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Network Analysis of the Walkability of

Denver's Light Rail and Bus Rapid Transit Network

And How This Can be Improved

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Capstone Project

for

Master's of Science in Geographic Information Science

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Abstract

This study evaluates how well the existing and proposed light rail and bus rapid transit lines in Denver serve residents who want to get by without a car. The number of residents and jobs within half mile and one mile walking distances of stations are calculated using network and buffer analysis methods. Results are compared to determine the accuracy benefit of conducting a network analysis rather than the more common buffer analysis. The study looks at ways to boost the number of residents and employees within walking distance by maximizing access around each station. It also quantifies the available land for Transit Oriented Development around each line since this type of development helps maximize the benefit of transit.

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Introduction

A great mass transportation system allows residents to not own cars or at least own fewer cars. This can save residents money, reduce traffic, reduce pollution, and make better use of land by reducing the need for parking and roads (Hodges, 2010) (Rowe, 2013). The key to a good network is the ability to move long distances through a city quickly and efficiently. Light rail and bus rapid transit are the two main methods used in Denver. If you live and work within walking distance of these stations car ownership can become optional.

This study will evaluate how well existing and proposed mass transit lines will serve riders who walk to transit and compare the results generated by buffer analysis and network analysis. The study will look at three aspects of how well transit lines serve riders who walk to stations. First, the number of residents and jobs within walking distance will be calculated. Then the current walkable area will be compared to the best-case scenario to see how many additional residents and jobs could be within walking distance if connections are improved. Lastly the amount of undeveloped land and parking lots will be measured to determine the potential for new development around lines to boost the population and job estimates.

The study will compare the results of network-analysis to buffer analysis to determine how much buffer analysis overestimates the number of residents and jobs within walking distance. Buffer analysis is more common then network analysis within the transit-planning field. By comparing the two types of analysis this study will give planners a frame of reference when deciding which method to use in the future.

This study focuses on distances of a half mile and one mile. Half a mile is the industry standard but one mile has been shown to have an impact as well. Property values a mile from a station show above market value and non-vehicle owners can push the range they can travel to stations by riding bikes rather than walking. This gives value up to at least a mile out from stations.

Literature Review

In the greater Denver area the Regional Transportation District (RTD) oversees mass transportation. RTD formed in 1969 to consolidate mass transit in and around the Denver area. For the first 25 years RTD consisted only of bus routes. Then in 1994 the first light rail line was opened. The Central line ran from downtown Denver down to I-25 and Broadway (RTD, 2015). Figure 1 shows the full rail and bus rapid transit (BRT) network analyzed in this study.

After the initial success of the Central line voters approved extending the line down south along Santa Fe close to C-470 on the south side of town. This extension, called the Southwest line, opened in 2000. A second spur near downtown called the Central Platte Valley line opened in 2002. When a massive construction project called T-Rex was undertaken to improve traffic along I-25 through the southern half of town light rail was added along the highway. This line also included a two station spur along the southern portion of I-225. The Southeast line was completed in 2006 (RTD, 2015).

While the Southeast line was under construction a bolder expansion of the light rail system throughout the Denver area was proposed to voters. The goal was to expand the light rail system all throughout the Denver area at the same time rather than approving and constructing one line at a time. The FasTracks plan called for extending the Central, Southeast, and Southwest lines plus converting the two stations along I-225 into a full-fledged line consisting of nine stations. It also called for constructing five other rail lines and one bus rapid transit line. The rail lines are the West, East, Gold, North, and Northwest lines and the BRT line is the US-36 line.

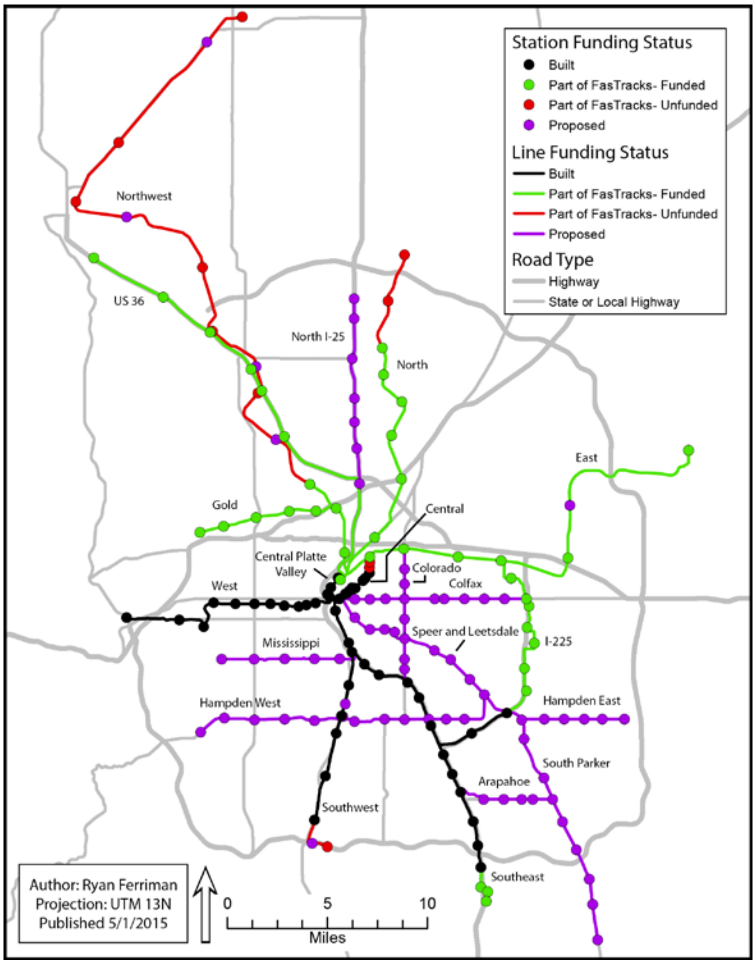

Figure 1. The funding status of all the rail and BRT lines and stations reviewed in this study.

The FasTracks plan was placed on the 2004 ballot for residents to vote on. It passed adding 0.4% to local sales taxes to fund the project. Funding has been an issue because costs have increased and due in part to the recession starting in 2008 sales tax revenues have fallen short of projections. The original budget was $4.7 billion (RTD 2004, 2-4). It has increased to $5.6 billion and this total no longer includes the extensions of the Central and Southwest lines, the final two stations of the North line, or the Northwest Line beyond its first station (Denver Regional Council of Governments 2014, 3). Despite the funding challenges the first line of the FasTracks program, the West line, opened in 2013. In 2016 the Gold, East, and US-36 lines will all start operation. The extension of the I-225 line from two stations to nine will be completed and the first station of the Northwest line will open in 2016 as well. The first six out of eight stations for the North line will open in 2018 and then the three stations comprising the Southeast extension will open in 2019. All remaining portions of the project remain in limbo (RTD, 2014).

