Chapter 3

CLIMATE CHANGE AND TRANSPORTATION

3.1 Climate Change and Transportation

As Environmental Protection Agency reported, transportation is responsible for about one-third of carbon dioxide emissions in the United States (Hockstad and Cook, 2012). In addition to carbon dioxide, transportation contributes to the emissions of other greenhouse gases. As result, most of the attentions and efforts are towards mitigations and reducing the effects of transportation in emitting greenhouse gases (Valsson and Ulfarsson,) to decrease its adverse consequences like climate change. While the technologies used in motor vehicles continue to improve in greenhouse gas emission efficiency, the increasing weight and power of vehicles that comprise the global fleet counter-balances these increases in efficiency, and, at the same time, the world auto fleet continues to grow in number, particularly in the developing world (Love et al., 2010).

It is undeniable that climate change is happening with the pace that its impacts are tangible especially on transportation infrastructures. Thus, along with mitigation plans to lower the speed of climate change happening, adaptation planning is crucial to maintain the resilience of transportation infrastructures.

Decisions relating to the maintenance, redesign, or retrofitting the existing transportation infrastructures, and design of new ones in response to climate change stressors will affect whether the transportation system works properly or poorly (TRB, 2008). Based on the current climatic knowledge five climate changes or weather events have been addressed as the ones that have the most drastic impacts on transportation. These five stressors are: (1) increases in very hot days and heat waves,

(2) increases in arctic temperatures, (3) rising sea levels, (4) increases in intense precipitation events, and (5) increases in hurricane intensity (TRB, 2008).

3.1.1 Climate Change and Surface Transportation

Different types of climatic and weather events affect surface transportation in different ways. Surface transportation is usually considered as vehicles on roadways, and trains. Therefore, the transportation infrastructures that might be affected are rail lines, bridges, tunnels, and roadways.

Sea level rise will cause more frequent interruption of roadway traffic and railroads in coastal regions and low-lying lands. This climate change stressor also causes inundation of roads, rail lines and tunnels in low-lying regions (TRB, 2008). Sea level rise will make storm surges more frequent and intense which cause temporary inundation of transportation facilities, damage to pavements and rail substructure, and finally chain disruption of roads, railroad, port, and airport (Love et al., 2010).

Intense precipitation usually affects roadway traffic condition due to more congestion which consequently results in increase of travel time. Unusually heavy rain leads to reduction in traction. Although this phenomenon will increase in the number of vehicles collision and accidents, increased precipitation appears to decrease accident's severity that positively affects number of injuries and fatalities (Love et al., 2010). Compared to a day without rainfall 1.5 to 3 cm of rainfall will fatalities by 8.6% (Leard and Roth, 2015). Road and railroad flooding, and mudslide associated with heavy rainfall would cause interruption of transportation systems(McGuirk et al., 2009).

As it was stated earlier, one of the key features of climate change affecting surface transportation is increased temperature or in the other word heat wave. This stressor has severe impacts especially on infrastructures such as bridges. Thermal expansion of bridge joint and pavement, asphalt rutting, and railway track buckling are among the infrastructures' damages due to extreme heat. Heat waves and rise in temperature also change commuter travel behavior. For instance, one study that was done in Toronto on the impact of weather on five modes of transportation, auto drive, auto passenger, transit, bike, and walk (Saneinejad et al., 2012). The travel data for this study was obtained from the 2001 Transportation Tomorrow Survey (TTS). Based on this research for six temperature change scenarios travel behavior changes drastically in each mode (Saneinejad et al., 2012). Based on this study the most drastic changes in the number of trips due to increased temperature, belongs to biking. 1 °C increase in temperature increases biking by 3%, 2 °C increase in temperature increases biking by 5%, 3 °C increase in temperature increases biking by 8%, 4 °C increase in temperature increases biking by 11%, 5 °C increase in temperature increases biking by 14%, and 6 °C increase in temperature increases biking by 17%. Temperature change has less effect on walking. For instance, 1 °C increase in temperature increases walking less than 1%, and 6 °C increase in temperature increases walking by 2.5%.

3.1.2 Climate Change and Air Transportation

Aircraft contribute to climate change in two principal ways. First, through the emission of greenhouse gases such as CO2, NOx and radiatively significant particles such as soot, and second through the generation of contrails which in turn may have an impact on the global heat balance (Love et al., 2010). Thus, finding ways to reduce the amount of energy consumption by aircraft will lower negative environmental footprints. Improved weather forecasts, provided in conjunction with improved air traffic management, offer opportunities to reduce fuel burn. The benefits can flow from number of areas. Improved destination terminal forecasts lead to lower amounts of fuel being carried and, all things being equal a lighter aircraft burns less fuel than a heavy one. Improved wind forecasts provide an opportunity for airline to maximize their tailwind components through the choice of track and flight level (Love et al., 2010).

