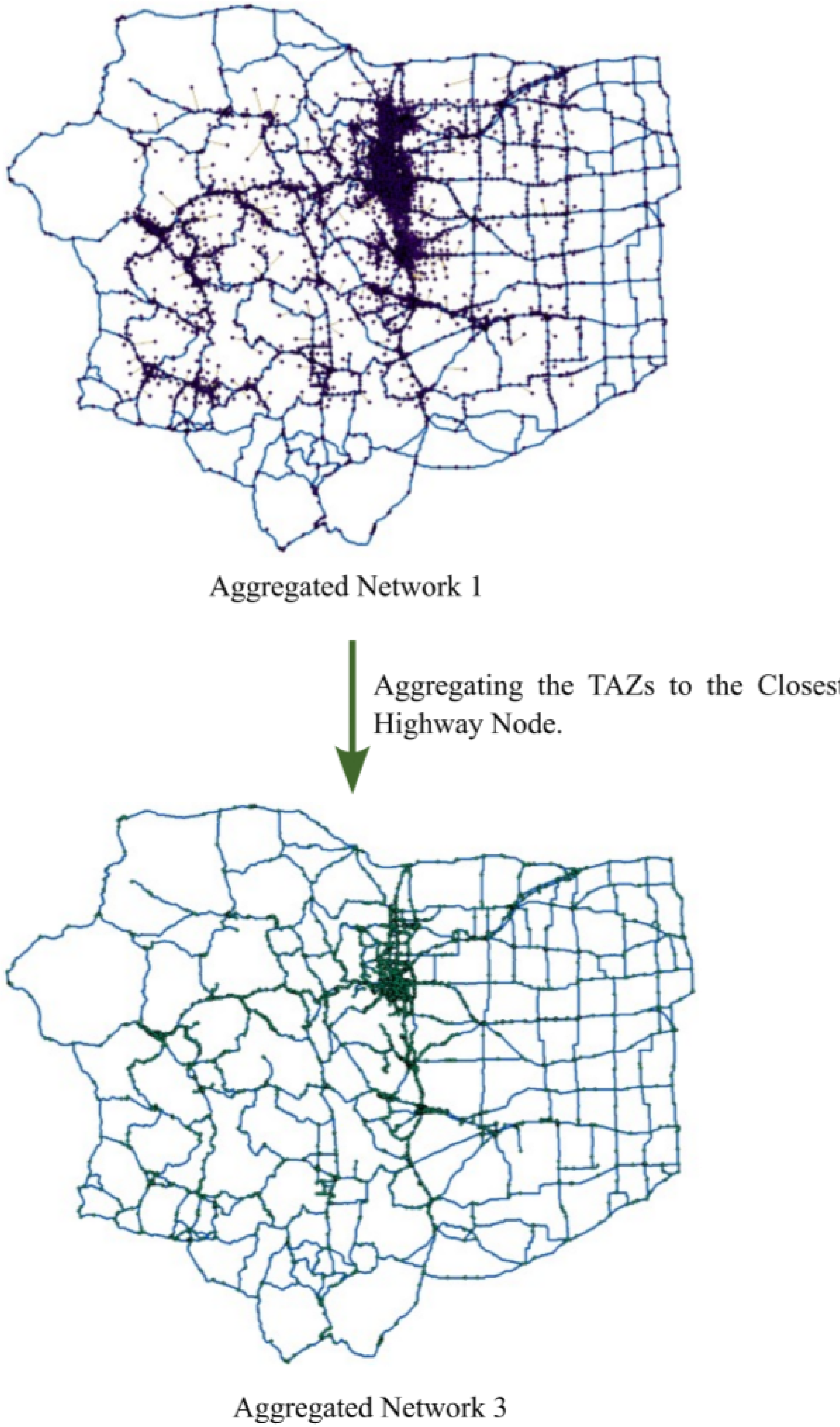

Figure 3.5: Alternative Aggregation of Network1 to Obtain Aggregated Network 3

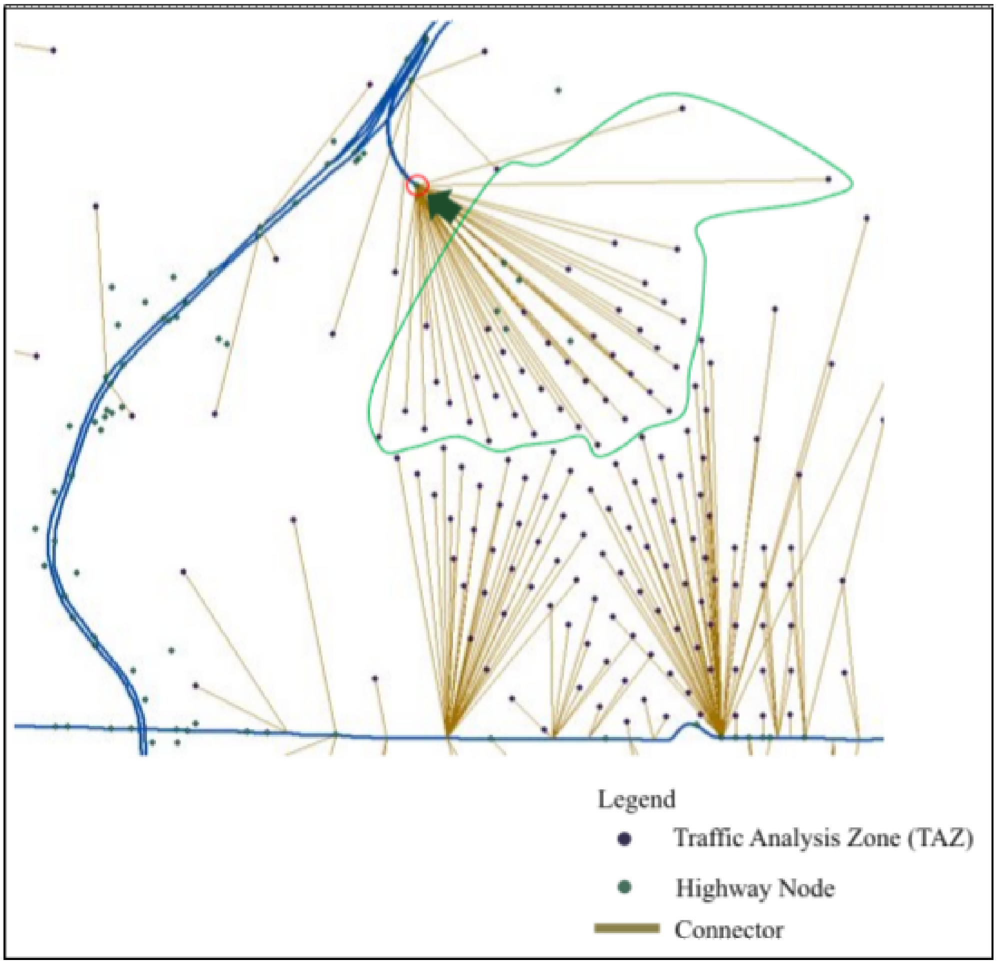

Figure 3.6: TAZs being Aggregated to the Closest Highway Node (Red Circle).

Freight Network

For freight detour analysis, the aggregated network 3 for cars cannot be directly used. This is because the traffic classifications have heavy vehicle (freight) restrictions within the Colorado state highway system. Therefore, freight network has to be provided from CDOT. Upon receiving the freight network data, we found that there were information missing about the segments that share with neighboring states (i.e., Utah, Wyoming, New Mexico, and Kansas), and also there were nodes not connected to one another, as shown in Fig. 3.7. The latter will affect the freight detour analysis, because incomplete node connections will lead to closed segments pertaining to these nodes yielding "No Best Detours". Since the network file does not have the connection between the incomplete nodes, it will be noted in the CDOT's Detour Identification Tool.

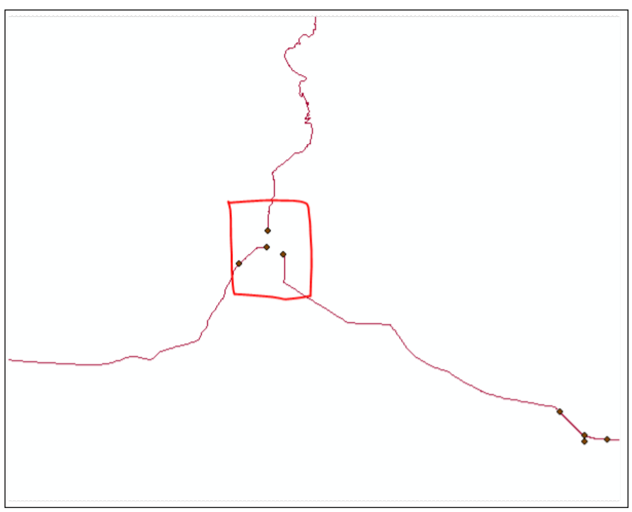

Figure 3.7: Incomplete Freight Network

Obtaining data from department of transportation in other states can be difficult since it is up to each department whether they want to share their information. In establishing the freight

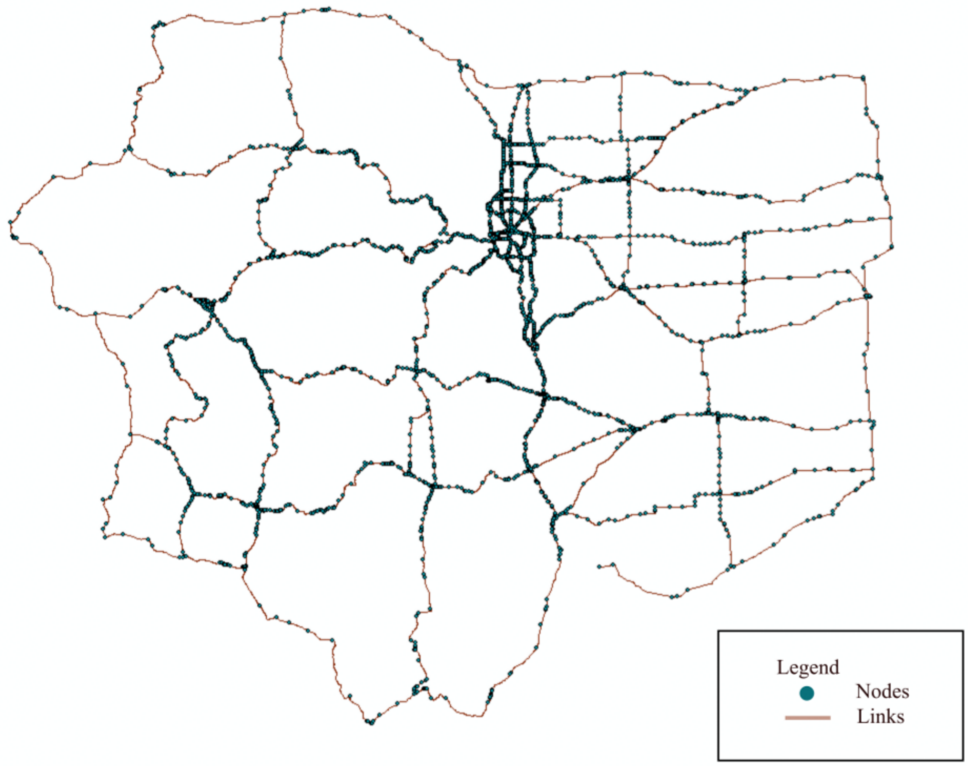

Figure 3.8: Entire Freight Network.

network, CDOT had to use some assumptions related to links shared with other states. Fig. 3.8 shows the freight network provided by CDOT in the end.

Comparing the car and the freight networks, it is noticeable that the freight network scale is relatively smaller than the aggregated car network. As expected, the freight detour analysis will have a shorter runtime than the car detour analysis.

3.1.2 Traffic Analysis using the Combined Distribution and Assignment Model

A different approach for the four-step model is used for this network analysis. Recall Fig. 3.1 for the combined model in the traffic analysis uses the trip generation and mode choice from the state-wide outputs and aggregated network as inputs for the combined model. This part will focus on the combined distribution and assignment model. There are some inputs that are required such as the travel demand. The travel demand be be given in various forms, either trip attraction and production at each node or an OD matrix (Wang and Jia 2020).

Based on the data provided from CDOT, the OD matrix has to be calculated from trip production and attraction of each OD node. The network performance and OD matrix are approximated using a combined traffic distribution and assignment model through optimizing the following objective function Z (Wang and Jia 2020),

$$Z\left(f_{i'j'}, T_{od}\right) = \sum_{i' \in I'} \sum_{j' \in J'} \int_{0}^{f_{i'j'}} c_{i'j'}\left(f\right) df + \frac{1}{\beta^{OD}} \sum_{o \in O} \sum_{d \in D} T_{od}\left(\ln T_{od} - 1\right) \tag{3.1}$$

where the first term represents the traffic volume and the travel times associated with trip assignment (i.e., user equilibrium) in Section 2.1.2. The second term modifies the travel demand rates between OD pairs (Wang and Jia 2020). The purpose of modifying the travel time is to have the travel demand consistent with the trip distribution (Bocchini and Frangopol 2011). Then $f_{i'j'}$ is the traffic capacity on the road segment from node i' towards node j' (in cars per unit of time) and $c_{i'j'}$ is the time required to cover the segment $i'j'$ and is a function of $f_{i'j'}$ shown in Eq. (3.5). Then β^{OD} is a parameter that is calibrated in the exponential decay function for T_{OD} in Eq. (3.2) (Wang and Jia 2020). This means that C_{OD} (travel time) will effect the decay function. The relationship between travel demand (T_{OD}) are inversely related to the travel time (C_{OD}). Where T_{OD} is the travel demand in the unit of time between OD pair and is distributed using the double constrained gravel model with exponential cost in the trip distribution model

$$T_{od} = X_o X_d O_o D_d \exp\left(\alpha^{OD} - \beta^{OD} C_{od}\right) \quad \forall o, d \tag{3.2}$$

subjected to $\sum_{O \in D} T_{od} = D_d \, \forall o$,$\sum_{d \in D} T_{od} = O_o \, \forall d$ and $T_{od} > 0$ for $\forall o, d$ (Wang and Jia 2020). Therefore, X_o and X_d are balancing factors with the origin zone *o* and the destination *d*. O_o is the trip production and D_d is the trip attraction to the destination zone *d*. The origin (O) and destination (D) will be column vectors that multiply by each other creating a O-D matrix size of 7000 x 7000 (given from CDOT). α^{OD} is parameter similar to β^{OD} which is a exponential decay function which needs to be calibrated by calculations. Here, α and β are already provided from CDOT in the network data and will not need to be calibrated. Note, if the travel time is too large then the travel demand will decrease because the drivers would not want to travel between the origin and destination based on considerably long travel time.

C_{od} is the travel time between origins *o* and destination *d*. Within the traffic assignment model, the trip demand, T_{OD}, must be assigned to the routes in the network. T_{OD} can be achieved by computing the travel time, C_{od}, using the shortest path and assigning the travel demand to the network. C_{od} can be calculated in Eq. (3.3) below. Cost C_{od} between O and D can be relative to the toll, cost, or time but in some cases it can be a combination.

$$C_{od} = \sum_{i' \in I'} \sum_{j' \in J'} c_{i'j'} \delta_{od,i'j'} \quad \forall i', j', o, d \tag{3.3}$$

$$c_{i'j'} \left(f_{i'j'} \right) = c^0_{i'j'} \left[1 + \alpha^{CF} \left(\frac{f_{i'j'}}{f^c_{i'j'}} \right)^{\beta^{CF}} \right] \quad \forall i', j' \tag{3.4}$$

$$f_{i'j'} = \sum_{o \in O} \sum_{d \in D} T_{od} \delta_{od,i'j'} \quad \forall i', j', o, d \tag{3.5}$$

where $\delta_{od,i'j'}$ is equal to one if the edge *i'j'* falls along the shortest path between *o* and *d*, and zero if criteria are not met. $c^0_{i'j'}$ is the required time to cover the edge *i'j'* in a free flow. α^{CF} and β^{CF} are fixed parameters which are also provided from CDOT.

Eq. (3.4) is the equation that is changed between the state-wide model and the new model, which considers congestion in the combined distribution and assignment model. The time required to cover the segment as a function of traffic capacity includes a ratio between the actual speed over the free speed, which will increase the value of $c_{i'j'}$ (travel time). In the statewide model, the travel time did not consider the ratio of speeds (i.e., no congestion effect). The second term in the bracket of Eq. (3.4) is zero in the statewide model but will be nonzero when using the combined distribution and assignment.

The combined distribution and assignment model above can be solved by using an iterative procedure (Bocchini and Frangopol 2011). The model emulates a static UE traffic assignment assigning trips to the shortest path, and based on the congestion level the travel time is updated iteratively (Denver Regional Council of Governments 2004). The iteration continues until the algorithm converges. Convergence means when the drivers can no longer improve their generalized cost.

Given the four-step travel in the new detour analysis considering congestion, the main focus was the combined distribution and assignment method since CDOT provided trip generation and mode choice. The model outputs are similar to those in Section 2.1.3 and include results related to the traffic flow, travel time, and distance.

3.2 Procedure to Run Detour Analysis

The detour analysis incorporates both car and freight data, but each detour analysis is run specifically for either the car or freight detour analysis. For example, when running the Car Detour Analysis, the freight data is held in place so that only the car is focused. This is done within the analysis by referencing the truck's UE baseline results (i.e, free flow speed, length, time, etc.). The same concept goes with the truck detour analysis, for which the car data is held in place so that the freight is focused. Again, the freight detour analysis would include the car's UE baseline results. Please refer to Fig. 3.9 and 3.10 for how the car and truck detour analyses are carried out.The detour analysis was developed in MATLAB and uses parallel computing to reduce the computational time.