The biggest remaining question mark is the Northwest line running from Denver to Boulder and then up to Longmont. Initially the line was proposed to be seven stations in length. Since then four additional stations have been proposed but not formally incorporated into the project. These would be in between the original seven stations rather than adding to the length of the line. Only the first station funded as part of the Eagle P3 project, which also includes the East and Gold lines, has funding (RTD, 2014). It is unclear at this time when the rest of the line will be completed and if the four proposed stations will be included. One factor undercutting the Northwest line is its proximity to the US-36 BRT line. Two of the initially proposed stations and two of the newly proposed stations on the Northwest line are located nearly on top of stations along the US-36 BRT line. This duplication of service reduces the number of new riders that would be served by the Northwest line since they will already be served by the US-36 BRT line opening next year. With one Northwest station already under construction and four other existing and proposed stations overlapping stations from the funded US-36 line the remaining benefit of the Northwest line is limited to six stations of which two have not been approved yet (RTD, 2014).

A few other question marks remain regarding the FasTracks project. The two station proposed extension of the Central Line to the East line remains unfunded. Also, an extra station has been proposed along the original length of the East line, but despite the East line opening next year a formal decision on adding the new station has not been made. Multiple questions remain about the Southwest line. FasTracks formally calls for adding an extension to the line with one station a C-470 and Lucent. A second station between the current end of the line and C-470 and Lucent has been proposed at Santa Fe and C-470 but it has not been formally approved. Also the Bates station has been proposed along the existing length of the Southwest line. It has been studied but not approved or denied yet (RTD, 2014).

These future proposals remain in limbo until the FasTracks funding tax is increased or until more time elapses for the original tax increase to accumulate enough funds. The original timeline called for all lines to be completed by the end of 2016 (RTD, 2004). There is no chance that this will happen. According to the latest timeline RTD posted on the FasTracks website the first six stations of the North line will open in 2018 and the Southeast extension will open in 2019. The Southwest extension and the last two stations of the North line could take until 2030. Finally, the Central Extension and the Northwest line could take until 2044 (RTD, 2014).

Going forward the network will need additional lines to continue providing a more comprehensive network. Already under consideration is a BRT line along Colfax from downtown Denver to I-225 in Aurora. The current local bus lines are at capacity and traffic flows exceed road capacity. The city of Denver reviewed options including streetcars and BRT and concluded that bus rapid transit was the most cost effective solution (City and County of Denver August 2014). This remains a proposal at this time. Exact station counts and locations have not been decided and funding has not been allocated. I also used maps of population density, employment density, and traffic counts to propose eight other lines for future consideration. The

Colfax line and these other lines may deserve consideration before the Northwest line. Ideally funds will be directed where they will do the most good unless politics get in the way.

The study needed to know how far people are willing to walk to a transit station. This is a combination of how fast they walk and how long they are willing to walk. It is also important to know how to measure the area that is in reach based on the distance people will travel.

Lots of sources list standards for walking distance to transit. The U.S. Green Building Council administers the LEED certification for new construction. Out of a possible 100 points the distance to transit is tied to five points (U.S. Green Building Council June 2014). A project must be located within half a mile of a bus rapid transit, light rail, or commuter rail station to qualify for the five points (U.S. Green Building Council April 2014, 19). They do no list how long or fast they think people are willing to walk to cover the half mile.

The Institute for Transportation & Development Policy has created a scoring system for the quality of Transit Oriented Development (TOD). They assign points for any project located within 1km of a mass transit station based on the rational that the distance can be walked in 15-20 minutes (Institute for Transportation & Development Policy March 2014, 48).

At a local level RTD has set a boundary of half a mile for TOD. They set that distance based on an assumption that people are willing to walk for 10 minutes (Regional Transportation District 2010, 2-1). This equates to a pace of three miles per hour. When evaluating the potential Bates station on the Southwest line in Englewood the local government set a quarter mile buffer for TOD based on an assumption that people will walk for five minutes and a one mile buffer for Mobility Oriented Districts based on riding a bike for five minutes (City of Englewood, Colorado 2013, 11). The quarter mile buffer was based off of walking for five minutes, which equates to the same three mile per hour pace that RTD used. The one mile biking buffer also was based on five minutes of travel which works out to 12 miles per hour which is a reasonable biking speed.

These buffer distances are calculated off of how fast people walk and how long they are willing to walk to get to a station. A meta-analysis of 41 studies with a combined 23,111 subjects found that for individuals aged 20-79 the average walking speed is 3.08 mph for men and 2.89 mph for women (Bohannon and Andrews 2011, 182-189). This is right in line with the assumptions made by RTD and the local station analysis that both set walking buffers based off of a three mile per hour pace. The U.S. Green Building Council did not list how they arrived at a half mile buffer. They did not list an expected walking time or speed but their half mile buffer is right in line with what RTD uses. The Institute for Transportation & Development

Policy set a 1 km buffer off of a 15-20 min walk. This equates to 1.9 to 2.5 miles per hour. That is reasonable if most people average 3 miles per hour. The meta-analysis backs up the walking speed assumptions made by the various standards.

The second part of factoring walking distance is time. The National Household Transportation Survey asked riders how long they walked to get to a station (Hoback, Anderson, and Dutta 2008, 681-692). I adjusted the survey times for a three mile per hour pace. This works out to 42.3% of riders walking 0.25 miles or less, 32.5% walking 0.25-0.5 miles, 13.5% walking 0.5-0.75 miles, and 7.3% walking 0.75-1 miles to get to a station. Based on this I will test half mile and one mile ranges. I can see why most studies look at a half mile range because 74.8% or transit riders walked a half mile or less to get to transit. I want to test one mile as well because you could bike to help cover the extra distance plus an additional 20.8% of riders walk between half and one mile. A one mile range covers 95.6% of all riders. Testing coverages beyond a mile does not make sense since very few people are walking that far to reach transit.

As for how to map out what is in walking distance, all the studies I found except for one used buffer analysis. Studies with maps always showed nice round coverages. Ones without maps used phrases like half mile radius or buffer analysis. One such example is a study conducted on how many people will live and work within half or one mile of the existing light rail stations and the stations being added as part of FasTracks in 2020. The study used a buffer analysis but acknowledged that this was not very precise (Picard 2010). The RTD TOD study used a buffer analysis as did the City of Englewood light rail study (Regional Transportation District 2010, 2-1) (City of Englewood, Colorado 2013, 11). The one exception is the TOD Strategic Plan put forth by the City and County of Denver (City and County of Denver 2014, 42-43). They touch on the drawbacks of buffer analysis and state that they used network analysis. They do not show the results of their findings however. They only list one example of the difference in results between buffer and network analysis.

I also looked at minimum parking requirements. New stations can result in less demand for parking. This in turn could free up more land for development around stations. Current minimum parking standards are questionable even in the absence of new transit. Minimum standards usually come from surveying nearby communities' standards or by consulting the Institute of Transportation Engineers (ITE). If nearby communities did not base their minimum parking requirements off of exhaustive studies simply copying those standards does not make sense. The ITE standards can be weak because they are based on average peak usage, which can overstate the need for parking most of the time. Also they can be based off of observing as few as four parking lots spread around the country. This has little to no bearing on local parking needs (Shoup 1999, 549-574). A study

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in King County, Washington, the county Seattle is in, compared parking at multi-unit residential buildings. They found that when comparing units in areas with high and low transit access that observed vehicles per unit were 0.96 and 1.23 respectively and that total spaces per unit were 1.01 and 1.64 (Rowe, Ransford, Morse, and Haas 2013, 25). This backs up the idea that parking needs will decrease when transit it put in. Lastly a study of land values in Los Angeles found that minimum parking requirements led to ineffective land use. They found that less value was added to properties than the cost of the land the parking was on plus the cost of constructing the parking spaces (Cutter and Franco 2012, 920). Transit will add value by reducing the need for parking and putting land to better use.

Design and Implementation

This study relied on four main data sets. They are population and employment figures, station locations, the network pedestrians can travel along, and dirt lot and parking lot locations. Only the population and employment data was available to download in a useable format. For the other three, they each involved unique challenges for compiling.

Population and Employment estimates were available through the Denver Council of Regional Governments (DRCOG). Transportation Analyses Zones (TAZ) can be downloaded from their site. These range in size from as little as a city block in downtown Denver to very large tracts of land outside the metro area. A polygon shapefile is posted on their website containing all of the zones. Separately they have posted an Excel sheet with estimated population and employment figures for each zone for the years 2020 and 2035 (DRCOG, 2015).

Next up was mapping out line and station locations. Using an aerial image basemap existing tracks and stations could be identified and mapped. The lines and stations from the FasTracks project that have not been built yet were mapped from piecemeal data on the RTD FasTracks website (RTD, 2014).

From there the next step was to propose some new lines. The City of Denver has floated a proposal to add a Bus Rapid Transit line along Colfax from Downtown to I-225 in Aurora (City and County of Denver 2014). Exact station totals and locations have not been proposed so the study proposes locations. The suggested locations are at busy intersections and are spaced to minimize overlap at the half mile walking distance. Additional lines are proposed for future consideration. Traffic counts, population density, and employment density were mapped to identify areas where transit would be in high demand. The previously acquired population and employment data from DRCOG was used along with traffic count data from DRCOG (DRCOG, 2015). Lines were spaced to minimize overlapping coverage at a distance of half a mile. These proposed lines will most likely be bus rapid transit since they follow roadways rather than railway right of ways.

The next step was building out the network for the network analysis. To perform a network analysis a single line feature class where segments break where they meet other segments is required. The starting road data came from the Colorado Department of Transportation (Colorado Department of Transportation, 2014). They publish data at a county level and split the roads into shapefiles for highways, major roads, and local roads. These three road types for all eight counties in the study area were merged to make a single road feature class. The planarize lines tool, topology, and a careful review of the service areas were used to fix issues where line segments did not break at intersections. Busy road sections were deleted from the network since they are not safe for pedestrians to walk along.

The next step was to add features that are not roads but that pedestrians can walk along. This included trails, pedestrian bridges, and parking lots. There are no source files for these features so they were digitized from an aerial basemap. This took days to complete. For practicality and time reasons this was only done for a diamond shaped coverage area extending a half mile out north, south, east, and west from each station. This allowed the walkable area to be calculated more accurately for the half mile coverage than for the one mile coverage. Testing results showed that this precision had more of an impact for smaller test areas because there was less of a chance for alternate routes to reach areas at the limits of the coverage area.

To determine how much land is available for redevelopment dirt lots and parking lots were mapped. This was accomplished by digitizing features from an aerial basemap. An effort was made to only map vacant lots. Parks, school land, and yards were not included. Only larger parking lots that had development potential were digitized. Lots that are smaller than the average building sizes around them were excluded. This process was time consuming, similar to digitizing extra features for the network.

The analysis began by running a network analysis on the stations at distances of half a mile and one mile. Service areas were calculated for each station so that estimates could be reviewed both at a station and line level. This is important to evaluate proposed stations for existing lines and the benefit of each station on proposed lines.

To avoid double counting residents and employees service areas could not overlap. This was a major flaw in the analysis done in 2010 on the number of residents and employees within a half mile or one mile of light rail (Picard, 2010). His analysis was run independently on each line resulting in double counting residents in the overlapping areas. Since this study generates numbers at a station level and then dissolves the station numbers to the line level two issues needed addressed.

The first issue was eliminating overlap between stations in a single line. This was accomplished as part of running the network analysis. In the service area settings the multiple facilities options was set to not overlapping. This way any overlapping areas were assigned to the station with the shortest path to the area. All lines with equal priority had to be tested at the same time so that shared areas could be accurately split. For areas where lower priority service areas were overlapped by higher priority service areas the erase tool was used to delete the overlapping area.

The second issue dealt with priority between lines. Top priority was given to existing lines and lines that have already been funded through FasTracks (Central, Central Platte Valley, East, Gold, I-225, North, Southeast, Southwest, US-36, and West). Second priority was given to lines that are part of the FasTracks plan but have not received funding yet (Northwest). Third was the Colfax line since it has been proposed by the City of Denver. Last priority was the lines proposed in this study. Each priority level was run through network analysis separately. Then the erase tool was used to delete any area where a higher priority feature overlapped a lower one.

In this process the only line that was not given equal priority along its entire length was the Central line. The final two stations are part of the FasTracks proposal but have not been funded yet. They were not given equal status to the existing Central line stations or the already funded stations on the East line that they overlapped with. This was done so the two stations could be analyzed without overemphasizing the number of people they would serve by counting residents and employees in areas already served by other stations.

The network analysis showed that in areas like along Colfax where the road grid was uninterrupted and coverage was at its maximum that the service area was a diamond extending the test distance due north, south, east, and west from the station. This is the best-case coverage. An example is shown in Figure 2.