3.2.1 Car Detour Analysis

For car detour analysis, Fig. 3.9 shows the process of how car and freight flow are modeled for car detour analysis. The model needs to incorporate freight flows in the car analysis. The initial step is running the freight traffic analysis to obtain the baseline results (main flow) without closing any highways segment on the freight network. Fig. 3.8 shows the freight network, which is a subnetwork of the car network. Then we assume there are fixed equivalent flows on the freight routes, e.g., 1 truck is the the same as 3 cars, which was based off of CDOT's toll roads. The toll roads cost are based off the number of axles a vehicle has, so assuming a standard freight has 6 axles and a car has 2 axles it is a fair assumptions to say 3 cars is equivalent to 1 freight and this is also the assumption used in CDOT's statewide model. The next step would be fix the equivalent car flow on the freight route and use User Equilibrium for "all cars". This will allow the entire network to be used by the car data.

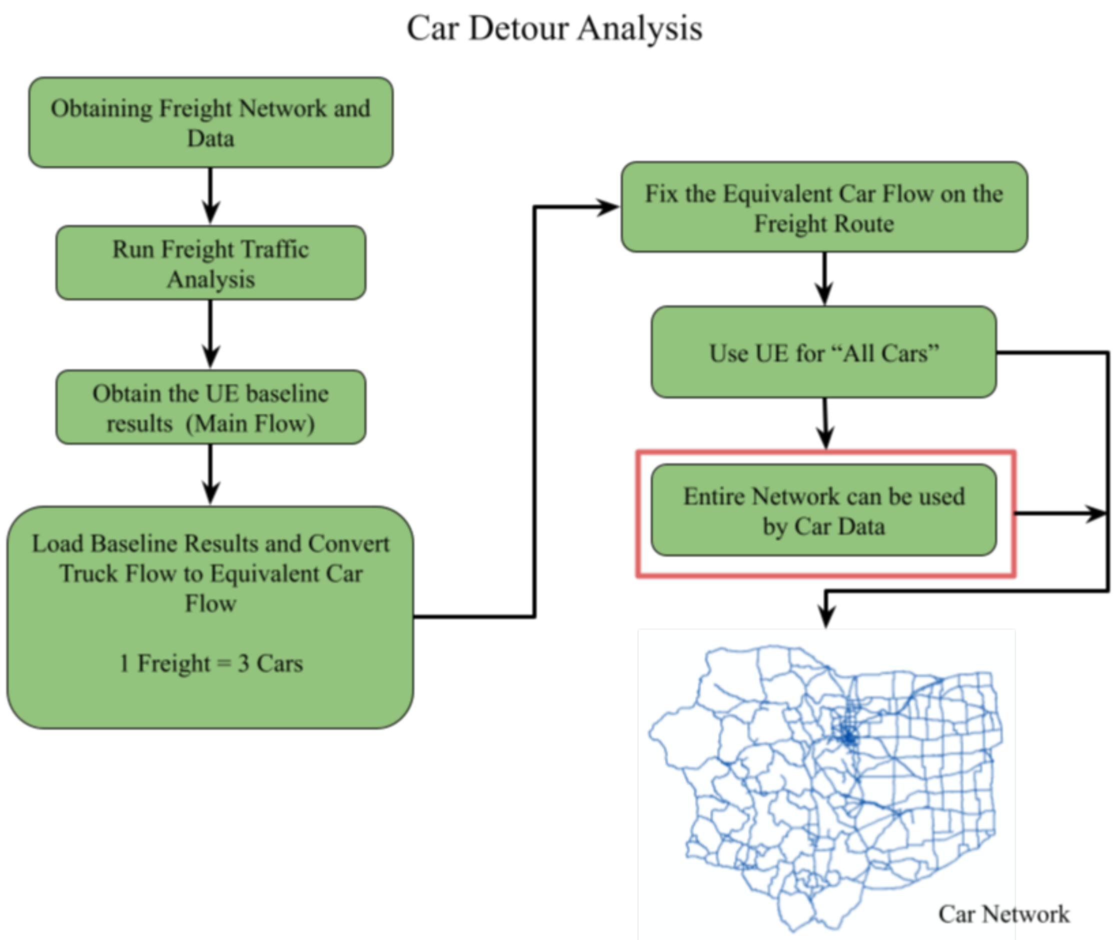

Figure 3.9: Flowchart for the Car Detour Analysis.

3.2.2 Truck Detour Analysis

For truck detour analysis,it is similar to the car detour analysis process. Fig. 3.10 shows an illustration of how the car and freight flow are modeled in the freight detour analysis. The freight detour analysis will incorporate the car flows. First, the car traffic analysis is run to obtain the UE baseline result (main flow) for the entire network without closing any highway segment. The UE baseline results for car flow is for the entire network. However, only the UE baseline for car flow on the freight route network is needed. So a python code was developed to index the nodes on the freight routes. This was done by gathering the freight network and going through the car's baseline results and get the index if the freight nodes are the same nodes as the baseline.

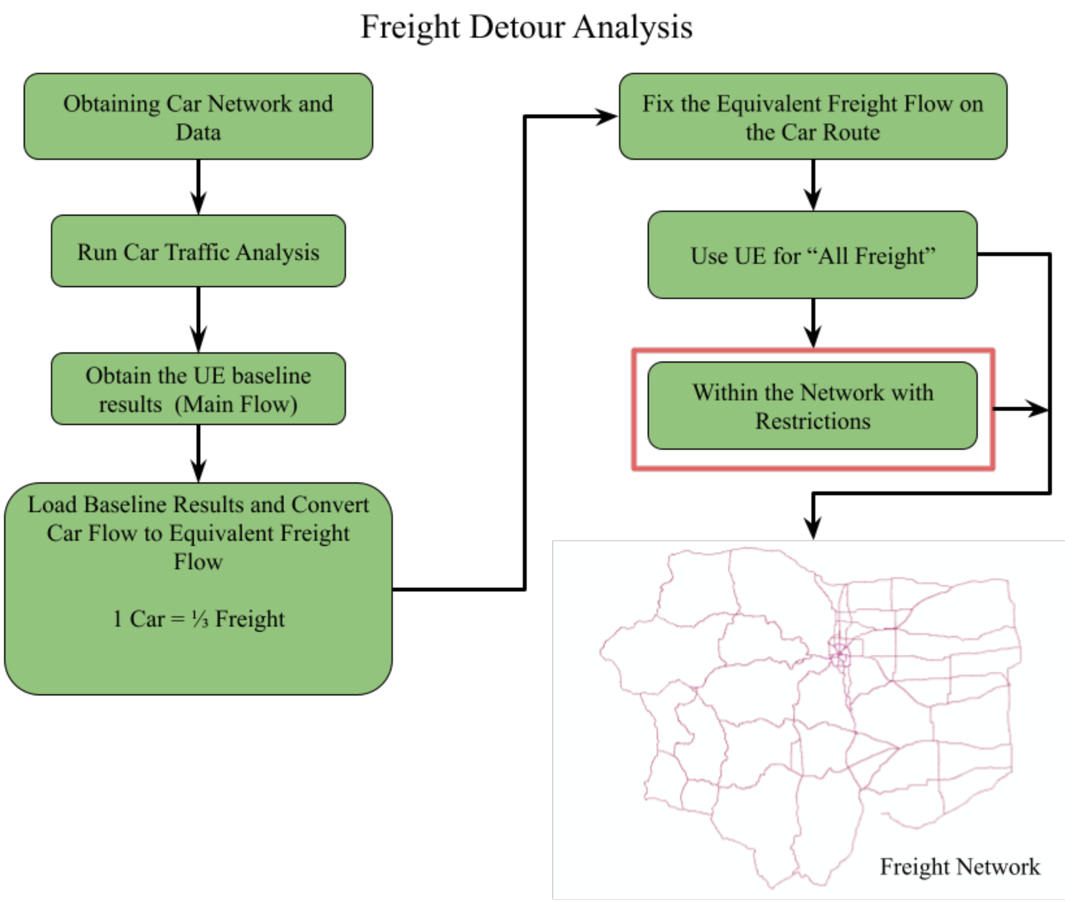

Figure 3.10: Detour Analysis Modeling Freight Flow.

Chapter 4:

Identify the Best Detours for All Highway Segments

4.1 Introduction

This chapter presents the procedure of identifying the first, second, and third best detours for any closed highway segment. This chapter also discusses the procedure of obtaining the nodes and segments for the closed highway segments based on the original network data. Example detour analysis results are also presented.

4.2 Procedure to Identify the First, Second, and Third Best Detours

Before running the detour analysis, a baseline run of the network (i.e., Aggregated network 3 in Table 3.1) is carried out first without closing any route/segment. The baseline run provides insightful information on the traffic flow, time, and distance. To identify the 1^{st} best detour for a particular road segment, we first close this segment and then run the detour analysis (i.e., run the network analysis using the updated network with only the corresponding road segment closed/removed), and the analysis would yield the 1^{st} best detour, and the traffic flow and additional time and distance for this detour. To identify the 2^{nd} best detour, we will further close the 1^{st} best detour and rerun the detour analysis, which will give the corresponding traffic flow and additional time and distance for the 2^{nd} best detour. Similarly, the 3^{rd} best detour can be established by further closing the 2^{nd} best detour and rerunning the detour analysis. Fig. 4.1

illustrates the procedure to identify the first, second, and third best detours if such detours exist. For practical purpose, we only consider up to the third best detour (if it exists). The above detour analyses are carried out for all 985 highways.

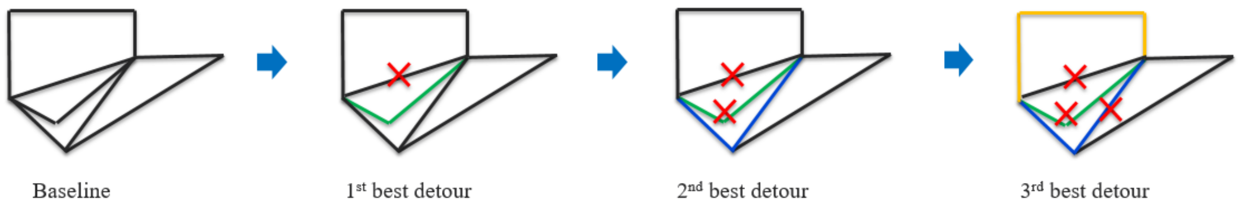

Figure 4.1: Procedures to Identify the First, Second, and Third Best Detours.

4.2.1 Obtain Closed Nodes and Links for Each Highway Segment

Gathering the nodes on the closed segment is essential for the detour analysis because such initial inputs are needed for the detour analysis to tell the model what nodes from the aggregated network are closed. This section will go into detail about the procedure for obtaining the nodes from the aggregated network to let the detour analysis know which highway segment is closed. The objective is to obtain the beginning and end nodes along with the nodes between the beginning and end nodes. This is done by developing a python code that references three of CDOT's comma-separated values (CSV) files. The first step was to open the "HighwaySegmentList-AllSeasonDetours-6-July2021-modified.csv" and gather the column of data that were important, including StatewideID, From Mile Point (MP), TO MP, Primarily Detour Route Name (AB Direction), and Secondary Detour Route Name (BA Direction). From the second file, "CDOTDetourRoutes-TimeHeldConstant-utm13m.csv", data on the Route-ID, Route-Name, Closure Start, and Closure End are gathered. The primary and secondary detour route names from the the first file were used as a way to connect both files. The last file, "StateHWY-CO", includes the large metadata of the entire network.

As an example, the above process is demonstrated for one particular highway segment. In this case, first we go to the highway segment's file to get the StatewideID "001A15" of the row and pull the primary detour (AB direction), for example, "001A-NB-001" with the closure of [0 10.053] MP. Fig. 4.2 shows a snapshot for this particular example.

				AB - Dir	BA - Dir
A	B	F	H	L	M
StatewideID	Route	FromMP	ToMP	PriDetourRouteName	SecDetourRouteName
001A15	001A	0.000	10.053	001A_NB_001	001A_SB_003

Figure 4.2: CSV File for Highway Segment.

Then moving onto the CDOT Time Held Constant files, using the route name (001A-NB-001), the associating closure start and end in MP for this case is found to be [0 9.886], as shown in Fig. 4.3.

ROUTE_ID	ROUTE_NAME	ROUTESUSED	CLOSURESTA	CLOSUREEND
201	001A_NB_001	287C, 014C, 025A	0	9.886
203	001A_SB_003	025A, 014C, 287C	9.886	0

Figure 4.3: CDOT Time Held Constant File.

Finally, using the vast network data, we use the Statewide ID (001A15) to find all the highways segment in the network called "SHSEGMENTC". Note that this will select all "SHSEGMENTC" for 001A15. The results will have mile points of [0 10.025] which exceeds the closure mile point [0 9.9886],so any values that do not fall in closure MP [0 9.9886 is dropped. Fig. 4.4 shows all the Statewide ID collected and sorted from the smallest to largest for the "ANODENEARF" column.

```
001A_NB_001 001A15
|   ROUTE_ID   ROUTE_NAME  CLOSURESTA  CLOSUREEND
1        201  001A_NB_001         0.0       9.886
|      FROM_ID  TO_ID  DIR SHSEGMENTC  ANODENEARF  BNODENEARF
1125     61084  61085    0     001A15       0.000       0.346
1138     61085  62227    0     001A15       0.346       0.346
1139     62762  62227    0     001A15       0.346       0.346
1135     62228  62762    0     001A15       1.000       0.346
1132     61072  62228    0     001A15       1.079       1.000
1140     61061  61072    0     001A15       1.236       1.079
1124     61060  61061    0     001A15       1.335       1.236
1141     61056  61060    0     001A15       1.546       1.335
1123     61043  61056    0     001A15       1.840       1.546
1121     61042  61043    0     001A15       2.353       1.840
1122     61042  61044    0     001A15       2.353       2.869
1131     61044  62037    0     001A15       2.869       3.702
1128     62037  62038    0     001A15       3.702       5.000
1142     62038  63558    0     001A15       5.000       5.482
1137     62040  63558    0     001A15       6.372       5.482
1129     62039  62040    0     001A15       7.419       6.372
1134     62039  62395    0     001A15       7.419       8.401
1133     62041  62395    0     001A15       8.954       8.401
1130     62041  61969    0     001A15       8.954       9.792
1127     61967  61969    0     001A15       9.886       9.792
61084
61967
```

Figure 4.4: StateHWY Information of StateWide ID (001A015)

In addition, it is important to note the value of direction of the segment because there are cases where the segment is bi-directional (0) or one way (1 or -1). In the network data, columns "ANODENEARF" and "BNODENEARF", which are MP from point A to Point B, are used in identifying the beginning and end nodes for the closed segment. The beginning node was done by identifying the smallest MP within the bounds. For example, referencing Fig. 4.4 the smallest MP is 0, which is in the "ANODENEARF" column, so the beginning node would be from the "FROM-ID" for that row. In contrast, the end node is determined from the largest MP, staying with the same example (001A15), the the largest MP is 9.9885 and falls into the "ANODENEARF" thus the end node will pertain to the FROM-ID. After the beginning and end nodes are established, the next step would be collecting all the nodes between the beginning and end nodes. This was done by going through each row of the "SHSEGMENTC" and comparing between the "ANODENEARF" and "BNODENEARF". If the direction of the segment equals 0, then go down each row, if "ANODENEARF" < "BNODENEARF" then the nodes are collected as [FROM-ID TO-ID] and move on the next row, if "ANODENEARF" = "BNODENEARF" then the nodes are collected as [TO-ID FROM-ID]. In general, if the largest MP was on the "ANODENEARF" column then the node was taken from the "FROM-ID" column, and if the largest MP was on the "BNODENEARF" column, then the node was taken from the "TO-ID" column. This is done for the entire segment. Note, if the direction is 1 or -1 only take the nodes [FROM-ID TO-ID] if "ANODENEARF" < "BNODENEARF".

4.3 Illustrative Example

Examples from the Aggregated network 3 in Fig. 3.5 have been tested in the detour analysis to identify the 1^{st}, 2^{nd},3^{rd}, and no best detours. Running all 985 highways segments will yield only one, two, three, or even no best detours.

4.3.1 Example Segment with No Best Detours

An example that would provide no best detours is presented in Fig. 4.5. The blue line represents the closed segment (007A15). Since the closure points are not on the entire segment, the driver will drive where the mile point is not closed until reaching the closed segment, which means that the driver has no chance of turning back. Thus no best detour will be outputted.

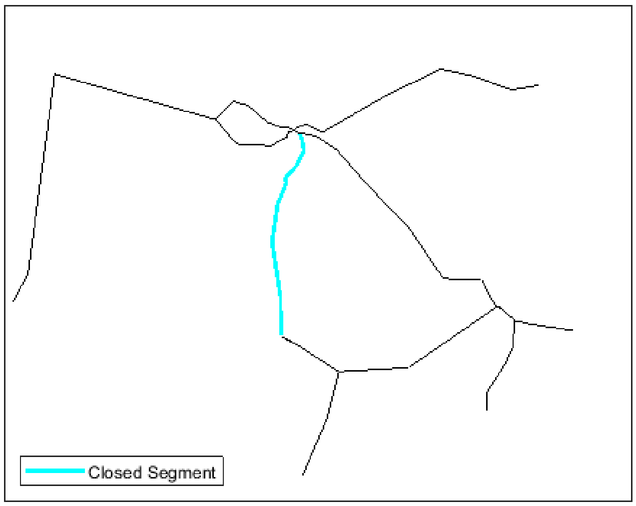

Figure 4.5: Example of Road Segment with No Best Detours (007A15).

4.3.2 Example Segment with One Best Detours

Fig. 4.6 displays a blue line that represents the closed segment (371A15). The detour analysis displayed the red line as the 1^{st} best detour when closing the blue line. However, rerunning detour analysis for the red line, there will be no other available detours. Since the red and blue segments are removed, no other available segments are present.

4.3.3 Example Segment with Two Best Detours

Fig. 4.8 below shows the green section which is the road segment (001A15 is the highway segment name) that will be closed. When closing the green section, the detour analysis identified the yellow section as the 1^{st} best detour. When closing both the green and yellow sections, the

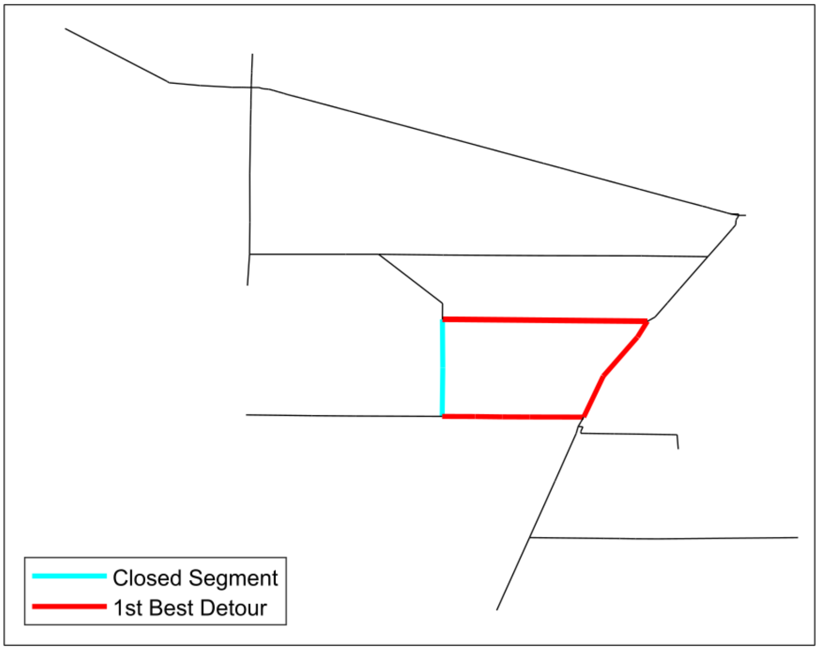

Figure 4.6: Example of Road Segment with 1 Best Detours (371A15).

detour analysis then gives the red section as the 2^{nd} best detour. However, for this particular highway segment being closed, there is no 3^{rd} best detour.

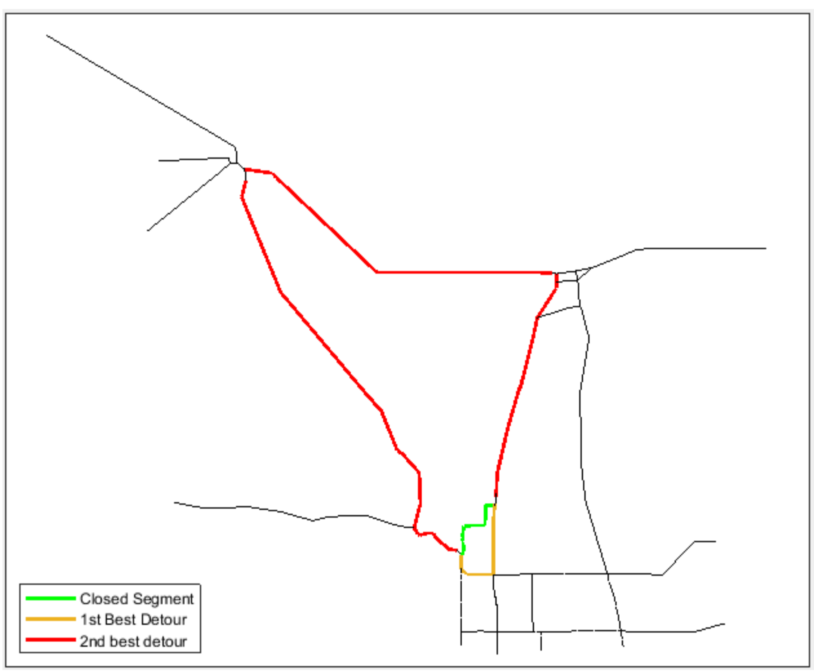

Figure 4.7: Example of Road Segment with 2 Best Detours (001A15).

4.3.4 Example Segment with Three Best Detours

Another example that would provide three best detours is also presented here, corresponding to choosing highway segment "006J89" and closing the direction from A to B. Running the detour analysis would give the red section as that is the 1^{st} best detour. Then closing the 1^{st} best detour and rerunning the detour analysis would give the yellow section as the 2^{nd} best detour. Finally, closing the 2^{nd} best detour, after running the detour analysis the black section is identified as the 3^{rd} best detour.

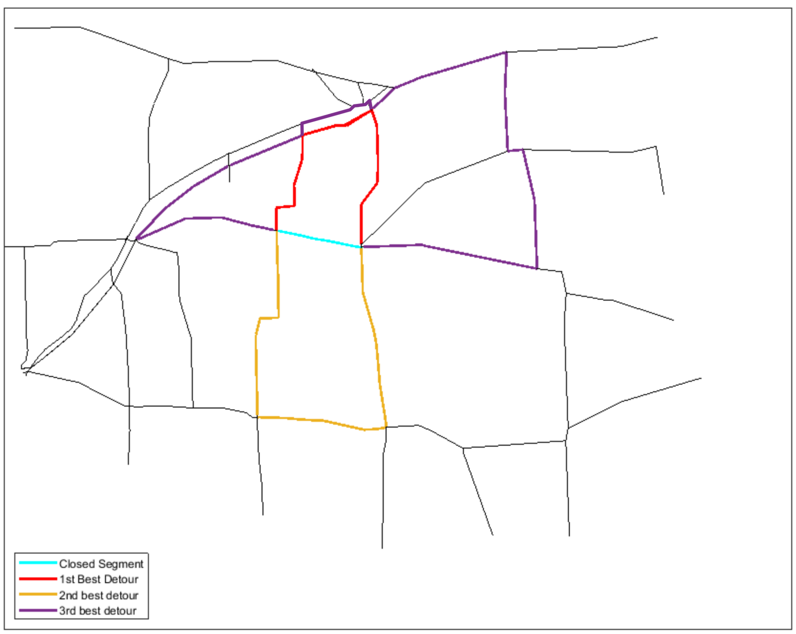

Figure 4.8: Example of Road Segment with 3 Best Detours (006J89).

Chapter 5:

Detour Analysis Results for Car and Freight

5.1 Introduction

This chapter presents the detour analysis results for both car and freight, and the updating of CDOT's Detour Identification Tool (i.e., add information on multiple detours, and the additional travel time and distance for each alternative detour). To speed up the analyses, High Performance Computing (HPC) computer clusters with many nodes are used. Python codes are also developed for post-processing of the results, and the results are also used to create and update CDOT's Detour Identification Tool's State Detour Map.

5.2 Implementation Details

To obtain the results for the detour analysis for car and freight, some initial parameters have to be set within the detour analysis.The detour analysis requires base information, for example, which segments from the highway system is to be closed. Since there are 985 highway segments for the car network that are bi-directional segments, the detour analysis can only run the analysis for one direction (AB or BA) at a time. Therefore, the number of detour analysis run for segments will have to be double of 985 highway segments factoring AB direction and BA direction. So a total of approximately 1900 highway segments will be analyzed for the car network. In addition, freight has approximately 1000 highway segment for both AB and BA directions. Once the segments for the closed detour was obtained through the procedure described in Chapter 4, the next step would be running the model, gathering results and post-processing the results.

5.2.1 Running Detour Analysis on High Performance Computing (HPC)

To speed up the analyses, High Performance Computing (HPC) computer clusters with many nodes are used.

The way the detour analysis works is the highway segment closed is considered a "JOB". For example closing "001A15" for AB direction is "JOB1" and BA direction is "Job2". The detour analysis can be run on the individual lab computers on MATLAB. However, running the program on MATLAB will be extensive since the lab computers have limited Central Processing Unit (CPU) which means the model can run one "JOB" at a time. Note that running a single job takes approximately six hours. Running the entire closed highway segment with approximately 1900 jobs on a typical lab computer with limited CPU capacity would take approximately 475 days which is unrealistic. To help reduce the computational time, more computing power is introduced as an High Performance Computing (HPC). A HPC is a supercomputer that has a set of interconnecting processors that work together, and clusters work at a much higher level of performance. Table 5.1 shows the comparison between a lab computer versus a HPC system, which corresponds to the Summit HPC. Summit HPC Cluster is a HPC system that is joint venture between Colorado State University (CSU) and the University of Colorado Boulder (CU), housed in Boulder, Colorado (Anderson et al. 2017).

Since the HPC is a server based system, files such as JOBs will have to be transferred from a local system to Summit's system. This is done through web-based application (e.g., WinSCP, FileZilla) that transfers data using SSH protocols. Once the data has been transferred to Summit's

Table 5.1: Comparison between lab computer and Summit HPC (Anderson et al. 2017)

Features	Standard Computer	Summit
# of "computers"	1	488 nodes
# CPU Cores	4 core	12,632 cores
Memory	16 GB	70.8 TB
Storage	512 GB	1.2 petabytes

server, the detour analysis will not run because a shell file needs to be developed to tell the nodes (computer) what to do with the folder.In particular, for the current detour analysis, the shell file is used for the terminal (e.g., PuTTY) to interpret, and tell the terminal to request one node, 24 CPU's per task, 4GB of memory per CPU, and a cancel detour analysis if the run time is over eight hours. The upper limit of eight hours is used because based on some tests most detour analysis can be finished around six hours on the HPC.

Since each job represents 1 of 1900 highway segment, a for loop is created within the PuTTY terminal that copy the same Job file but modify the Job number pertaining to the highway segment. However, due to the limited storage space on Summit's server a maximum of 400 jobs can be created at one. Once all the jobs are created in the PuTTY terminal we run all 400 jobs by incorporating a for loop by telling it to go into each job folder to run the detour analysis. A log file will be created in each Job file similar to a status report to inform if there is any error and report the run time for the detour analysis. Finally, running detour analysis for all the highway segments in the entire highway network took approximately two weeks including queuing time.

5.2.2 Post Processing of Detour Analysis Results

Once all detour analysis has been done for all 1900 highway segments, a python code was developed to automatically extract and post-process the results, including the traffic flow, time, and distance for the detours as well as the nodes for the suggested detours for each of the closed segment. In particular, the objective was to go through the results for all the closed segments, and the code will open up the traffic flow and gather the distance and time for the detour nodes. The sum of the times and distance will be denotes as $Time_1$ and $Distance_1$. Then the corresponding time and distance are collected from the UE baseline's traffic flow. The sum of time and distance will be labeled as $Time_0$ and $Distance_0$. To calculate the additional time and distance, Eq. (5.1) and (5.2) are used, which was done for all the 1900 highway segments.

$$AdditionalTime = Time_1 - Time_0 \tag{5.1}$$

$$AdditionalDistance = Distance_1 - Distance_0 \tag{5.2}$$

The next step was identifying the routes used on the detour. This was done by first identifying the nodes used on the detour from the results file. The overall objective was to identify the routes. However, this can be difficult since each segment has a Mile Point (MP) to determine the routes but those values were not given. So for simplification, this was done within the python code by gathering the nodes (FROM-ID and TO-ID) and the associated segment name of each node. Once the all the segment names have been collected, the duplicates names are then dropped thus giving only unique route segments used for the closed segment.

5.3 Detour Analysis Results for Car

5.3.1 Additional Travel Time and Distance for Detours Considering Congestion

A new updated state detour map has been generated with the newly calculated additional time (minutes) factoring in the congestion effects. The map is shown in Fig. 5.1. Note that the results are plotted for the 1^{st} best detour in the AB direction, and to see the results for BA direction please refer to Appendix. A. Fig. 5.2 shows a state detour map with the corresponding additional travel distance for each highway segment for AB direction for only the 1^{st} best detour. The maps for the BA direction look similar to those for the AB direction. As expected, central Denver would yield smaller additional travel times and distances but the state highways outside Denver will have longer additional travel times and distances. For example, Interstate 70 (I-70) is an essential interstate that runs along Colorado's west-east interstate highway, and Fig. 5.3 illustrates the Glenwood Canyon outlined in the black circle. The upper portion of Fig. 5.3 shows an actual closure caused by natural hazards (e.g. flooding, mud slides, rock slides, etc) (Colorado Department of Transportation 2021). The bottom portion of Fig. 5.3 depicts the corresponding segment and the additional added detour time in updated state detour map based on the detour analysis that considers congestion. The closure of Glenwood Canyon on I-70 would cause significant additional travel time shown with the red line denoting that closure of this highway segment will create an additional added detour time of more than 2 hours. The significant increase of additional travel time from the closure will yield a significant additional detour travel distance shown in Fig. 5.2 denoted in red, which represents an additional detour distance of more than 120 miles.

Table 5.2 compares the statistical difference between the state-wide model and the new detour analysis for additional travel time for the AB direction. Table 5.3 shows the statistical difference for the BA direction.

Some notable takeaways are that the additional travel times between the two analyses are not too different. The number of segments with added detour time of up to 15 minutes seems to be overestimated in the state-wide model. Also, it is essential to note that the number of segments with added detour travel time of more than an hour seems to be underestimated for the state-wide

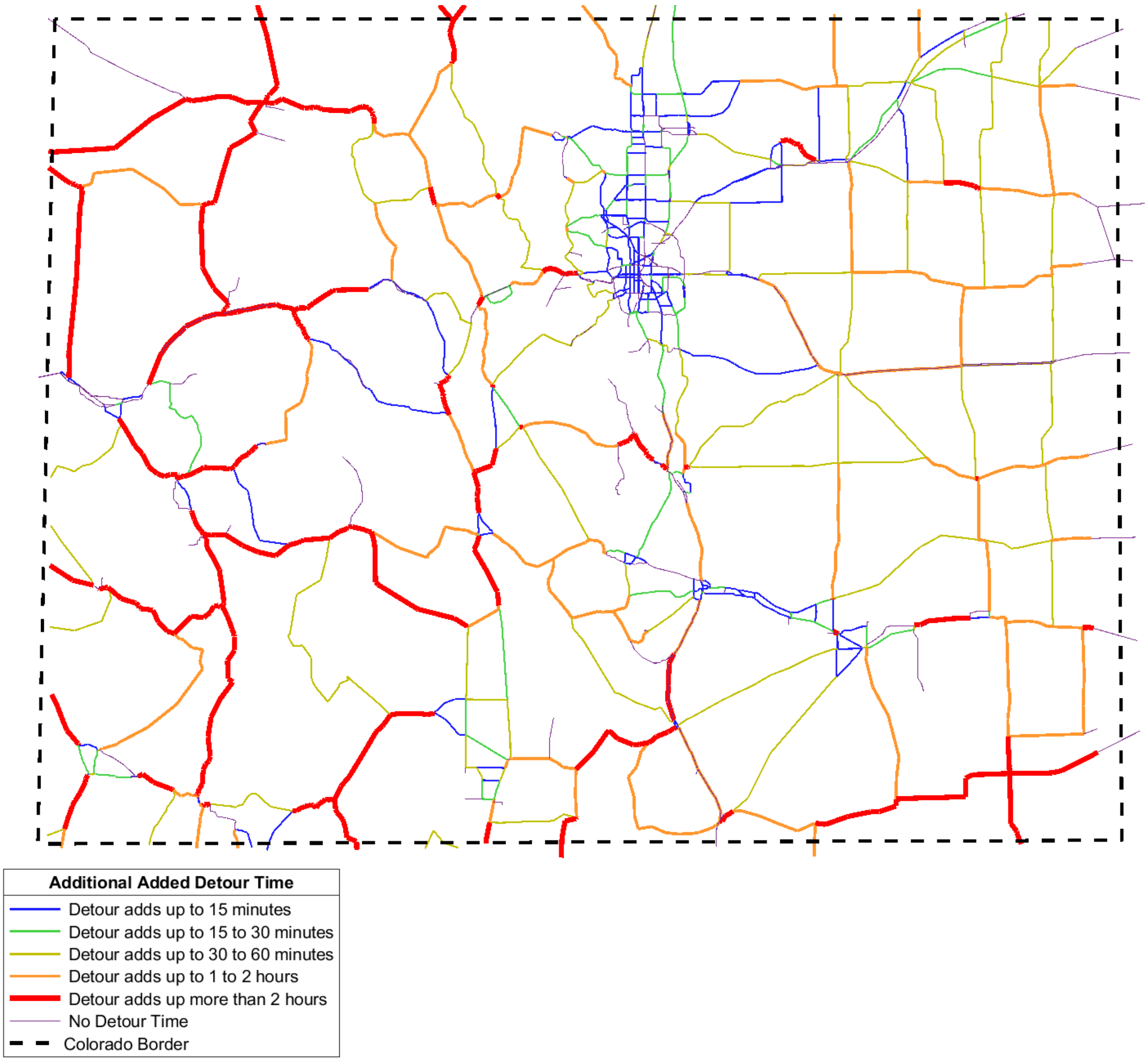

Figure 5.1: Updated State Detour Map with Additional Travel Time Considering Congestion.

Table 5.2: Statistical Differences Between State-Wide Model and New Detour Analysis for the Additional Travel Time for the AB Direction.