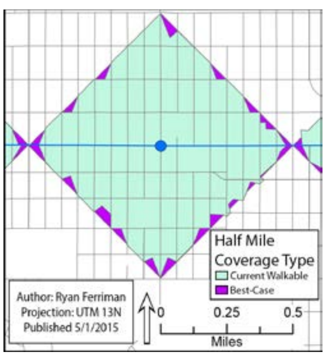

Figure 2. Example of a nearly perfect coverage in an area with a nearly complete road gird.

The best-case coverage areas were mapped from anchor points set the appropriate distances from the stations. To split overlapping areas the Create Thiessen Polygons tool was used to find out which station was closest to a given area. The same priority that was used for the network analysis to give some lines priority over others in overlapping areas was used for the best-case coverages too.

After determining the network analysis coverage area and the best-case coverage area a buffer analysis was run for each distance to compare overall figures. Instead of testing each line separately buffer figures were calculated for two subsets. Existing and FasTracks lines were one group and and proposed lines were the other.

Figure 3 shows the steps performed on all three coverage types to get population and employment estimates for 2020 and 2035.

The last step was analyzing land use. This was done by using the clip tool to clip each land use type by the network analysis service area. Then the Dissolve tool was used on the line column to consolidate the numbers down to one total per line.

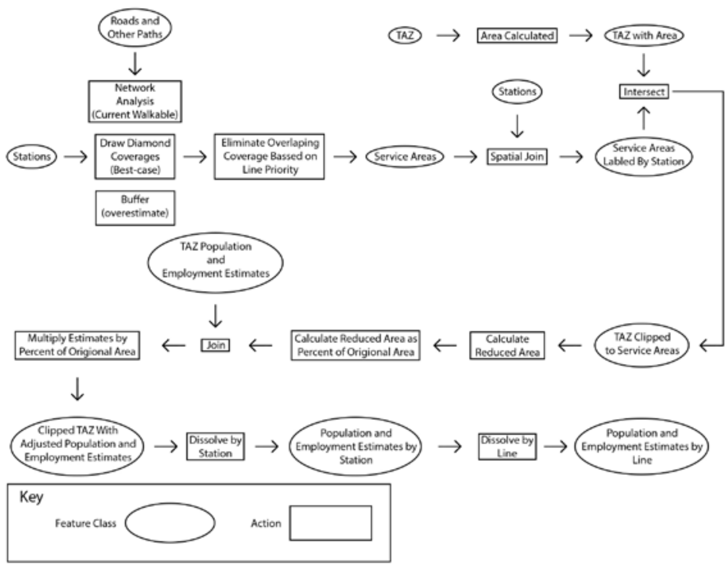

Figure 3. Steps taken to estimate population and employment at station and line levels for 2020 and 2035.

Results

This study looks at how well the RTD mass transit lines support riders who do not own cars. Traditionally this has been done with buffer analysis. This study looked at the ways network analysis outperforms a buffer analysis when determining how many people are served by transit and how service can be improved in the future.

The core calculations for the study are the projected number of people who will live and work within a half mile or one mile of each line in the years 2020 and 2035. Standard industry practice when determining service areas is to draw a circular buffer around each station. This study ran this method to compare results with alternative methods. This study looked at two other coverage areas for each distance. The current coverage is a network analysis of the current roads and trails as well as all planned pedestrian bridges. The best-case coverage assumes a perfect road grid that maximizes walkability.

Figures 4-7 show the population and employment totals for 2020 and 2035. Each figure is for a different coverage area and distance combination. These figures are the basis for the analysis that follows. Figure 8 sums up the population and employment figures for 2035 and consolidates all four charts into a single chart that simplifies analysis. This chart makes it easy to see at a glance which lines serve the most residents and employees.

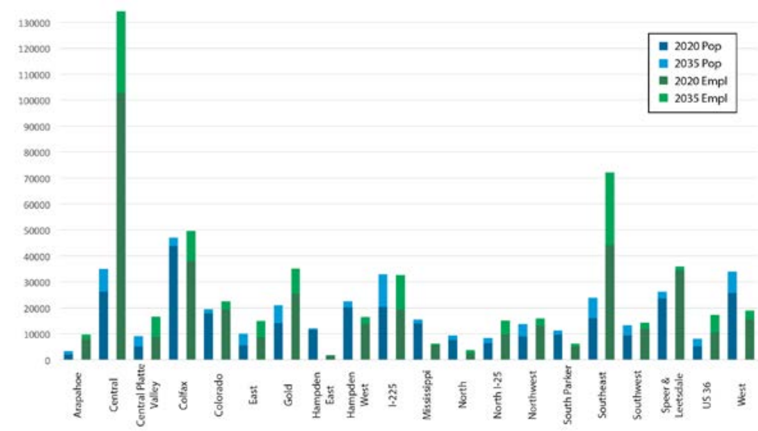

Figure 4. Half mile current coverage area population and employment totals for 2020 and 2035.

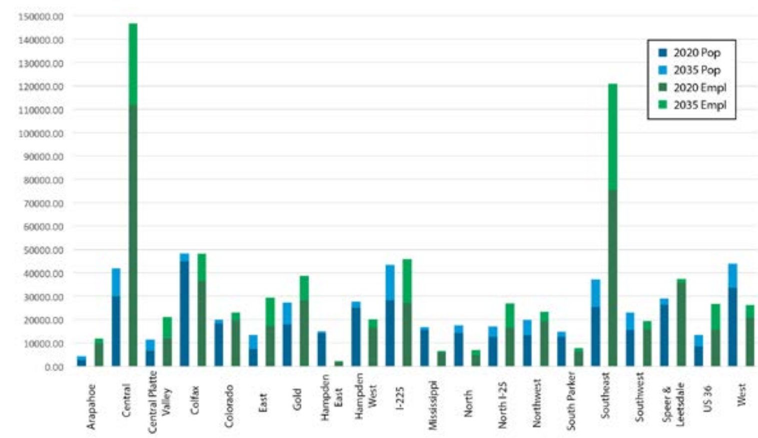

Figure 5. Half mile best-case coverage area population and employment totals for 2020 and 2035.

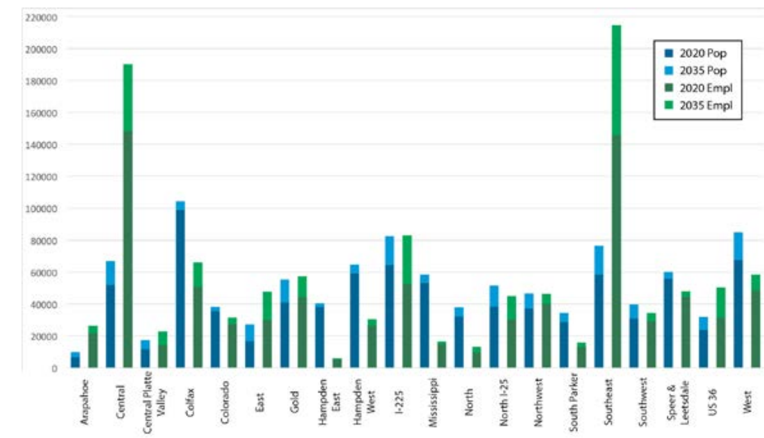

Figure 6. One mile current coverage area population and employment totals for 2020 and 2035.

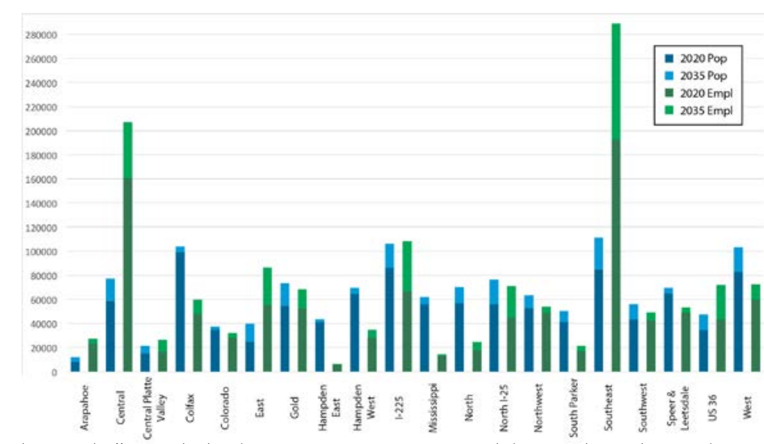

Figure 7. One mile best-case coverage area population and employment totals for 2020 and 2035.

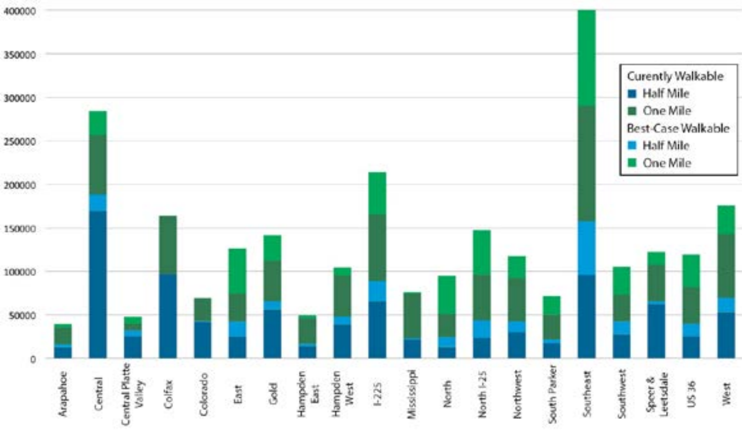

Figure 8. Consolidated population and employment count figures for current and best-case coverage areas tested at half mile and one mile distances.

Table 1 shows the 2035 combined population and employment for all three coverage types at both distances. This confirms that buffer analysis overstates the number of residents and jobs within walking distance of stations. Best-case coverage is only 72.9% and 83.5% of the buffer totals at half mile and one mile distances respectively. The network analysis covers only 56.8% and 66.5% as many residents and jobs as the buffer analysis. This confirms that buffer analysis overstates how many people live and work near transit.

Table 1. Summed up 2035 population and employment for all existing and proposed lines.

Coverage Type	Distance	Summed Pop & Empl	% of Buffer
Current	Half Mile	914105	56.8
	One Mile	2125396	66.5
Best-Case	Half Mile	1172955	72.9
	One Mile	2668563	83.5
Buffer	Half Mile	1608786	
	One Mile	3196740	

Table 2 shows the total population and total employment figures for the existing lines plus the planned and proposed stations in the FasTracks program. In 2035 if it is all built and nothing is done to improve road connections 5.5% or residents and 15.4% of jobs will be within a half mile of stations. Out to one mile 14.8% of residents and 33.5% of jobs will be within walking distance. If the connections around stations are maximized the network could serve up to 20.2% of residents and 43.4% of employees at a distance of one mile. Buffer analysis offers a much rosier but inaccurate prediction of 26.4% of population and 51.5% of employment. There is a significant difference between the buffer calculation and the other two.

Table 2. Population and Employment projections for 2035 for existing lines plus FasTracks lines and the percent of the total RTD service area served.

				% of total in the RTD service area	
Coverage Type	Distance	Population	Employment	Population %	Employment %
Current	Half Mile	210018	375559	5.5	15.4
Best-Case	Half Mile	291921	504976	7.7	20.7
Buffer	Half Mile	402116	669704	10.6	27.5
Current	One Mile	564572	816890	14.8	33.5
Best-Case	One Mile	768414	1057003	20.2	43.4
Buffer	One Mile	1006562	1245739	26.4	51.1

Table 3 shows the same figures for the nine proposed lines. The current coverage would serve 4.3% of residents and 6.7% of employees out to half a mile and 12.1% of residents and 11.7% of employees out to one mile. If connections are optimized for a distance of one mile the lines max out at serving 13.7% of residents and 13.1% of employees. Buffer analysis overstates the best case scenario listing 16.3% of residents and 13.3% of employees served at a distance of one mile. The employee prediction is fairly close to the best-case coverage but the population prediction is 2.6% higher.

Table 3. Population and Employment projections for 2035 for proposed lines and the percent of the total RTD service area served.

				% of total in the RTD service area	
Coverage Type	**Distance**	**Population**	**Employment**	**Population %**	**Employment %**
Current	Half Mile	165365	163163	4.3	6.7
Best-Case	Half Mile	192607	183451	5.1	7.5
Buffer	Half Mile	290859	246107	7.6	10.1
Current	One Mile	459863	284071	12.1	11.7
Best-Case	One Mile	523392	319754	13.7	13.1
Buffer	One Mile	620206	324232	16.3	13.3

Combining the coverages of both sets of transit lines we get 26.9% of residents and 45.2% of employees within a one mile walking distance of transit along the current road network. The best-case network would serve 33.9% of residents and 56.5% of employees. If 45.2% of the 26.9% of the residents living within walking distance of transit also work within walking distance then 12.2% of the population live and work within walking distance and would not need cars for commuting. In the best case scenario where

56.5% of the 33.9% of residents living within walking distance of transit also work within walking distance, then 19.2% of residents would not need a car to commute. These are rough calculations. The numbers could be better in actuality because people who want to walk and live or work within walking distance of transit may look to move near or find a job near transit to make walking and commuting by transit possible.