	State-Wide Model	New Detour Analysis
# of Detours up to 15 mins	489	411
# of Detours up to 15 - 30 mins	112	118
# of Detours up to 30 - 60 mins	129	117
# of Detours up to 1 - 2 hrs	65	111
# of Detours up to 2 - 4 hrs	31	69

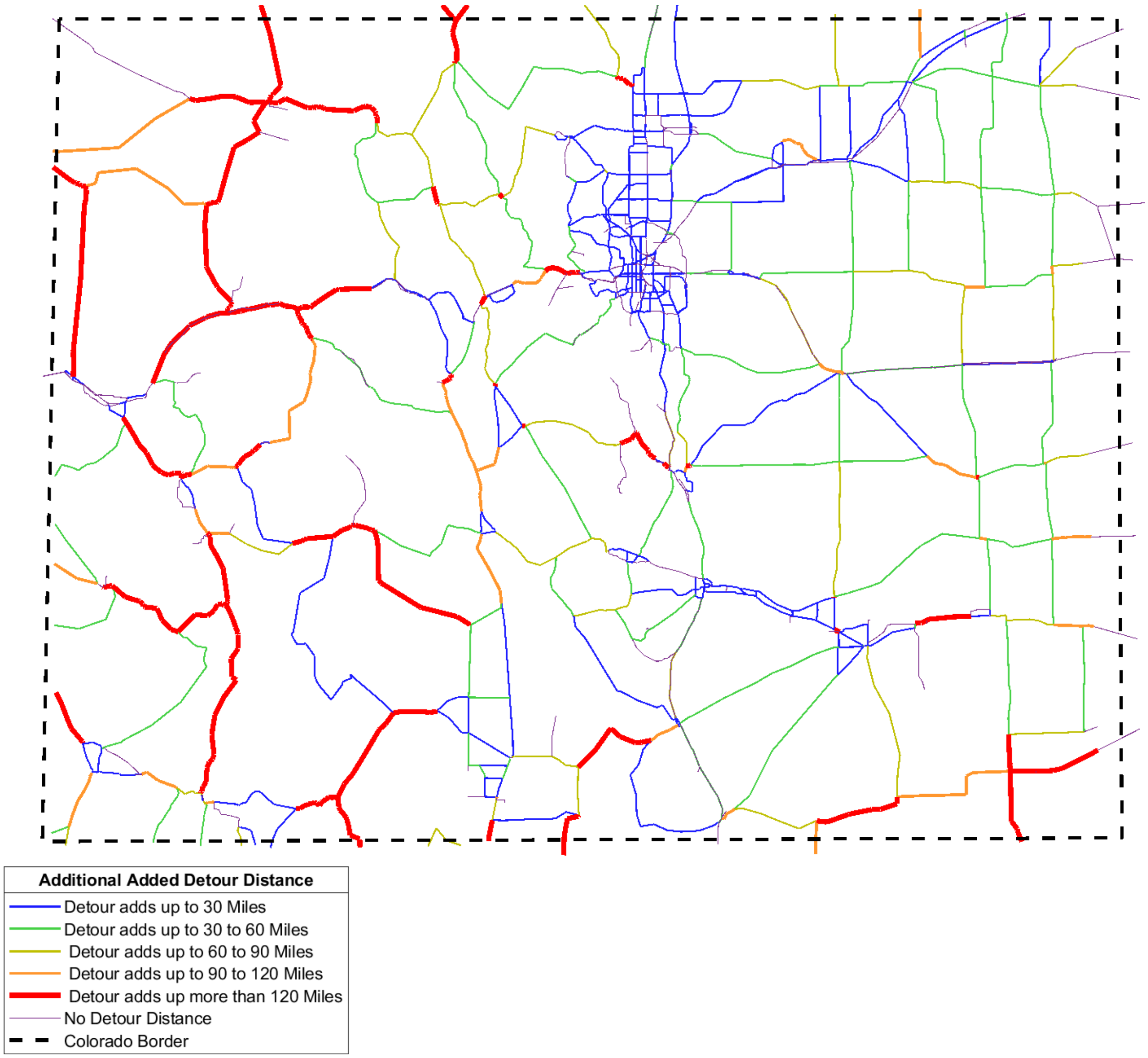

Figure 5.2: Updated State Detour Map with Additional Travel Distance.

Table 5.3: Statistical Differences Between State-Wide Model and New Detour Analysis for the Additional Travel Time for the BA Direction.

	State-Wide Model	New Detour Analysis
# of Detours up to 15 mins	491	411
# of Detours up to 15 - 30 mins	113	121
# of Detours up to 30 - 60 mins	132	119
# of Detours up to 1 - 2 hrs	68	113
# of Detours up to 2 - 4 hrs	30	70

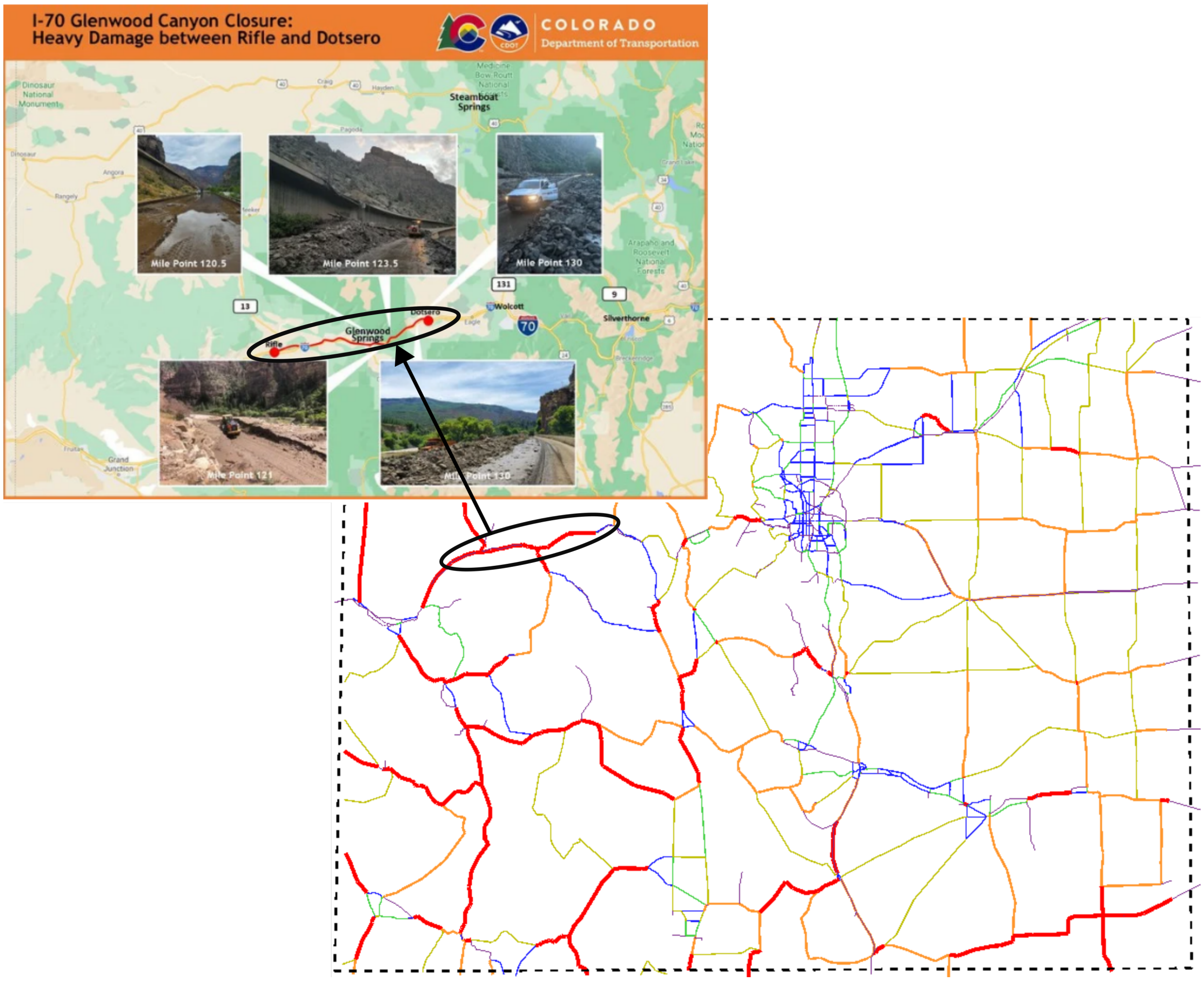

Figure 5.3: Illustrative Example of Glenwood Springs on the State Detour Map (Colorado Department of Transportation 2021).

model, and in the new detour analysis, these numbers nearly doubled for both AB and BA directions. This is because the new detour analysis considers congestion and the travel time is expected to increase compared to the analysis that neglects congestion. Overall, this will reduce the number of segments with lower additional detour time and increase the number of segments with higher additional detour time. Hence the observations in the tables. The number of detours with less than 15 minutes will decrease, again due to congestion and travel times increasing for both AB and BA direction. Tables for statistical difference for both AB and BA direction were created to understand the difference because the state detour maps are similar for both directions, so having the statistics helps augment our understanding of the two analyses. The new detour analysis generated approximately the same number of detours additional times to 15 minutes for both AB and BA directions.

A map of the difference in additional travel time between the new detour analysis and the state-wide model is displayed in Fig. 5.4. Take note that most road segments fall under the green lines meaning that the difference between the state-wide model and the aggregated network is roughly 5 minutes. In contrast, greater than 20 minutes of differences occur with interstates surrounding central Denver's exterior. Notice that for some road segments there will be negative values in the time difference, which signifies that the state-wide model overestimates the additional travel time than the new detour analysis, but the difference is typically very small. The negative values may be due to the fact that state-wide model and the aggregated network are not exactly the same networks though the aggregated network is a good representation of the state-wide model network. Most of the time differences are positive values, which is expected, since the new detour analysis considers the congestion effects that will most likely increase the travel time on the detour.

5.3.2 Update the Detour Information in CDOT's Detour Identification Tool

Currently CDOT has developed several tools to support resilient transportation, and one of their tools is the "Detour Identification Tool", an excel file that contains vast amount of data. One of the tabs is labeled as "DetourInfo", which contains information about the highway segments (i.e., Route Name, Route Used On Detour), and a snippet of the excel file was shown in Fig. 2.4. In addition CDOT has calculated their own additional time and distance without congestion effects.

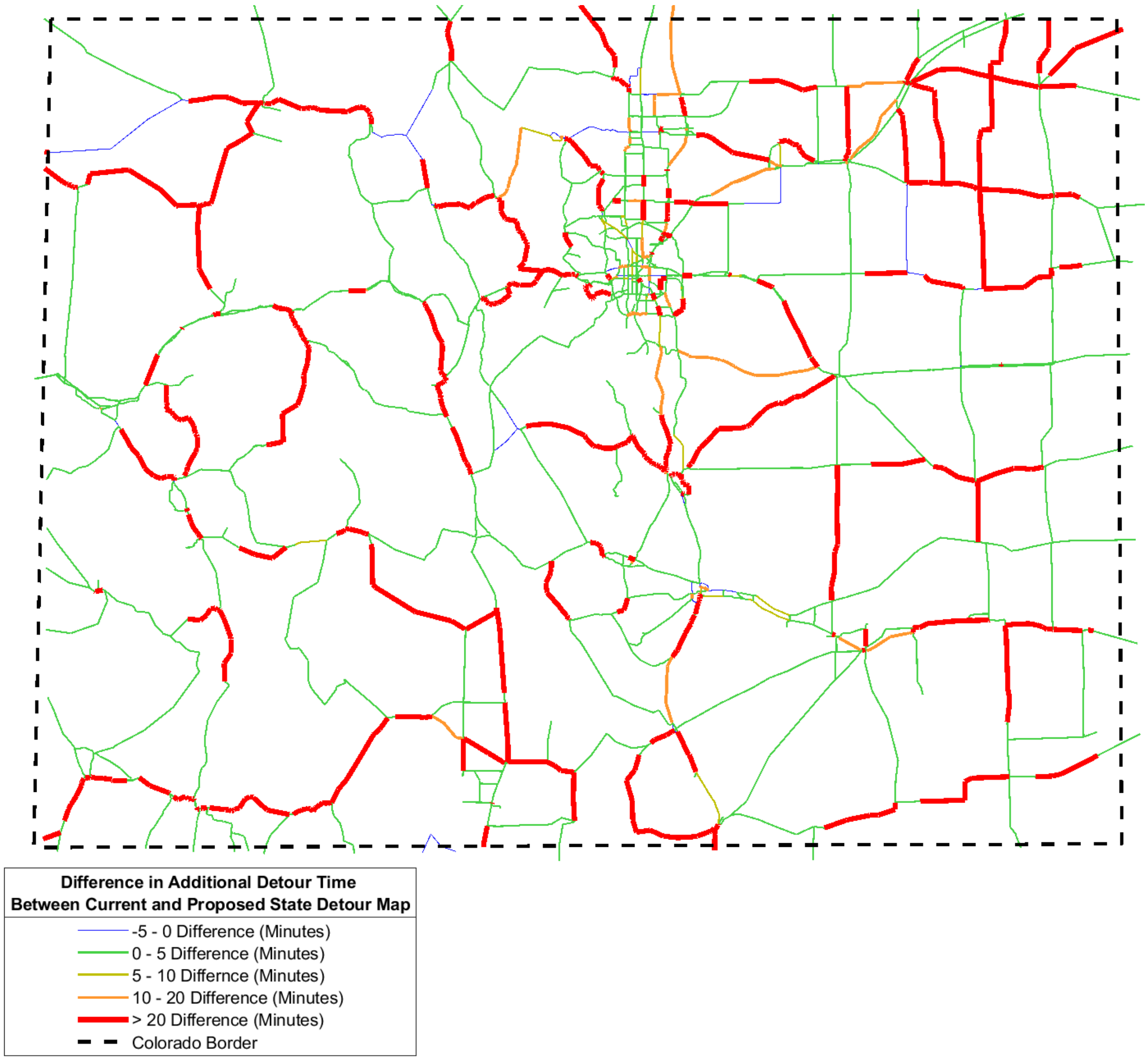

Figure 5.4: The Map Shows the Difference in Additional Travel Time Between Those from the New Detour Analysis and Those from the State-Wide Model.

Instead, with the additional time and distance generated from the detour analysis considering congestion effects, we append this information to CDOT's current "Detour Identification Tool". A series of columns have been added such as routes used on detour, 1^{st}, 2^{nd}, and 3^{rd} best detours, which are shown below in Fig. 5.5.

In addition to CDOT's Detour Identification Tool, they have their own version of "State Detour Map" as illustrated in Fig. 2.5. However, the tool does not have a state detour map that includes the additional travel distance (miles). The tool will be updated by including the state detour map for travel distance developed here (as shown in Fig. 5.2), so that users have the option of state detour maps for both additional travel time and distance.

Route	RoutePlusDir	StartMP	EndMP	NameInRouteSystem	AddedTime	AddedDist	Car_Route_Used_On_1st_Detour	Car_1st Best Addtional Time (Minutes)	Car_1st Best Addtional Distance (Miles)	Car_Route_Used_On_2nd_Detour	2nd Best Addtional Time (Mint
006N	006N_WB	141.992996	141.81799		5	0.5					
007A	007A_EB	0	19.249	007F_EB_001	17.126851	14.963436	007A.036B	62.5575	47.1182		
007A	007A_WB	33.08	19.249	007G_WB_001	30.876667	24.918991	036B.007A	32.9603	24.9197	036B.007B.119A.072B	57.2458
007A	007A_EB	14.91	16.086	007F_EB_012	2.121323	0.310946	007E	0.5182	0.3109	007A.036B	70.0066
007A	007A_WB	16.086	14.91	007F_WB_002	2.121325	0.310946	007E	0.5182	0.3109	007A.036B	70.0069
007A	007A_WB	19.249	0	007F_WB_001	16.820633	14.963436	007A.036B	62.5577	47.1182		
007A	007A_EB	19.249	33.08	007G_EB_001	31.182886	24.918991	007A.036B	32.96	24.9197		
007B	007B_EB	49.506	50.639	007B_EB_001	4.529908	1.870847	093A.036E.036B	3.4989	1.869	119A.072A.093A.170A.036B.157A.119B	83.9258
007B	007B_WB	50.639	49.506	007B_WB_001	4.077525	1.689511	036B.036E.093A	3.1109	1.6915	036B.119B.157A.170A.093A.072A.119A	91.8477
007C	007C_WB	60.683	53.457	007C_WB_001	8.546977	8.183602	287C.042A	9.5034	6.6488	287C.052A.119B.157A.007C	25.9367
007C	007C_EB	52.29	53.457	007C_EB_001	5.162238	2.925196	036B.119B.157A	4.6358	2.9238	036B.157A	5.3171
007C	007C_EB	53.457	60.683	007C_EB_007	8.783718	8.435546	042A.287C	9.4481	6.6488	007C.157A.119B.052A.287C	25.9733
007C	007C_WB	53.457	52.29	007C_WB_023	5.506797	3.756707	157A.036B	4.7263	3.7591	157A.119B.036B	6.2613
007D	007D_WB	68.432999	68.32		5	0.5					
007D	007D_WB	76.957	61.877	007D_WB_003	0.768328	7.603376	025A.470N.287C	1.4964	3.676	025A.052A.287C	11.035
007D	007D_EB	76.957001	77.052002		5	0.5					
007D	007D_EB	61.877	76.957	007D_EB_001	0.266727	7.109295	287C.470N.025A	2.3033	4.1264	287C.052A.025A	10.7127
007D	007D_WB	77.052002	76.957001		5	0.5					
007D	007D_EB	68.32	68.432999		5	0.5					
007E	007E_WB	1.592	0		0	0					
007E	007E_EB	0	1.592		0	0					
008A	008A_WB	8.683	2.902	008C_WB_001	1.301786	1.877499	121A.285D.391A	2.5532	2.1506	121A.006G.391A	11.6324
008A	008A_EB	2.902	8.683	008C_EB_009	1.483278	2.25209	391A.285D.121A	2.8079	2.2921	391A.006G.121A	11.0681

Figure 5.5: Updating Detour Identification with Additional Time and Distance Considering Congestion.

5.4 Detour Analysis Results for Freight

5.4.1 Additional Travel Time and Distance for Detours Considering Congestion

A new state detour map has been assembled with additional time (minutes) factoring in the congestion effects. As anticipated, the freight detour analysis would have longer detour times of more than 1 hour. The map in Fig. 5.6 shows the additional added detour time for freight for the first best detour in the AB direction.