There are three ways to boost how many people and jobs are located within walking distance of transit. Build more lines and stations, maximize the road and trail network around the stations to increase the area within walking distance, and develop dirt lots and redevelop parking lots within the walkable area to provide more housing and jobs.

The analysis so far has looked at the impact of adding more stations and lines and the benefit of maximizing coverage. These are the figures in Figures 4-8 and Tables 1-3. The study also looked at what it takes to maximize coverage. Figure 9 shows the current and best case coverages around all the lines. Planners can use this map to identify areas for improvement.

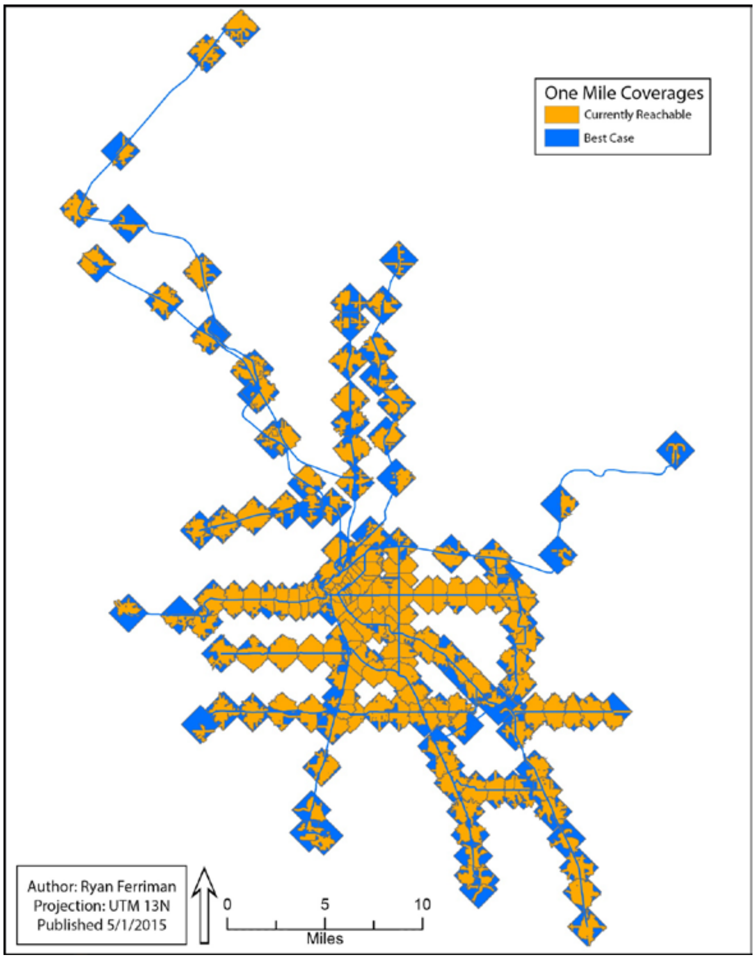

Figure 9. Map comparing the current coverage area and the best-case coverage area.

Nothing can be done to make up for permanent obstacles like buildings or private land that will remain off limits to the public. Improvements can be made in two other ways though. The first way is to install pedestrian bridges. Working with Figure 9 in ArcMap I was able to identify six instances where highways cut coverage areas in half. When bridges or tunnels are not present to cross an unsafe road pedestrians are limited in where they can reach. The two westernmost stations on the West line are a perfect example. These stations have half the coverage area they could have because pedestrians cannot cross 6th Ave which is right next to the stations.

The other way to transition from current coverage to best-case coverage is to complete development around a station. When there are large chunks of vacant land, like farmland, with no roads in them those areas are not included in the current coverage. Transit planners cannot force development but over time these undeveloped areas will build up and help maximize coverage. Putting in stations before coverage is maximized could help accelerate development. Most of the large best-case coverage areas in Figure 9 that are not reachable now will fill in with future development. Coverage areas that are split in half can be helped with pedestrian bridges as described above. Planners should look closely at development plans to determine if more weight should be given to current coverage numbers or best case figures.

The last thing that transit planners should look at is the availability of dirt lots to develop and parking lots to redevelop within the current coverage areas. The more acres of dirt lots and parking lots there are the more potential there is for transit oriented development. These projects boost the usefulness of the lines by providing additional housing and offices close to stations. Figure 10 shows the total acres of dirt lots and parking lots within the current coverage area at distances of half a mile and one mile. Figure 11 shows the locations of the available sites along the lines and gives a sense of how they are distributed and how big the individual plots are. Old structures that could be razed and redeveloped could be considered as well but they cannot be easily identified from aerial imagery.

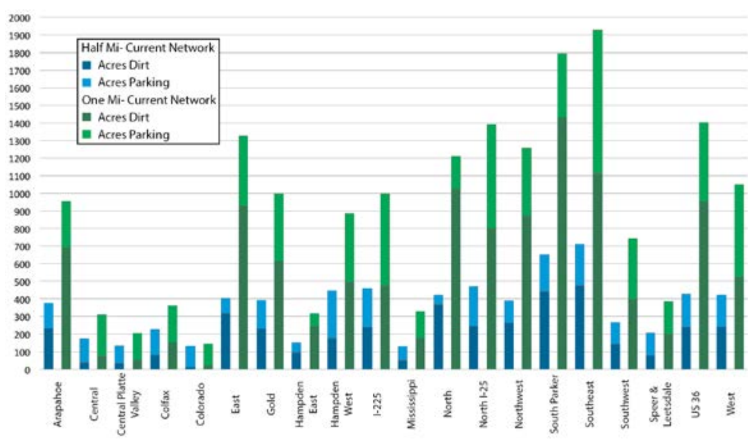

Figure 10. Acres of dirt lots and parking lots within the half mile and one mile current coverage areas. The height of each bar is the combined acres.