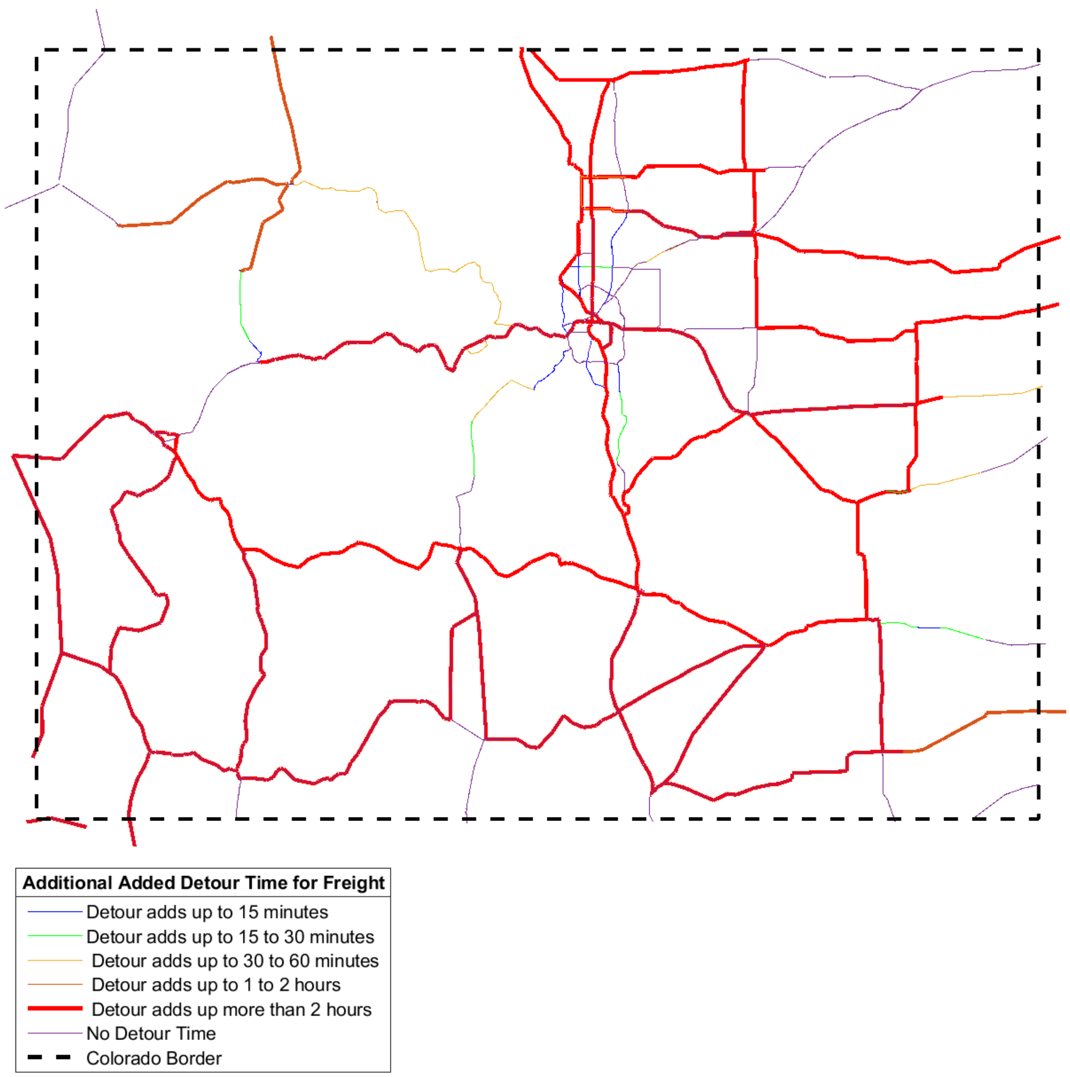

Figure 5.6: State Detour Map for Freight Detour Analysis for Additional Travel Time.

Since the freight network has longer highway segments, Fig. 5.6 shows that the detours are much longer than the state detour map for the car detour. Considering congestion, these additional travel times for the freight network yield hours of additional travel time. It can be seen that Central Denver has various colors other than red because of the added travel time since the closed segments and alternative detours are much shorter than two hours. In addition, a detour map has been assembled with additional travel distance (miles), as shown in Fig. 5.7. The state detour map for additional travel distance is similar to Fig. 5.6 for the detour time. Typically, the detour time is correlated with the detour distance, so locations with high detour times (red) will also have considerable detour distance. The state detour maps for detour time and distance for the AB direction and the BA direction are very similar, therefore, the maps for the BA direction are not shown here.

5.4.2 Update the Detour Information in the CDOT Detour Identification Tool

CDOT's current detour identification tool to support resilient transportation does not provide information on freight (heavy vehicles). In addition, their detour identification tool does not have a state detour map for the freight network that includes the additional detour travel time and distance. The state detour map will be updated for both additional travel time and distance within the detour identification tool. Recall Fig. 2.4 provides a report of all highway segments (i.e., Route Name, Route Used on Detour, MPs, etc.), and the additional time and distance from the car detour analysis have already been appended, as previously illustrated in Fig. 5.5. Similarly, the detour information related to freight detour are added as new columns to the current excel, where information such as the routes used, additional time, and distances for the freight network's 1^{st}, 2^{nd}, and 3^{rd} best detours is added.

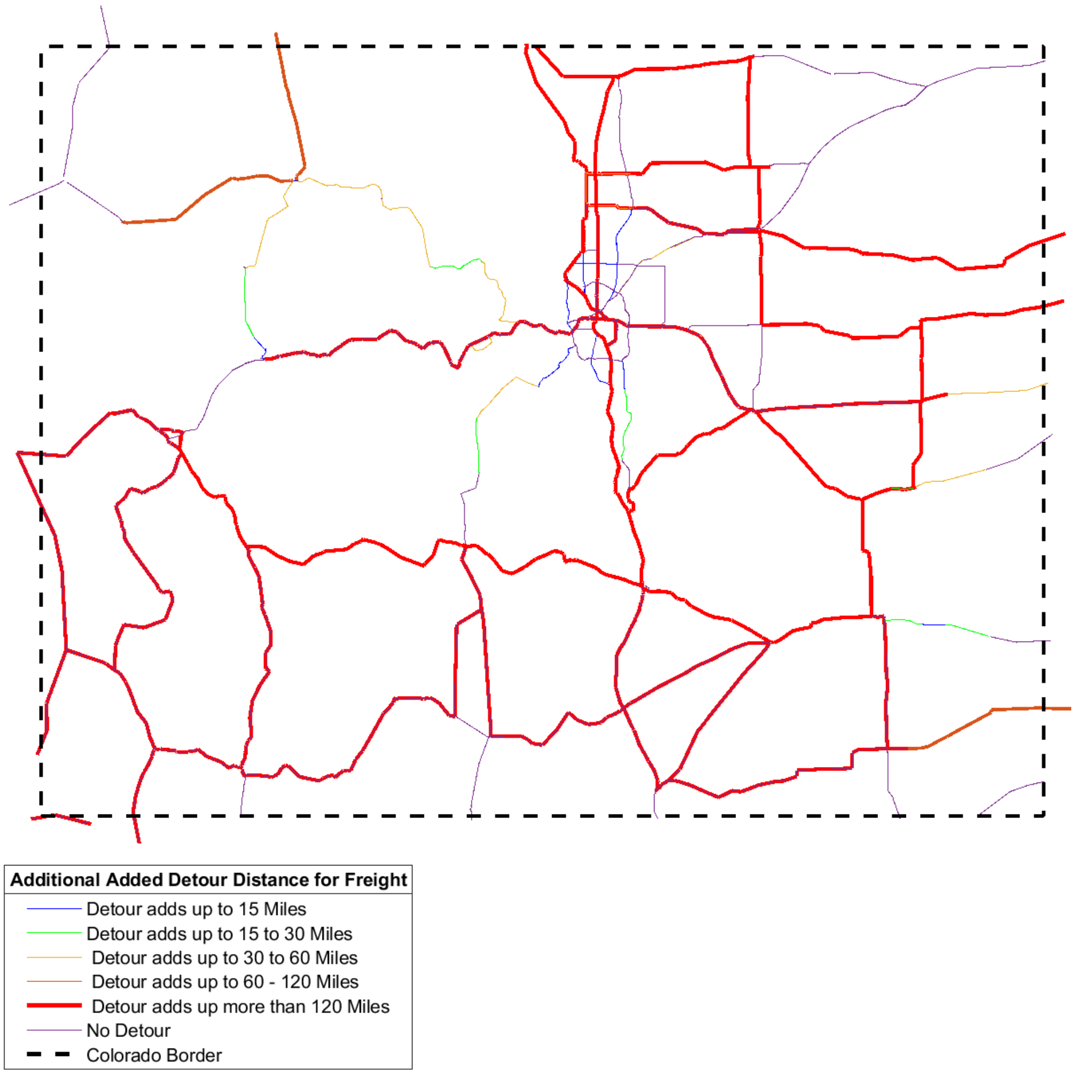

Figure 5.7: State Detour Map for Freight Detour Analysis for Additional Travel Distance.

Chapter 6:

Develop a New Redundancy Metric for CDOT using Detour Analysis Results

6.1 Introduction

The current methodology for roadway redundancy, their underlying assumptions, and results generated by the analysis for the redundancy metric will be reviewed first. A new redundancy metric will be proposed for CDOT based on fundamental principles that CDOT's study panel has suggested. Also, the goal is to create a new redundancy metric that incorporates the availability (whether there are multiple redundant options) of detours. The idea is to weigh the different detours based on the extra travel time and distance generated from the new detour analysis factoring congestion rather than weighing all detours equally. CDOT's current redundancy score for each highway segment is then updated based on the newly proposed redundancy metric.

6.2 New Redundancy Metric

6.2.1 Principles in Developing the New Redundancy Metric

Some key considerations were made in the development of the new redundancy metric. After discussion with CDOT's study panel, it seems that there are some consensus on:

- If a segment has no detour or only has one detour, then it should be the least redundant.
- If there is more than one detour, then we can start weighting different detours.

- Time should be weighted more than distance. It is important to note that based on driver's perspective, they would care more about the time it takes rather than distance because they would rather care for how long it would take rather than how far to get to their destination.

6.2.2 Proposed New Redundancy Metric

First, we would like to stress that there are multiple ways to establish the new redundancy metric. Here taking the above principles in consideration, we propose the following candidate new redundancy metric,

$$RS = 1 + \frac{T_0}{T_1}W_1 + \frac{T_0}{T_2}W_2 + \frac{T_0}{T_3}W_3 \tag{6.1}$$

where RS is the redundancy score, T_0 is the total travel time (minutes) for the closed segment, T_1 is the total travel time on the 1^{st} best detour for the closed segment, T_2 is the total travel time on the 2^{nd} best detour for the closed segment, and T_3 is the total travel time on the 3^{rd} best detour. If there is no 1^{st}, 2^{nd} or 3^{rd} best detour, then T_1, T_2 or T_3 will be set to ∞ thus making the second, third, and fourth terms on the right hand side of Eq. (6.1) go to zero. Different weights are assigned to each of best detours. W_1, W_2 and W_3 are selected as 2, 1 and 0.5, respectively. With this selection, theoretically the redundancy score can take values from 1 to 4.5. Note that different weights could be selected as well.

Some considerations in the proposed redundancy metric are: (1) an additive functional form is used to reflect the principle of having multiple or more detours is better than having no or fewer detours; (2) when there is no best detour, then it should be the least redundant, and the RS of 1 is then directly assigned; (3) only travel time is included in the definition of the new metric, considering that there is actually strong correlation between travel time and travel distance. Regarding (3), we did an investigation. In particular, the results from the detour analysis (e.g., additional time and distance) were plotted with each other to check the correlation between the additional time and distance. As can be seen from Fig. 6.1, they have strong correlation. Due to the strong correlation of time and distance, in Eq. (6.1) only time is included while distance is not included.

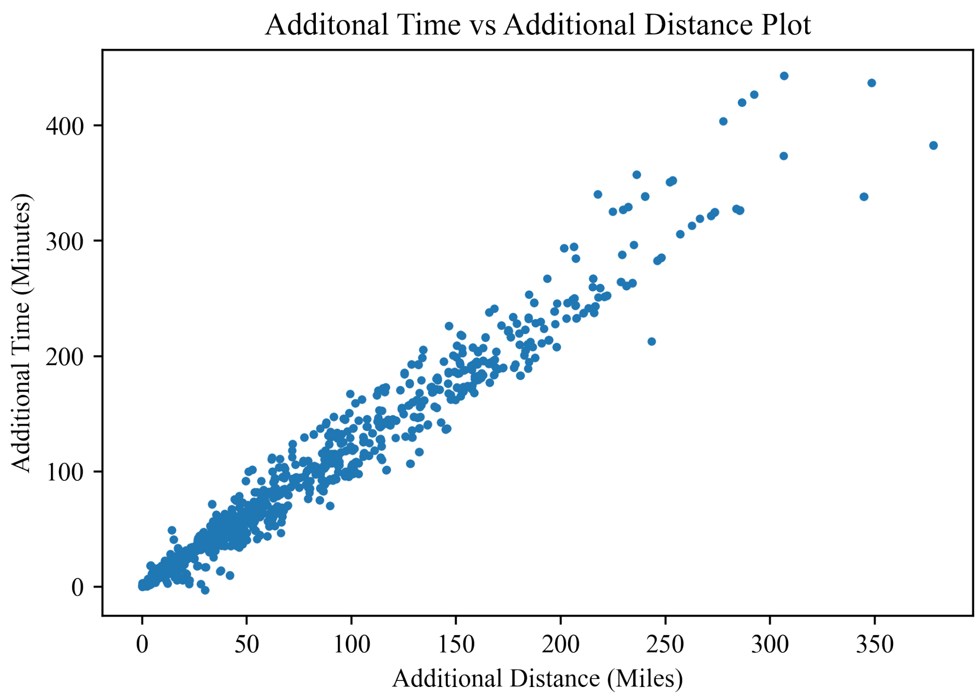

Figure 6.1: Additional Time vs Distance.

6.2.3 Updated Redundancy Score and Map

A histogram has been plotted for the Redundancy Score (RS) in the AB direction and BA direction, shown in Fig. 6.2 and 6.3, respectively, to understand the approximate representation of the distribution of the RS for all road segments.

From Fig. 6.2 and 6.3 we can see that the redundancy score with the value of one had the most frequency. In contrast, the occurrence of a high redundancy score is rare based from the figures.

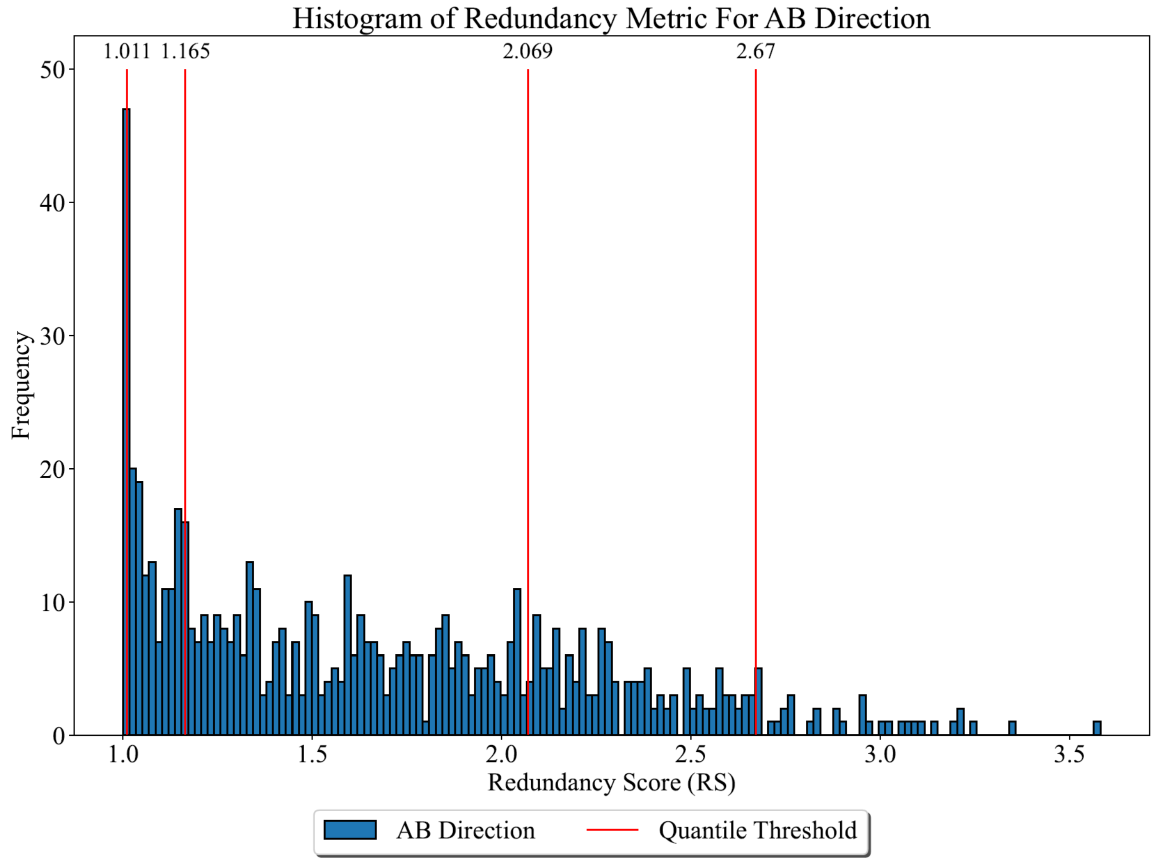

Figure 6.2: Histogram of Redundant Score for AB Direction.

This is consistent with the number of best detours from the detour analysis. There are 1282 road segments with only one best detour, 627 with two best detours, and only 20 with three or more best detour. Given the few segments with a 3^{rd} best detour, it is understandable that the distribution would taper off as the proposed redundancy score increases. Using the above thresholds, we define the ranges of RS values that correspond to different impact categories based on a quantile system discussed with CDOT's study panel. The quantile of [0.05, 0.25, 0.75, 0.95] was used, and with this selection 50% of the segments fall into the moderate impact category, but it is important to note that the quantiles can be subjected to change based on the target use of classifying segments into different categories. The results are shown in Table 6.1, Fig. 6.2 and

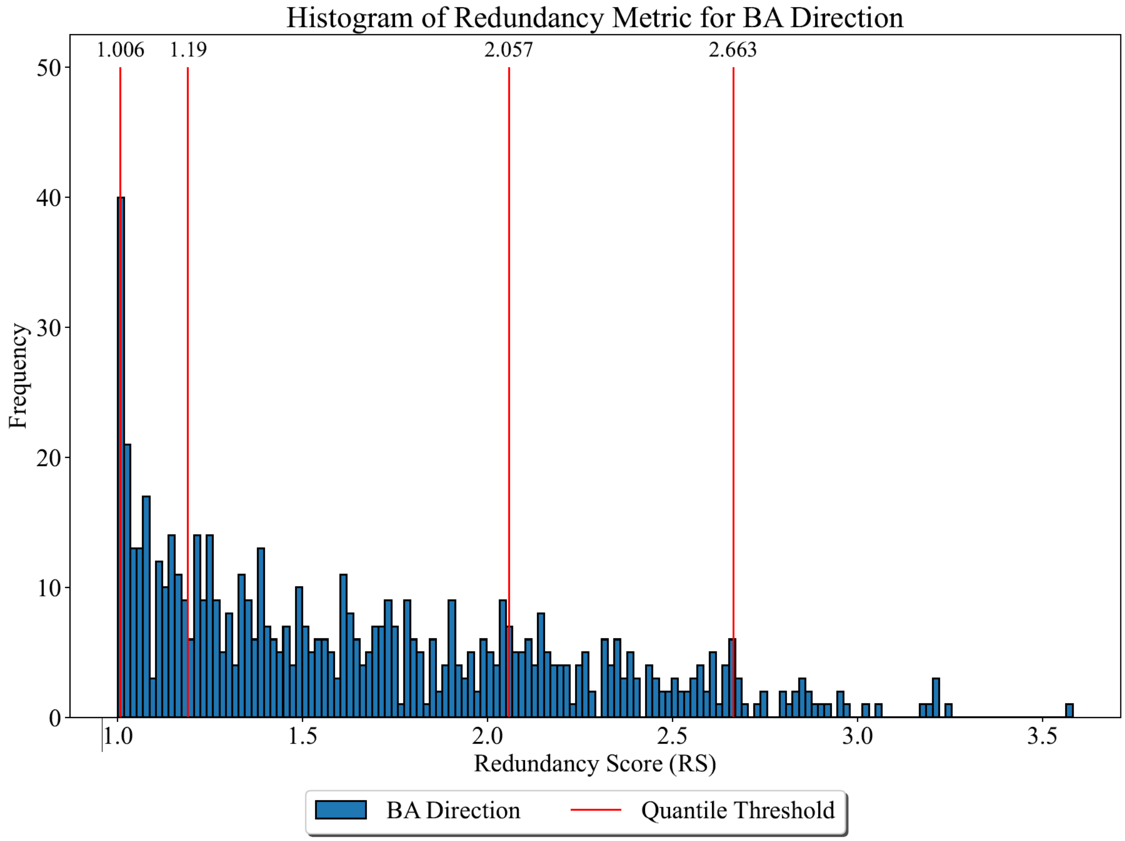

Figure 6.3: Histogram of Redundant Score for BA Direction.

6.3 have red vertical lines to indicate the thresholds corresponding to the quantiles for the AB direction and BA direction, respectively.

Table 6.1: New Proposed Redundancy Score, Impact Category with Corresponding Criticality Score Shown in Parenthesis.

-	**Criticality Score**				
Impact Category (Critical Score)	**Very Low Impact (1)**	**Low Impact (2)**	**Moderate Impact (3)**	**High Impact (4)**	**Very High Impact (5)**
Redundancy Score (Proposed One)	2.670 - 4.5	2.069 - 2.670	1.165 - 2.069	1.0114 - 1.165	1 - 1.0114

A new redundancy map is then generated, the procedure is identical to creating Fig. 5.1 for additional travel time for detours considering congestion. Fig. 6.4 shows the updated redundancy map with the new redundancy metric.

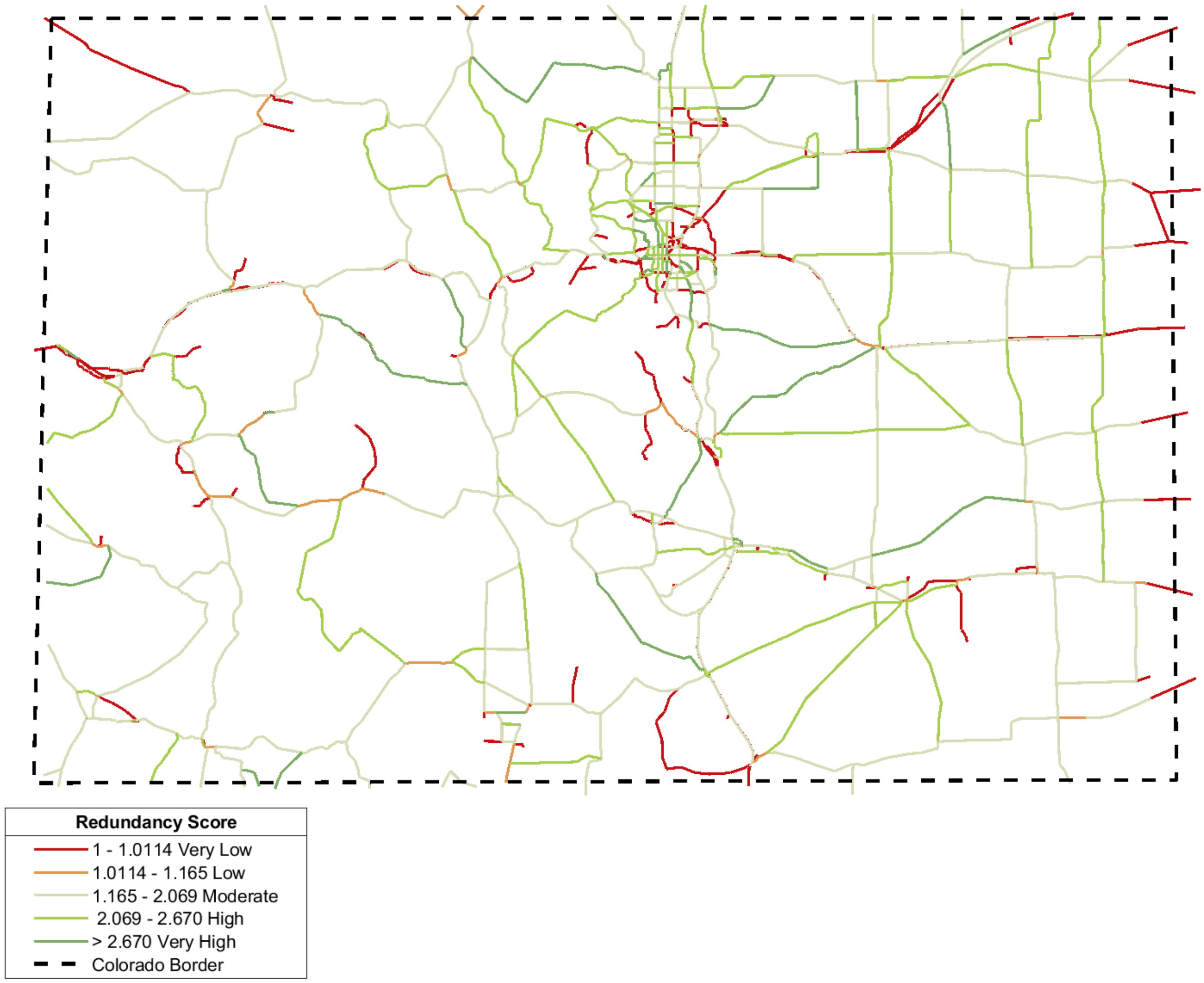

Figure 6.4: Updated Redundancy Map.

It can be seen that majority of the segments have a moderate (lighter green) based off the redundancy metric, meaning that they have some redundancy such that their closure would have moderate impact on the trips on these segments. The green lines correspond to segments with high redundancy, meaning that they have a lot of redundancy such that their closure would have very low impact on the trips on these segments. The red lines in contrast mean that the closure of corresponding segments would lead to high impact on the trips on these segments, with potentially high additional detour times (or even no best detours). The new map highlights segments with low redundancy, and such information can be used to identify critical segments in the state highway system so that improvements can be implemented to enhance the redundancy of the state highway system. Compared to the current redundancy map in Fig. 1.2, majority of the segments for the current redundancy fall into very high impact outside of central Denver, so closure of those highway segments will negatively impacts the Colorado state highway system. In comparison, the updated new redundancy map (which considers congestion and factors in different weights for each best detour) shows moderate and high impacts for majority of the map. However, both current redundancy and proposed redundancy map in Fig. 1.2 and 6.4 have similar impact categories (i.e., moderate and high) for highway segments that are located in central Denver. Note that Fig. 1.2 for current redundancy map and 6.4 for the new redundancy maps are developed based on different methodologies. Again, recall that the current redundancy map is based on the links connected to a node (as described in Chapter. 1.2), while the new redundancy metric factors in weights from each best detours and the additional travel time. This difference should be taken into account when trying to interpret and compare these two maps.

To visualize the difference between the current redundancy metric and the newly proposed redundancy metric, Fig. 6.5 below shows the histogram between the current and proposed redundancy indexes. Some notable differences are the differences between the redundancy index with the value of 2, 3, and 5. The current redundancy method had a frequency of more than 30,000 with a redundancy index of 1, 2, and 5. However, the new proposed redundancy index had a smaller frequency of less than 10,000, so the difference is more than 20,000, which is significant. Redundancy Index values of 1 and 4 have a minimal difference of approximately 5,000 occurrences.

Fig. 6.6 shows a bubble map using circles representations of a numerical size of the redundancy index. For example, look at the value 1 on the x-axis (current redundancy index) and the y-axis

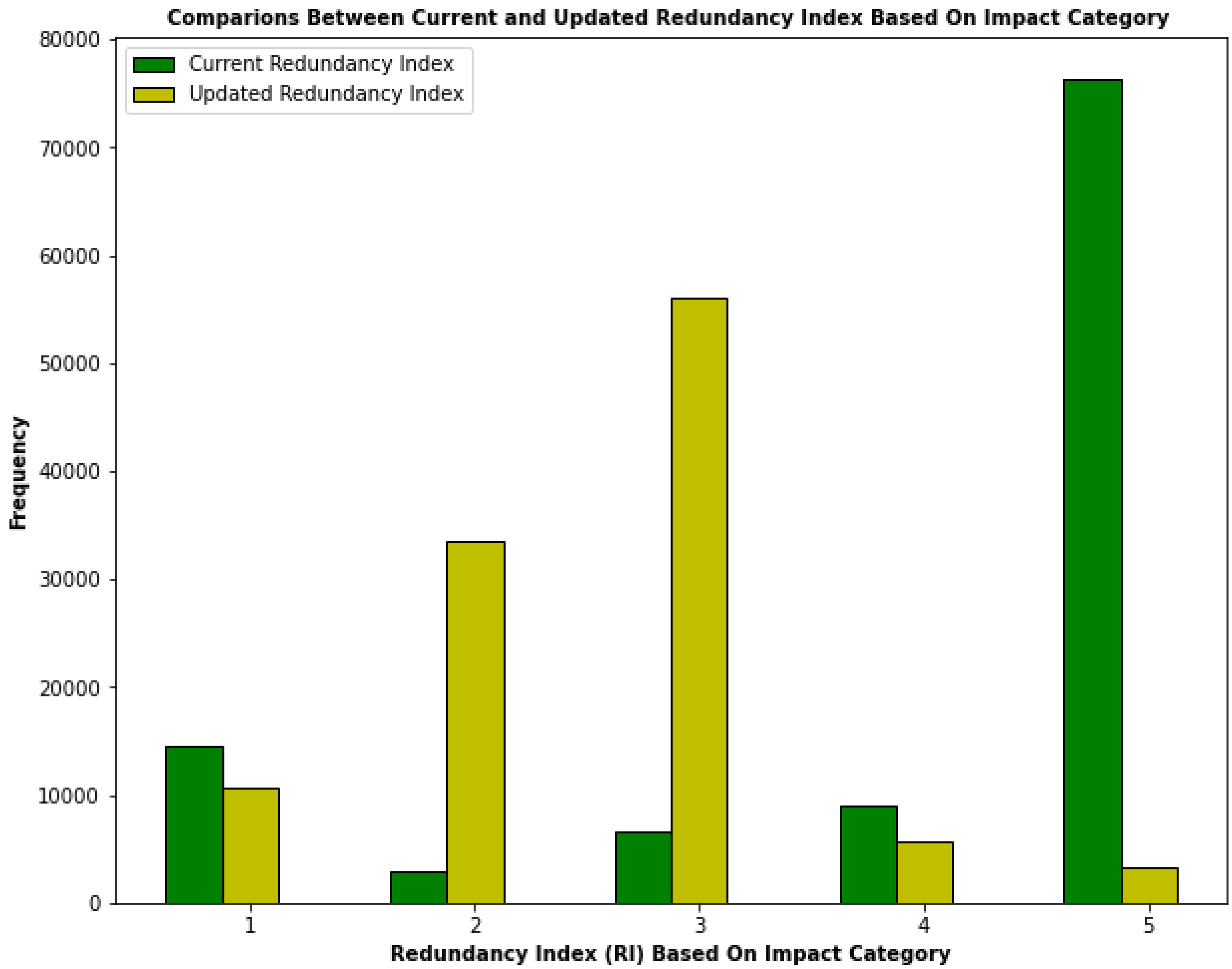

Figure 6.5: Comparisons Between Current and Updated Redundancy Index Based On Impact Category

(updated redundancy index) values (1, 2, 3, 4, and 5). The x-axis shows the current redundancy index, and the y-axis displays the proposed redundancy index. Previous highway segments with a redundancy index denoted as 1 are recalculated and redistributed to values of 1 to 5. Each size of the bubble refers to the frequency of each index. So most of the current redundancy index of 1 has a new value redundancy index of 3 from the updated redundancy index. A significant observation would be the current redundancy index of 5, as most of the values recalculated were less than 5, and most segments were assigned values of 3, 2, and even 1. A green linear line indicates baseline control values if the current and new proposed redundancy index would have all the circles on the line. For example, segments for current redundancy will have an index value of 1, and the proposed redundancy will have an index of 1 if there is no difference between each methodology for computing redundancy metric. The general idea is that circles under the linear line illustrate that the proposed redundancy metric is less than the current redundancy index and vice versa for larger circles above the linear line.

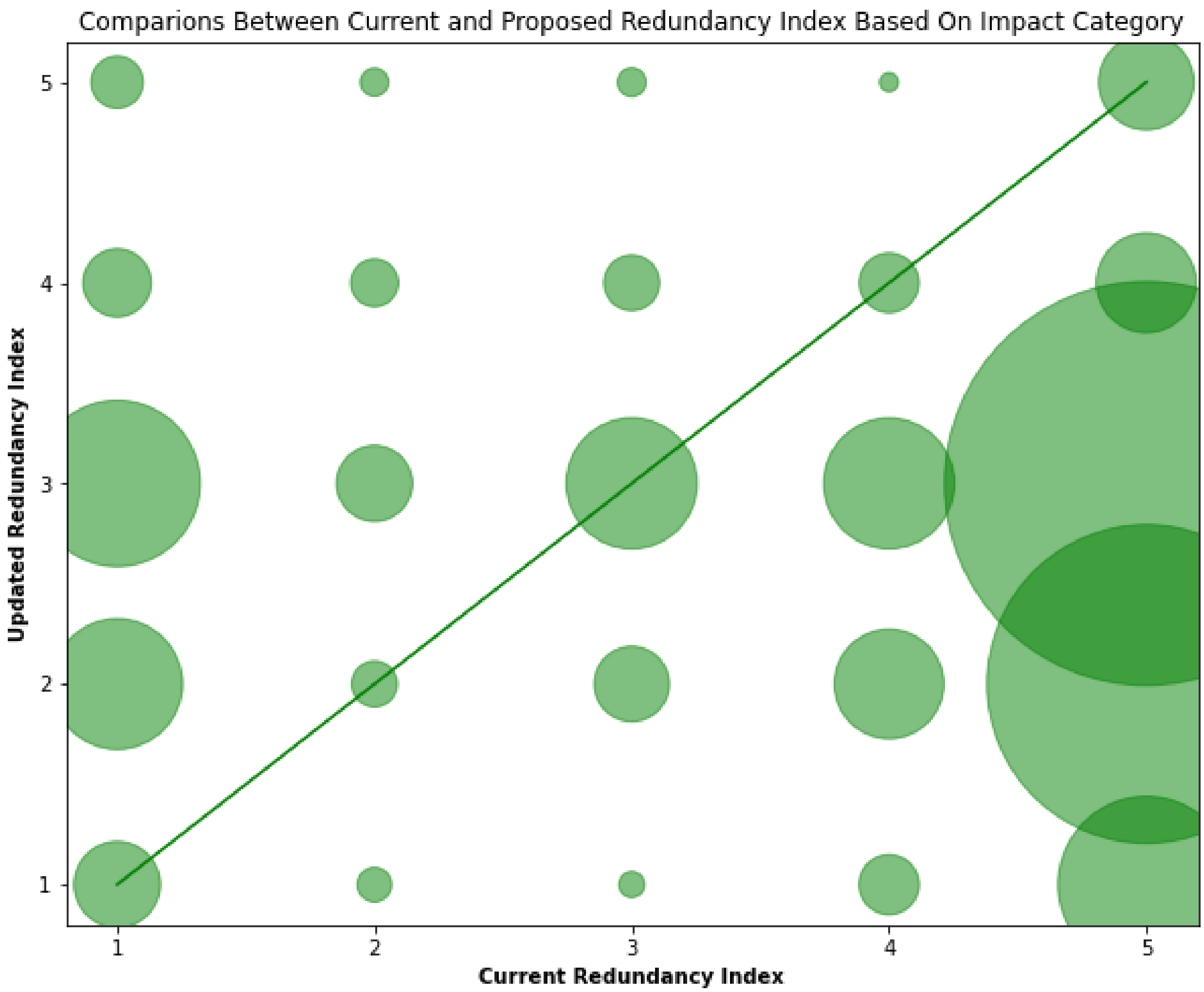

Figure 6.6: Comparisons Between Current and Updated Redundancy Index Based on Impact Category

6.2.4 Updated Criticality Score Based On Proposed Redundancy Metric

The proposed new redundancy metric can be used by CDOT to replace the current redundancy metric and recalculate/update the Criticality Score in CDOT's interactive resiliency mapping application shown in Fig. 6.7.