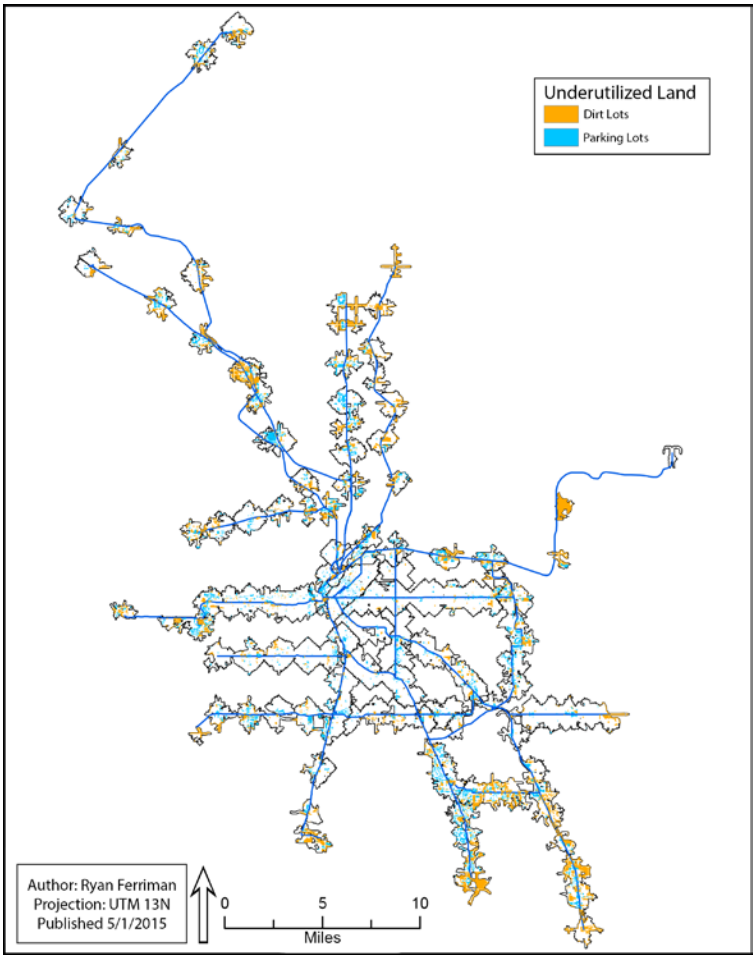

Figure 11. Map of dirt lots and parking lots within the one mile current coverage area.

Based on these figures there is a lot of potential for development along the existing Southeast line. There are 710 acres available to develop within a half mile. If developers are willing to go out to one mile there are 1929 acres available. To help maximize transit an effort should be made to encourage development around the existing lines and the ones under construction. Of those lines the East, North, and US-36 lines have the most potential with between 1200 and 1400 acres available. This is a way to boost access to transit without having to build additional stations or lines. Of the proposed lines the South Parker line has the most potential with 1793 acres available to develop within one mile.

Of the four original transit lines and the seven in FasTracks six have received full funding. These are the Central Platte Valley, Gold, I-225, Southeast, US36, and West lines. The Central, North, and Southwest lines have extensions that are not funded yet and the East and Southwest lines each have a proposed unfunded station mid line. Lastly, the Northwest line has six planned and four proposed stations that have not been funded. To help decide if they are worth funding figures were calculated just for these stations.

The extension of the Central line is a tossup. The main drawback is that the area covered by the two station extension is already well covered by other stations along the Central and East lines. The half mile current coverage for the two lines only serves 410 residents and 52 workers. At one mile 1886 residents and 946 employees are within walking distance. This is much smaller number of beneficiaries than normal. On average for the 166 stations studied there are 6171 residents and 6632 employees per station within the one mile current coverage. The line may be worth constructing for other reasons though. The extension connects downtown directly to the airport. Since 15% of all jobs covered by the network are along the central line this connection is valuable. The stations along the extension are much closer together than on other lines and no parking will be constructed so these stations should be cheaper to construct than others. The convenience the extension provides and the relatively low cost may make it worth building despite serving relatively few people at the new stations.

The additional station along the East line makes sense. The area is just starting to develop but by 2035 the one mile best-case coverage area for the station will serve 4993 residents and 933 employees. This represents 12.5% of the residents and 1.1% of the jobs along the line. It is worth completing because no additional track is needed and since the line is still under construction the station can be built without interfering with regular service along the line.

The last two stations on the North line have not been funded yet. Based on the one mile current coverage together they would serve 14.6% of the residents and 6% of the employees along the line based on while comprising 25% of the stations. As seen in Figure 10 there is a lot of undeveloped land around those stations and the best-case coverage is much greater than the current coverage. By the time the North line opens in 2018 it may make sense to start construction on the final two stations. By that point development in the area may have improved enough to support the stations. Right now the coverage is too spotty.

The Southwest line has three separate questions to answer. A station called the Bates station has been proposed along the existing line. The one mile current coverage reaches the stations fair share of residents and employees along the line. Since no additional track is needed the cost of the station is probably justified. FasTracks calls for extending the line to C-470 and Lucent adding one station at the end of the line. A secondary proposal has been floated to add a second station between the C-470 station and the current end of the line station. This would be at C-470 and Santa Fe. It makes sense to either build both stations or wait. Since most construction costs are tied up in acquiring land for and installing the track building both stations will cost only a little more than building only one of them. For the time being it may not be wise to proceed. Together the stations would represent 25% of the stations on the line but even in a one mile best case scenario they would only serve a combined 31.3% of residents and 12.2% of employees. The low percent of employees could justify shifting transit dollars to other projects first despite the above average number of residents at the stations.

The tougher question for planners has been how to handle the Northwest line. One station will open in 2016 but the rest of the line remains in limbo. The original plan called for six additional stations but four others have been proposed as well. There are two significant challenges for this line. The first is that four of the unfunded stations are located right next to stations on the US-36 BRT line that is opening next year. Since residents and employees near those stations will already be served by BRT the only benefit of constructing the heavy rail would be for more reliable service or possibly faster transit times. Between the overlapping stations and downtown Denver the BRT does not make any stops while the Northwest rail line would make three additional stops. This might wipe out the traditional speed benefit of heavy rail. Transit times have not been proposed so which method would be quicker is not known. The four stations' current one mile coverages will only serve 7154 residents and 7786 employees combined by 2035. This is well under the average for the 166 stations tested. They serve on average 6171 residents and 6632 employees per station. For the line to be built it needs to be primarily on the merits of the six other stations.

I do not see enough benefit from the other six stations to justify the line. It would be the longest line constructed and yet entire 11 station line would serve the same or fewer residents and employees within it's one mile current coverage than four of the eight proposed lines that do not have funding yet. Since those four lines would serve at least as many people and cost less they should take priority.

Discussion

This study was an attempt to more accurately evaluate the number of residents and jobs within walking distance of transit stations then past studies have. The main focus was on using network analysis rather than the common practice of buffer analysis to determine what areas can be reached on foot. Additional steps were taken to show the difference between what can be reached currently compared to a best-case scenario and to find out how much land is available for redevelopment as transit oriented developments.

This is the first study I know of that used network analysis rather than buffer analysis to determine how many people live or work within a certain distance of transit stations. This provides more accurate numbers for planners to base decisions off of.