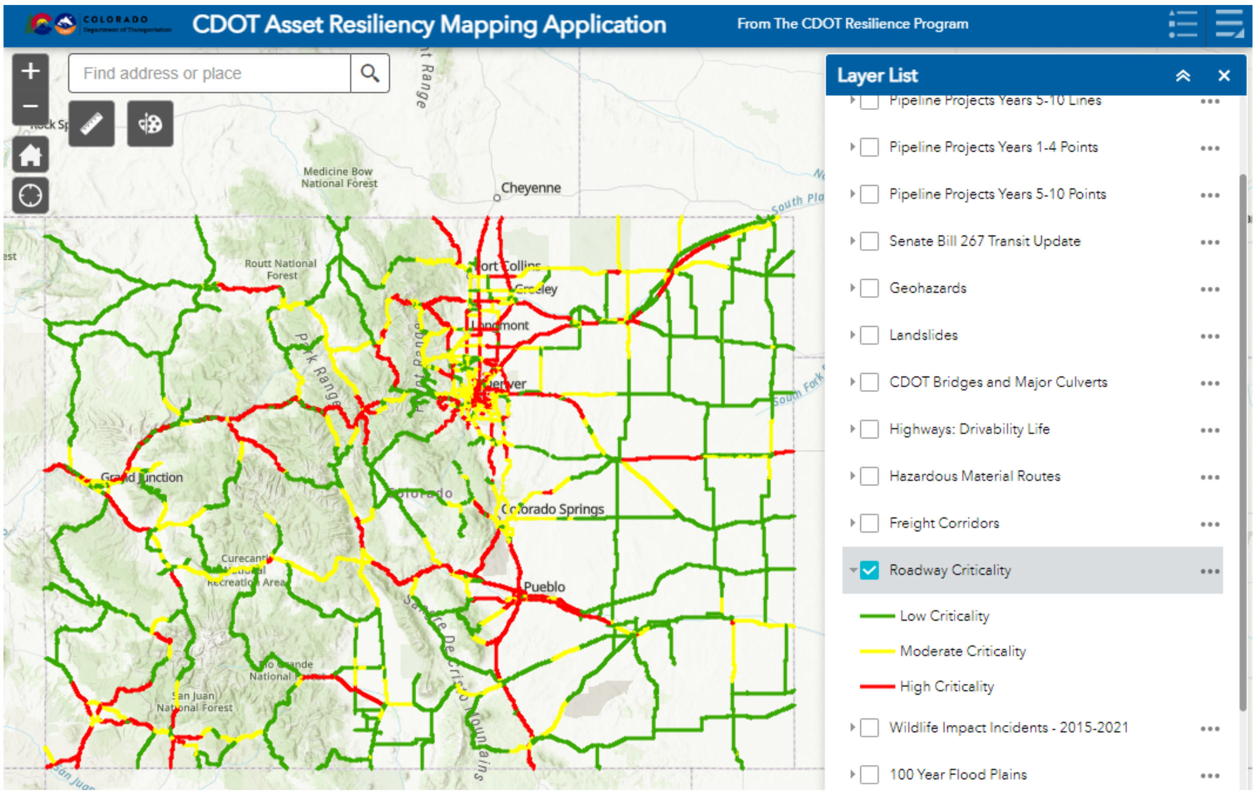

Figure 6.7: CDOT Interactive Resiliency Map Showing Roadway Criticality.

Using the shape file (HighwayCriticality.csv) provided from CDOT, we can see the associated values assigned to each highway segment based on the mile points. With the new proposed redundancy metric generated from subsection. 6.2.3 a column has been added to the pre−existing shape file called, "New Redundancy Index". This allows the study panel from CDOT to see the comparison between the old methodology and the proposed redundancy metric.

The criticality score is recalculated using the newly proposed redundancy metric, and Fig. 6.8 shows a histogram between the current and newly recalculated criticality score. From the histogram, a notable difference is the frequency height. The current criticality score's height is higher at 15,000, and the recalculated criticality score's height of 10,500. There is a slight discrepancy between the current and new criticality scores with mean and standard deviation. The current criticality score's mean is 22, and the new proposed criticality has a mean of 20. Notice that the thresholds (standard deviation) for the newly recalculated criticality are more significant than the current criticality score. The upper and lower threshold of the recalculated criticality scores is 28 and 11. The upper and lower threshold for the current criticality scores is 27 and 12.

Fig. 6.9 shows the updated criticality map from the proposed redundancy metric. Criticality is the measure of importance to a resilience system Colorado Department of Transportation (2015). The red lines illustrate high criticality meaning that closure of that specific segment would negatively effecting CDOT's resilience. From Fig. 6.9 most of Central Denver (e.g., I-25, I-36, E470, etc.) and I-70 are the most essential routes on the Colorado state highway system. The green lines illustrate the low criticality and most highway segments are located outside of central Denver.

Note, that the thresholds (low, moderate, and high criticality) for updated criticality map can be adjusted based on the user. The lower and upper threshold for criticality score change due some highway segments based on the correlation that the higher redundancy score will yield a higher criticality value. With an updated criticality map, the map can be used to determine the resiliency of the Colorado State Highway System and guide activities to enhance its resilience.

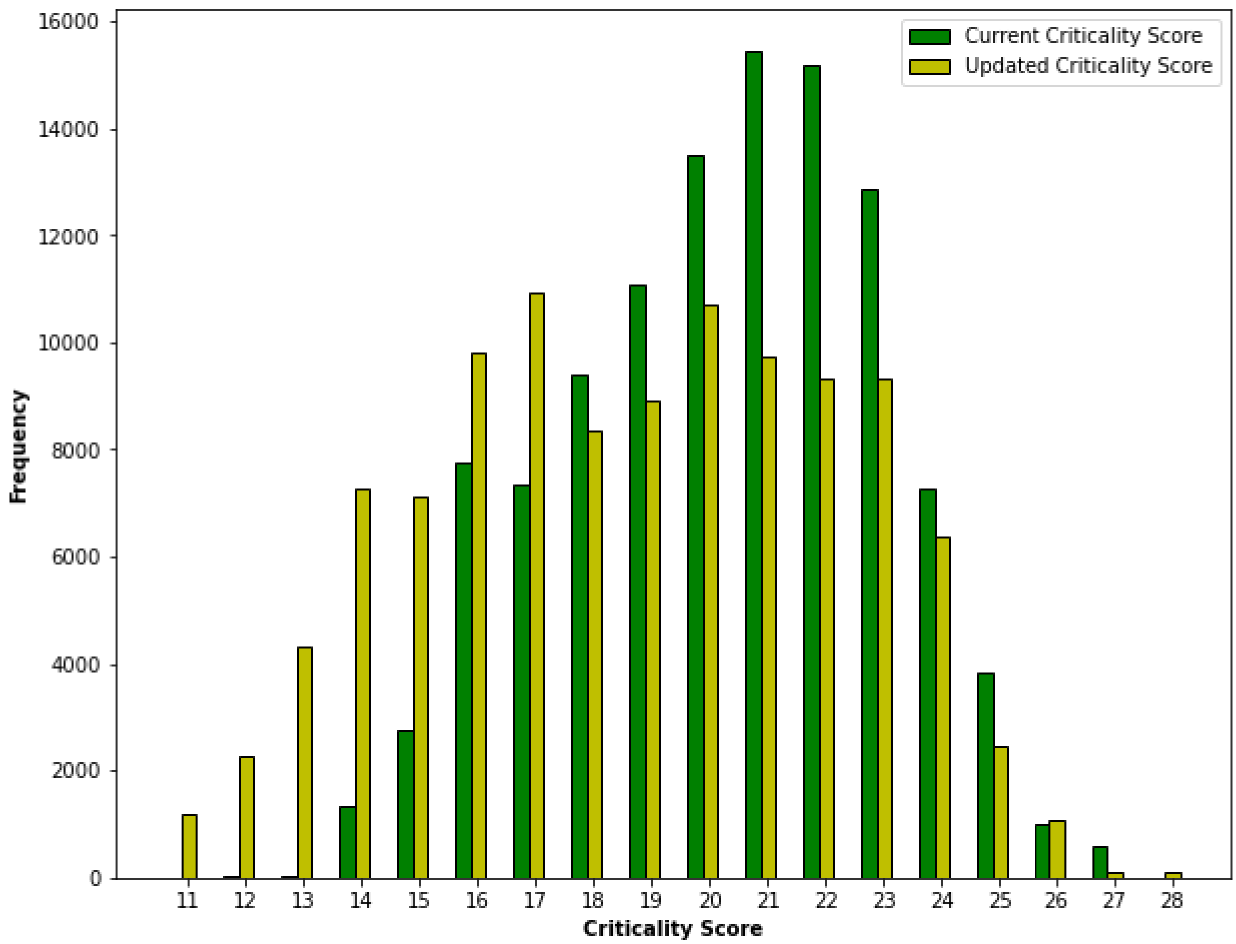

Figure 6.8: Histogram of the Current and Updated Criticality Score

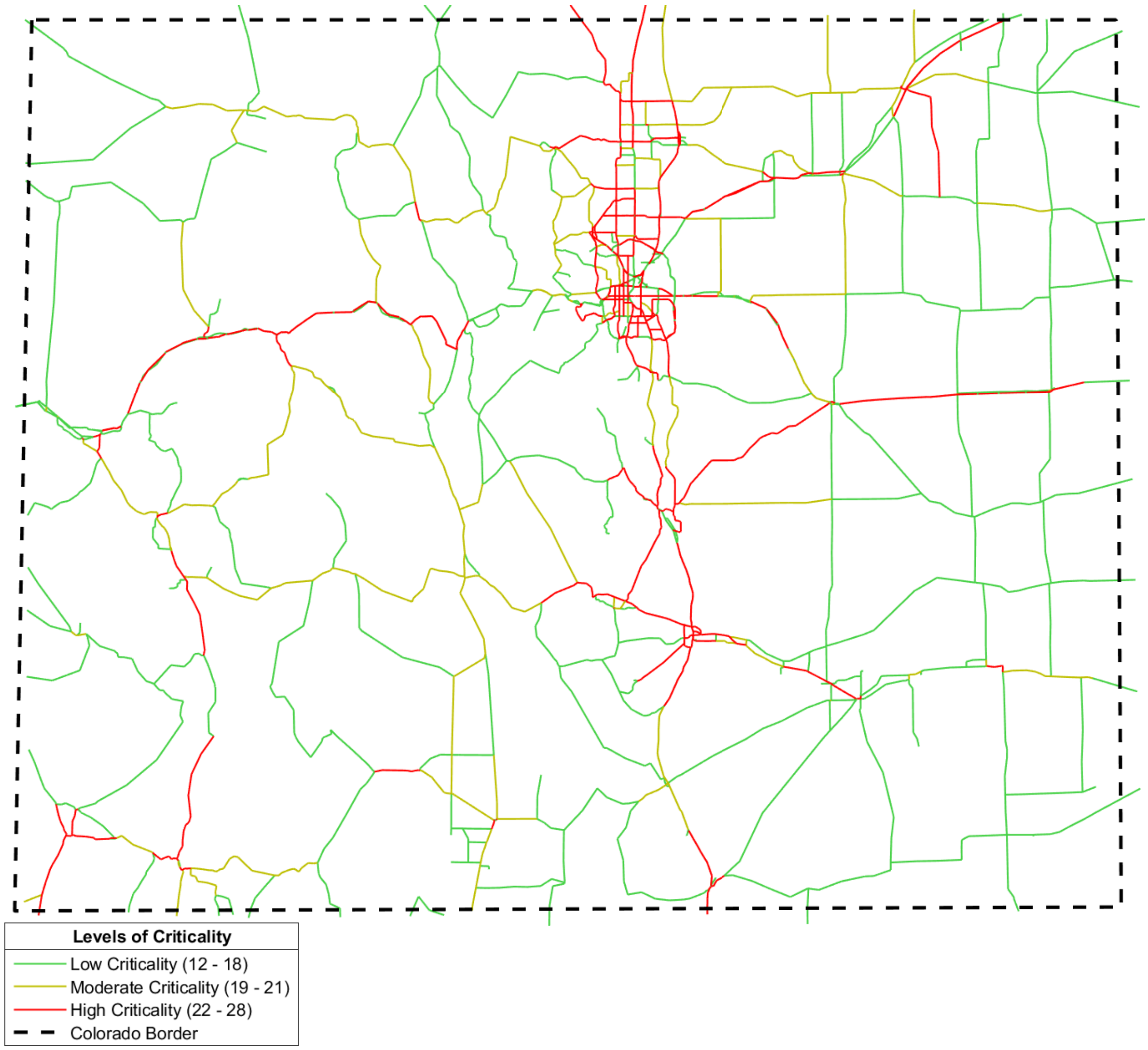

Figure 6.9: Updated Roadway Criticality with New Redundancy Metric.

Chapter 7:

Products and Implementation

This chapter presents the products and implementation that CDOT's study panel will receive upon completing the report and research. Files including codes (python and MatLab), shapefiles, maps, and excels are produced for CDOT's study panel to utilize in their resiliency program. Codes developed in MatLab and python are relatively small, and they run each task efficiently rather than a massive code that potentially has a longer run time. The codes are created for post-data processing raw data into valid data to help determine the additional travel and distance calculation and redundancy score calculations. CSU research team will submit the codes with various comments allowing the users to change the desired information. The primary detour analysis code has been sent to CDOT's coding department with instructions on running the analysis on either a standard lab computer or an HPC system. For example, if CDOT's study panel decided to change the weights in Chapter 6 eq. 6.1 and agreed that 1^{st} would be more important than the 2^{nd} best detours. Then the user can change the variables from the python code to change the values from 2 to 1 and rerun the analysis. Other codes generate figures based on the data's additional travel time, distance, and redundancy score.

A shapefile is a simple format that stores the geometric locations and attributes information of the geographic features (nodes). Detour analysis from the car and freight network has been appended to the current CDOT's Identification Tool and will be presented as a shapefile. The aggregated network for the car detour analysis is output into a shapefile. The study panel can import the shapefile into either TransCAD or ArcGIS to run their traffic analysis if desired. A shapefile for the freight network will not be output because CDOT provided the freight network.

Chapter 8:

Conclusions

In this report, the overall objective is to develop an improved redundancy measure for the Colorado State Highway System considering the availability of multiple detours, and the additional travel time and distance on the alternative detours considering congestion. Using the improved redundancy measure to update Colorado State Highway's Criticality score.

Chapter 2 focused on discussing CDOT's current detour analysis that uses CDOT's State-wide Model. Aspects related to the transportation network, the traffic data, the traffic analysis model, and the modeling of car (e.g., passenger car) and freight (e.g., heavy vehicles) flow were presented. In addition, CDOT's Detour Identification Tool was also presented. Through the descriptions and discussions, main limitations of the existing detour analysis were highlighted. One key limitation was that the current detour analysis used All or Nothing (AoN) algorithm for trip assignment that could not consider congestion thus the flow and capacity on the alternative routes could not be accounted for.

Chapter 3 focused on the new traffic simulation model that was developed for the detour analysis. A four step model with combined distribution and assignment model was developed for traffic analysis that takes into account the congestion effects. To address the computational challenges associated with running the full transportation network of the Colorado state highway system with large number of nodes, links, and TAZs, an aggregated network method was introduced by aggregating the TAZs to the closest highway node, which led to aggregated network with reduced number of nodes and links. Then the aggregated network was used for detour analysis where the traffic analysis could be done in a reasonable amount of time. An improved way of modeling both car and freight flows was also proposed to improve the accuracy of the traffic analysis.

Chapter 4 introduced the procedures to identify the first, second, and third best detours for each individual route (i.e., closed highway segment) using the traffic analysis model developed in Chapter 3. A python code was developed to automate the process of obtaining the nodes and segments for the closed highway segments based on the original network data.

Chapter 5 focused on the detour analysis results for both car and freight. HPC was used to run the detour analysis for all the road segments, and computer codes were developed to post-process the results to establish the additional time (minutes) and distance (length) for all the alternative detours. Such detour information was used to update CDOT's Detour Identification Tool by adding information on multiple detours and the additional travel time and distance for each alternative detour (that considers congestion effects), compared to the current version which only has information on the first best detour and the additional travel time and distance do not consider congestion.

Chapter 6 focused on development of the proposed new redundancy metric. A redundancy metric was developed considering congestion effects on the Colorado State Highway system. Several key principles based on feedback from CDOT were used to develop the new redundancy metric. Different weights were assigned to different best detours (e.g., the second best detour and the third best detour were weighted differently). Due to high correlation between the additional travel time and distance and the fact that many drivers typically care more about travel time, calculation of the new redundancy metric only included the travel time as inputs into the formula. Based on statistics of the new redundancy score, quantile values were established to define the bounds for different impact categories, e.g., very low impact, low impact, moderate, high and very high impact. Then such information can be used to update CDOT's Criticality Score. This will help CDOT allocate funding to prevent closure of segments that would significantly affect the transportation system.