When I began the process I thought that buffer analysis was a bad choice because it assumes perfect conditions where there are no obstacles preventing you from walking in a straight line from where you are to a station. I thought that any difference in coverage area would be the result of obstacles like large buildings or big tracts of private land that could not be crossed. Instead the biggest issue was that even with a perfect road grid only a diamond shaped area could be reached with the points touching the edge of the circle created by a buffer. This results in a best-case coverage that is only 63.7% of the buffer coverage. From there obstacles like buildings, a lack of roads due to undeveloped land, and barriers like highways further reduced access.

The study calculated population and employment using buffer analysis, network analysis (current coverage), and the maximum area that network analysis could cover without obstacles (best-case). After accounting for overlapping coverages the final results show that Network analysis calculated combined population and employment totals equal to 66.5% and 57.1% of the buffer analysis at distances of half a mile and one mile respectively. Best-case coverage totals were 72.4% and 82.9% of the buffer calculation for distances of half a mile and one mile. This was an analysis of 166 stations so the effects are not thrown off by one or two fluke station results.

It was a little surprising that the final population counts came out closer to the buffer results then the generic coverage comparison of a diamond to a circle implied. This can be attributed to two factors. The first is that I did not double count areas where coverages from stations overlapped. Since buffer analysis generates a larger coverage for each station there would be more overlap between stations and therefore a greater reduction in the area surveyed. This would reduce the difference in the coverage areas. I would caution that every study area is different. Depending on how much overlap there is between coverages other networks tested may end up with a bigger or smaller variation between network analysis and buffer analysis.

The second factor is that populations and employees are not distributed evenly. As you move away from a prime station location population and employment density drop off giving less weight to areas on the edge where only the buffer analysis is measured. This was confirmed by comparing what percent of the buffer area the network analysis area covered and then contrasting that with the population and employee count difference for 2020. What I found is that the half mile network analysis covered 45.7% of the area covered by the half mile buffer but it contained 57.3% as many residents and employees. The one mile network analysis covered 51.4% of the area covered by the one mile buffer but contained 66.5% as many residents and employees. This confirms that the further out from a station you get the population and employment density decrease reducing the impact of testing larger coverage areas.

The lesson going forward is that network analysis will result in lower population and employment counts then a buffer analysis but that the difference may not be as great as you would expect. The more overlap there is between coverages and the faster population and employment densities decrease as you move away from a station the less difference there will be.

Network analysis is more accurate and avoids overstating how many people are within a giving walking distance of transit.

A secondary benefit of network analysis is that it shows you what areas are currently unreachable that otherwise could be reachable. This allows you to identify opportunities to improve service. This method can be used to improve coverage around existing stations or to identify opportunities to get the most out of newly proposed stations. The most obvious way to boost walkability is to build pedestrian bridges over highways to keep coverage areas from being cut in half. This is a significant opportunity. With the current FasTracks cost set at $5.6 billion to construct at most 50 new stations the cost works out to $112 million per station. The latest pedestrian bridge under construction is across I-25 just south of Colorado. The total cost is $8 million (City and County of Denver 2011, 5). When the average station costs $112 million and a pedestrian bridge only costs $8 million doubling the coverage area for less than 8% of the initial cost is well worth it. Even in places where the coverage area is not doubled the cost is likely worth the benefits.

The final benefit is to identify opportunities for Transit Oriented Development. By comparing a feature class of vacant lots to the network analysis coverage you can find lots that are within walking distance. A buffer analysis would incorrectly identify some lots as being in walking distance.

I am a firm believer that accuracy is critical when making decisions involving large sums of money. When investing billions of dollars into transit it is important to know that you are operating off of the most accurate information possible. It takes time to gather the necessary information for a network analysis but it is much cheaper than basing billions of dollars in investments on bad assumptions.

Areas for Further Research

This project provides lots of information on existing and proposed transit lines around Denver. This information is helpful for determining where future lines will be added to improve service. The main limitation of this study is that costs have not been determined for the proposed lines. Conclusions about which proposed lines should be priorities cannot be determined without factoring in costs. A line that serves twice as many residents and employees is not better if it costs three times as much money. I view these results as being very important for making decisions but these results are limited in value until costs are determined.

Aside from the lack of cost information the biggest limitation in a study like this is how to handle overlap between potential stations and lines. For this study I did not allow the coverages from lines to overlap since I did not want to double count residents and employees. I created a priority hierarchy to determine how overlapping areas would be split between lines. Not double counting prevents overstating the benefits of the network as a whole but it presents a challenge when deciding between lines to build if funds are not available for all of them. The issue is that if only one of the two overlapping lines is built it serves the entire overlapping area not just its half of the shared area. For example, lets say lines one and two overlap an area containing 20000 residents and employees. They split the difference and each add 10000 to their total. Then when deciding whether to build lines one, two, or three it comes down to two and three. They cost the same to build but line three serves 3000 more than line two. Line three sounds better until you realize that the 10000 overlap applied to line one would be served by line two if line one hasn't been built. Add that back into line two's total and now it serves 7000 more than line three. There are far more combinations than can be tested in advance. The other issue is that stations where two lines meet are only included in one line's totals. If only the line not including the station is built it might be worth adding the station to the line increasing the residents and employees served. There are more scenarios than can be calculated in advance. I would recommend using the numbers in this study to narrow down the options and then test each line separately to get figures that are not affected by unbuilt lines.

This study used a network analysis to determine what area could be reached on foot. The analysis follows linear features out from a fixed point like a station. The benefit of this method is that it takes obstacles into account rather than assuming that you can walk straight out from a station in any direction. The challenge is how you build this network. The features you decide to add or not add limit the final results. I started with the full road data provided by the Colorado Department of Transportation. I removed highways because they are not safe to walk along but I could not evaluate every road for safety. A future analysis could remove high traffic roads with no sidewalks from the analysis since they are not safe to walk along. In addition areas like parking lots and parks provide a challenge. I added connections around the edges of parking lots and along paths in parks but this still limited possible connections. Since you can walk at any angle through a park or parking lot the paths I traced out are somewhat more restricting then reality.

Another limitation is that this study does not account for crime concerns. The distance people are willing to walk to transit is affected by crime risk. If you do not feel safe walking to a station you will not walk and the usefulness of the station is diminished. Crime data could be mapped using hotspot analysis and compared to the station locations to identify potential conflicts.

A final consideration is that a good transit network ties together more than just homes and jobs. Access to fresh food, culture, medical care, shopping, other forms of transit, and parks are important. These additional factors need to be taken into account when deciding where to invest transit dollars. Some examples include the East line providing access to the Denver International Airport, the Colorado line having a stop for the Denver Zoo and the Museum of Nature and Science, and the Southeast, Northwest, US 36, and University lines all having stops next to major malls. These added connections help meet the basic needs of riders so they can live without a car.

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