Chapter 7 finalizes the products and implementation from the research. CDOT's study panel will receive various files (e.g., python, MatLab, and shapefiles) that can be executed from CDOT with supporting documents on how to execute the code for further detour analysis for either car or freight network. Shapefiles are compiled from results discussed in Chapter 5 along with visual representations of the State Highway system of Colorado illustrating an updated additional travel time, distance, updated redundancy, and recalculated criticality score. These are the deliverables that the study panel will receive upon the research competition.

8.1 Future Directions

In the development of the detour analysis and the new redundancy metric, there are some key recommendation that can be considered for future research work.

1. As mentioned in Chapter 6, depending on the purpose of the redundancy metric and how it will be used, different redundancy metrics can be established by using different functional forms and by assigning different weights to different terms. Future research may look into how to establish multiple redundancy metrics that are tailored towards specific uses rather than having only one single metric.

2. The redundancy of highway segments that are identified as having high impact can be improved by including additional connections (e.g., by including local roads rather than

only considering state highways). The redundancy map created in this report can be used to guide such planning.

3. Due to the large scale of the full network, aggregated network is used for detour analysis in this report so that the analysis can be done in a reasonable amount of time, which is also preferred by CDOT. In the future, detour analysis models leveraging the power of GPU (graphics processing unit) can be developed that can run large scale simulations in reasonable amount of time.

4. The quality of the capacity data is recommended to be improved before using it for the detour analysis, since it directly impacts the detour analysis results. In this report, the capacity data used in the State-wide model was used (e.g., TransCAD capacity) to perform the detour analysis. However, some of the data are not up to date. Also, there are some inconsistencies/discrepancies between data from mutliple sources, e.g., there are differences in the data from TransCAD and the data from OTIS (Online Transportation Information System). In the future, the capacity data could be checked and updated based on the up-to-date data such as road characteristics, observed flow, etc. Also, more data samples (e.g., observed flow) should be used to increase the prediction accuracy. However, note that updating the capacity based on the up-to-date data would be a major task by itself, requiring many resources. Therefore, the update of the capacity data may be considered as a separate project in the future. The detour analysis could be updated once the updated capacity data is available.

5. The readiness of freight data is recommended to be improved before using it for the freight detour analysis. The networks connecting the state border (e.g., Utah, Mexico, Kansas, and

Wyoming) seem to have incomplete data (e.g., incomplete nodes and links not connected to one another).

Appendix A:

Additional Figures from Results

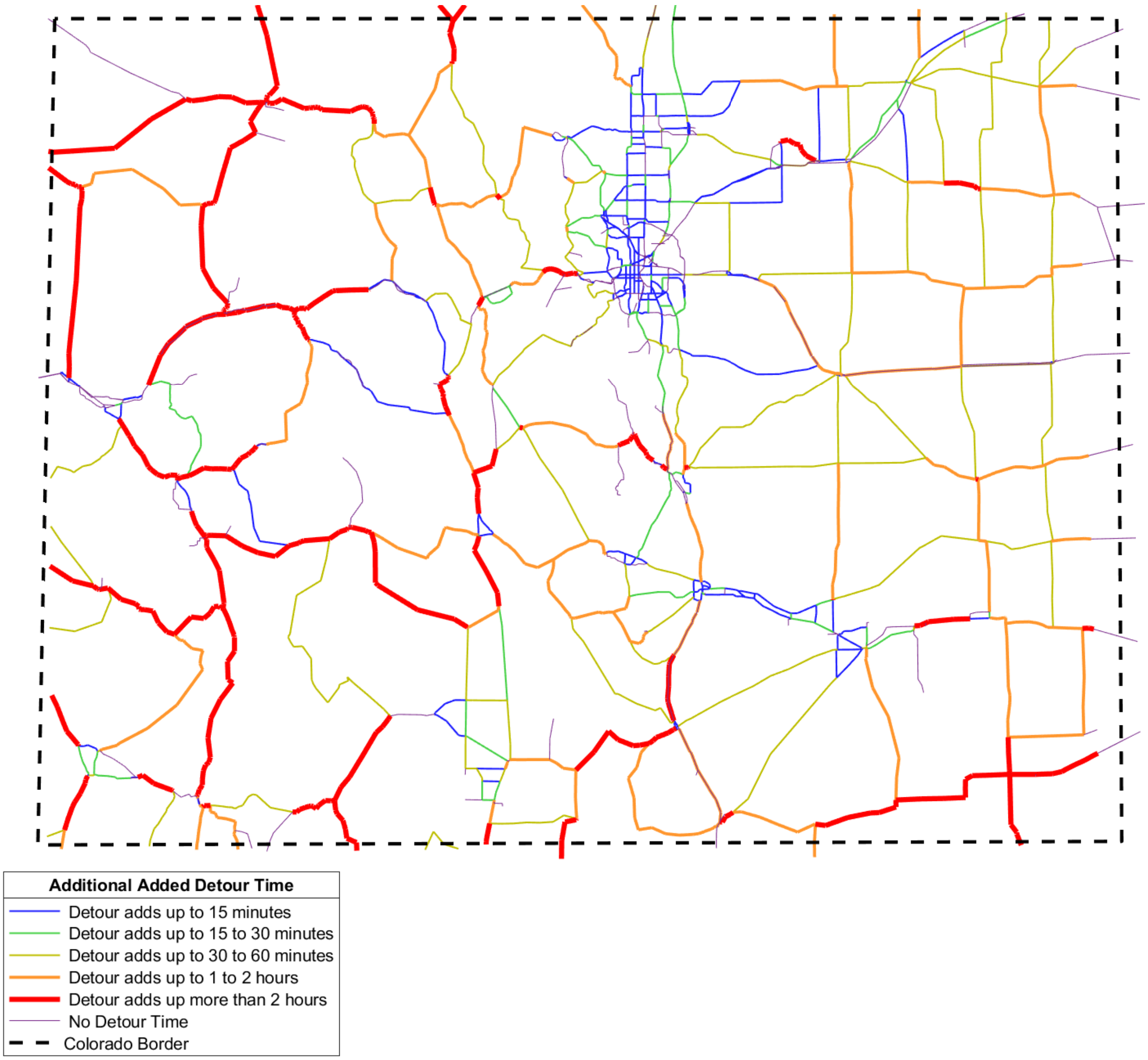

Figure A.1: Updated State Detour Map with Additional Travel Time Considering Congestion in BA Direction.

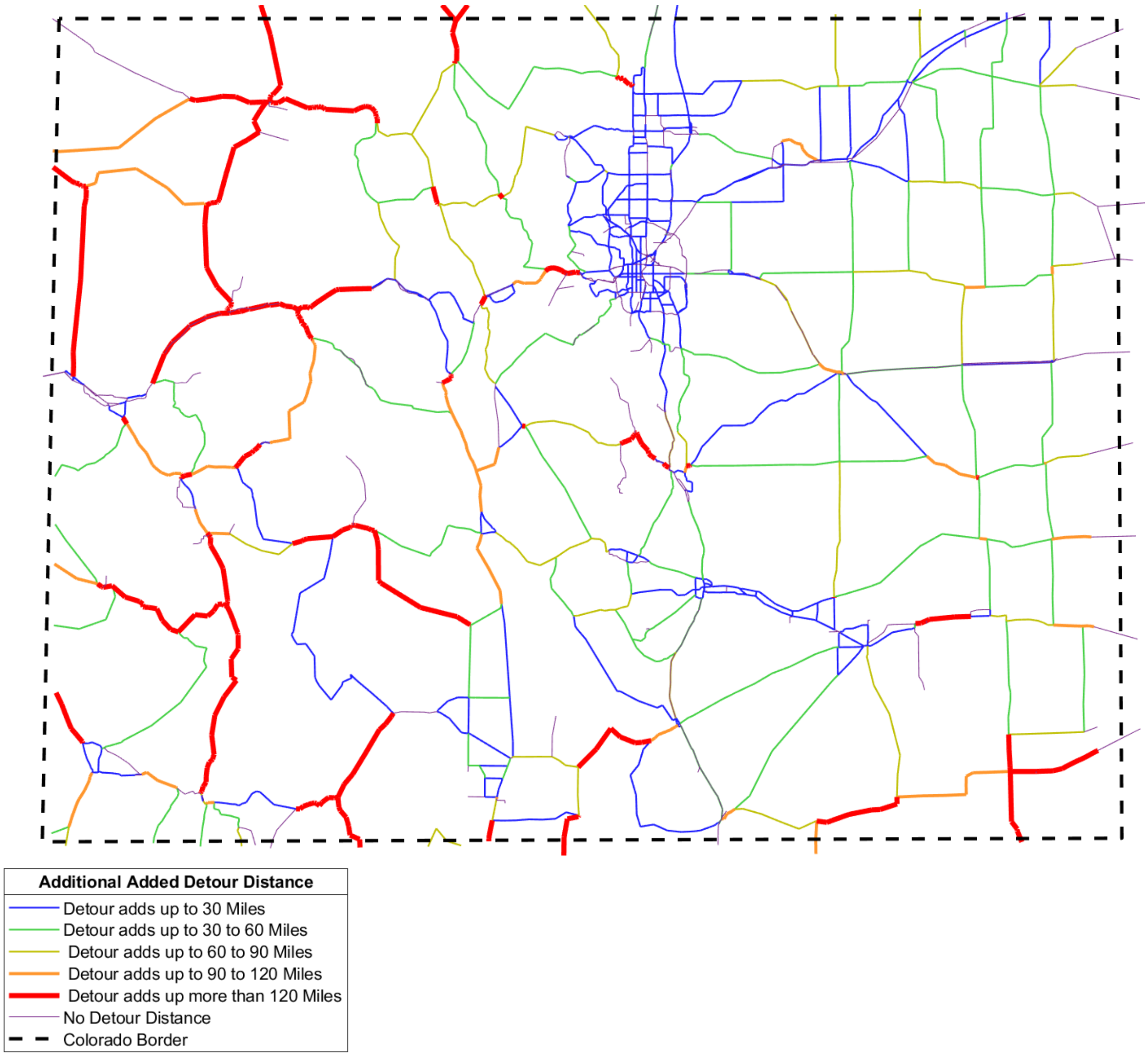

Figure A.2: Updated State Detour Map with Additional Travel Distance Considering Congestion in BA Direction.

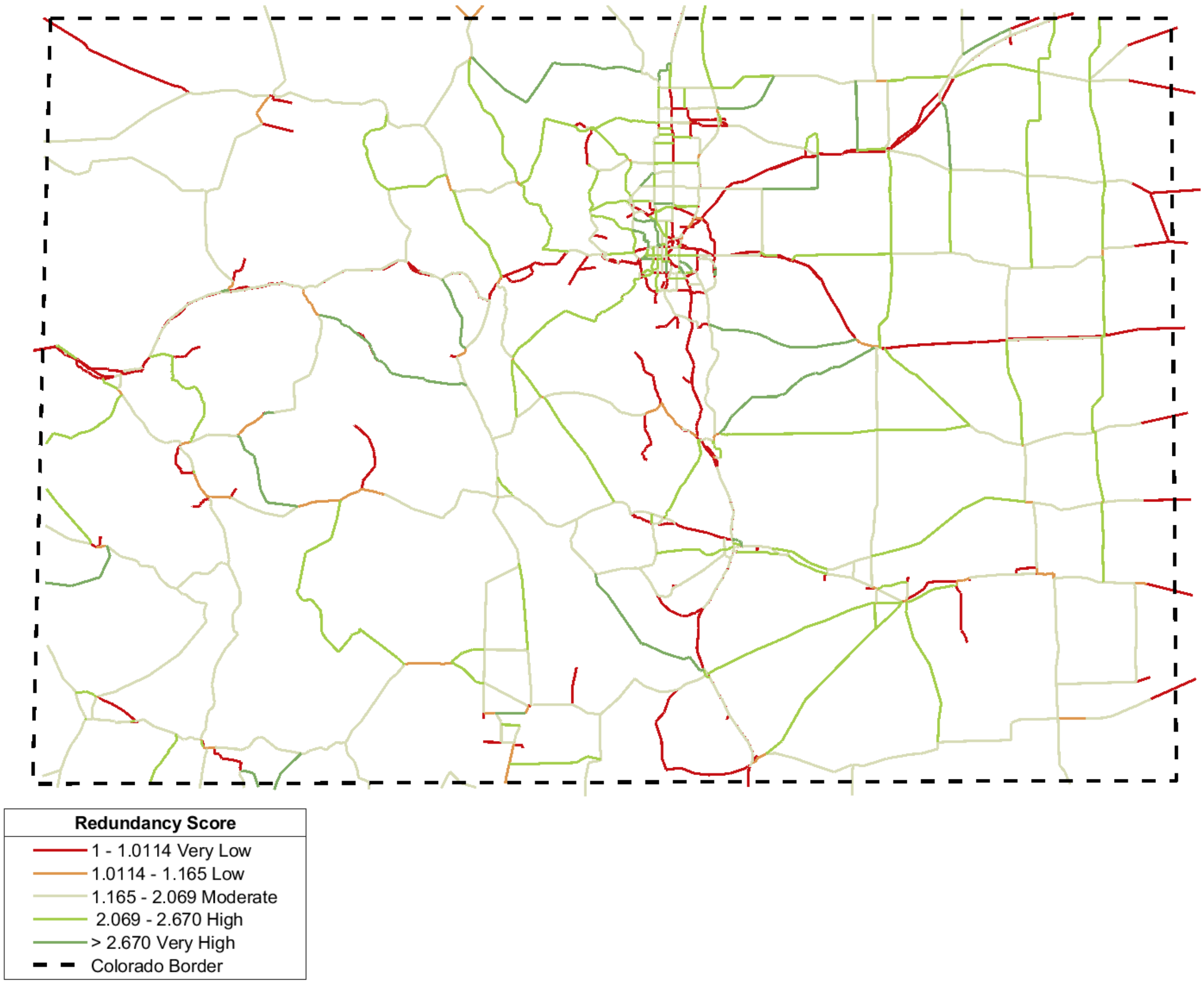

Figure A.3: Updated Redundancy Map for AB Direction

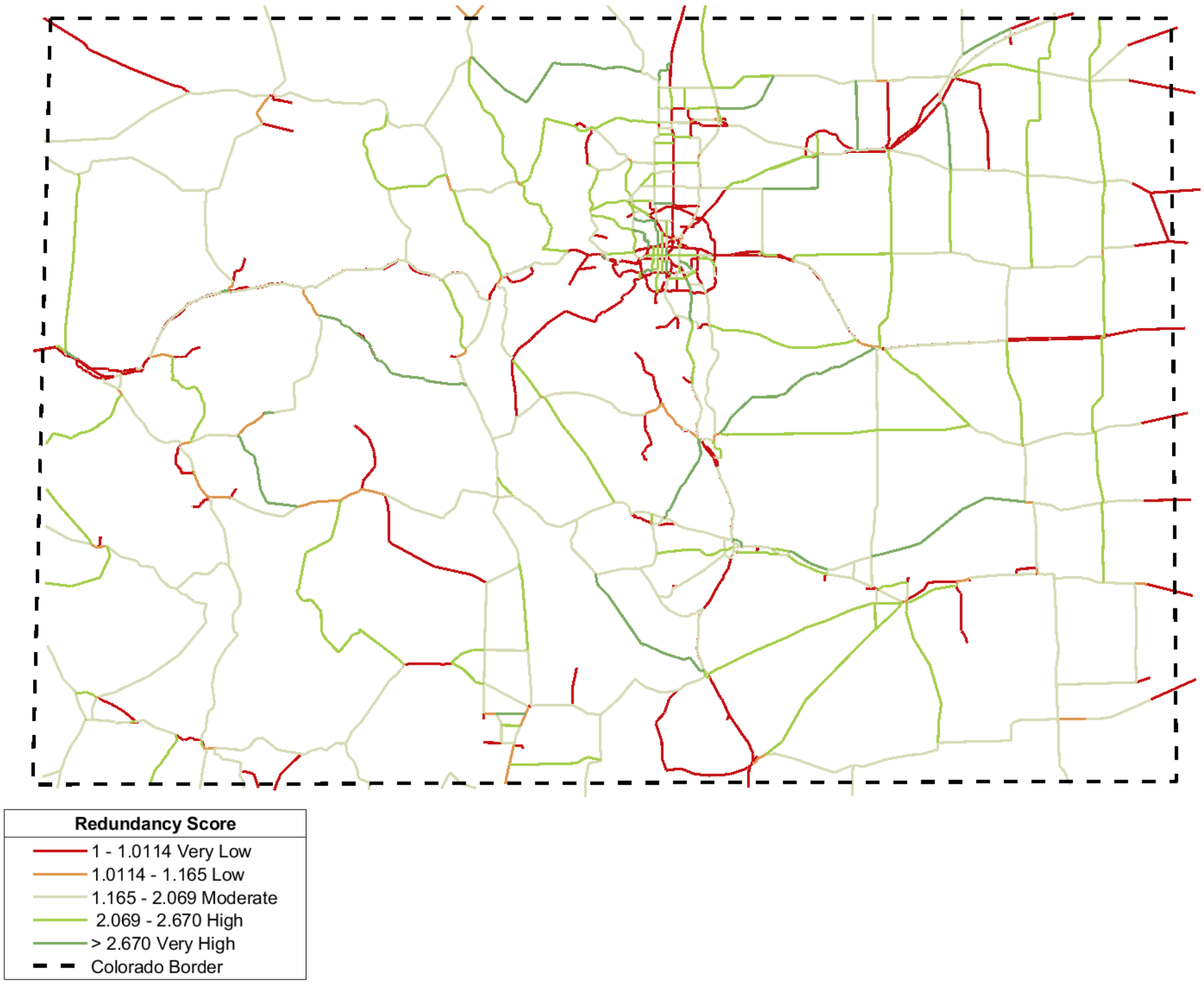

Figure A.4: Updated Redundancy Map for BA Direction

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