Climate change stressors (e.g. sea level rise, flooding, intense precipitation, and heat waves) influence air transportation from two points of view. First, they cause damage and deterioration to runways and other airport infrastructures. Second, these events disrupt airport's services ranging from an hour to several days, or in case of sea level rise permanent inundation of runways. Wind speed and visibility are the two most important weather features in aviation sector which can be influenced by climate change. A good example of economic loss due to different types of bad weather is San Francisco International Airport. A study by Eads et al (2000) shows that poor visibility in the summer months and rain storms in the winter months' lead to substantial delays and numerous cancellations. Compared to good weather, cancellations per day increase by a factor 2 to 3 when weather is bad in the morning, and by a factor 3 to 4 when weather is bad all day.

3.1.3 Climate Change and Maritime Transportation

International shipping in 2007 accounted for about 2.7 per cent (870 million tons) of the global manmade CO2 emissions, and based on medium emission scenarios by 2050, in the absence of reduction policies, emissions produced by maritime transportation may grow 150 to 250 per cent (compared to 2007 emissions) due to growth in world trade (Buhaug et al., 2009).

There are serious efforts in shipping industry to reduce the amount of emissions through International Maritime Organization (IMO). A plan which addresses greenhouse gas emissions from trading goods by ships internationally, has been made by IMO. This plan is committed to reduce emissions through rules and regulations and at the same time promises a robust trading system (Love et al., 2010).

The International Maritime Organization's study confirms that there is substantial potential for GHG emissions in international shipping both by technical regulations and operational strategies. These mitigation strategies are two sided: first by reducing the speed on which ships are operation that cause significant decrease in emitting greenhouse gases this is called slow steaming. The second strategy is designing the engines in a way which produce less emissions and be more environmental friendly (Love et al., 2010).

Maritime transportation like other modes of transportation has reciprocal relationship with climate change and global warming. This means that climate change has adverse effects on this mode. Lowering the water level on rivers due to droughts and less precipitation in many regions of the world such as middle east and Africa makes shipping and sea transportation impossible. This has socioeconomic impacts on societies in these regions.

3.1.4 Extreme Weather Events and Transportation

As it was mentioned in previous section, heavy rainfall will increase accidents and traffic casualties. Although these accidents are caused by a multitude of factors including driver error and dangerous driving, the influence of weather on accidents and disruption is a major contributing factor, with over 20% of accidents being associated with the effects of meteorology (Edwards, 1999a). As a sector, transport is almost continuously subjected to meteorological hazards which impact upon the efficiency of its operations (Thornes, 1992)and cause injuries and fatalities across all modes (Edwards, 1999b). The impacts of rain (Andrey et al., 2003;Changnon, 1996), wind (Baker, 1993), high temperatures (Chapman et al., 2006;Dobney et al., 2009), ice and snow (Chapman and Thornes, 2006) have been well documented, and affect road, rail and water transportation (Jaroszweski et al., 2010).

Preliminary studies have highlighted the range of impacts that predicted climate change will have on all modes of transportation. This includes direct impacts on vehicles (e.g. heavy rain reducing tire friction or increased winds overturning heavy goods vehicles) as well as impacts to hard infrastructure (e.g. rail cuttings which may subside causing hazards and costs in repairs). However, there are also potential benefits and positive effects including the reduction of cold weather hazards such as ice and snow, all of which must be considered when ensuring a resilient future transport network, again emphasizing the need for a formal assessment (Jaroszweski et al., 2010).

Andrey et al (2003) show that the relative risk of collisions increases for every type of precipitation event in Canada while Andrey shows that collision rates for those precipitation events not involving snowfall are generally decreasing. McGuirk et al (2009) note that heavy rains also lead to road and railway flooding and mudslides that can further disrupt transportation systems. A similar situation has been reported more recently in Australia, with up to 200 train cancellations per day in the summer of 2009 as extreme heat led to buckling of lines throughout the above ground rail network. Clearly rail infrastructure faces some major challenges globally if these two examples are representative of the issues more generally. Although coastal inundation by global sea-level rise will be a problem for unprotected transportation infrastructure in low lying areas, Gornitz et al (1982) show that the most devastating impacts are likely to be associated with changes in extreme sea levels resulting from the passage of storms in coastal regions, especially as more intense tropical and extra-tropical storms are expected (Love et al., 2010).

3.2 Climate Change and Non-Motorized Transportation

Sidewalks, bike lanes, and trails can all be used for transportation, recreation, and fitness. There are several benefits associated with the development of non-motorized transportation in a society. Some of these advantages are economic, such as increased revenues and jobs for local businesses, and some are non-economic benefits such as reduced congestion, better air quality, safer travel routes, and improved health outcomes. United States is currently experiencing high unemployment rate, unsustainable use of carbon-based energy, and a national obesity epidemic. All three of these problems can be partly addressed through increased walking and cycling. Providing pedestrian and cycling infrastructure for the purposes of commuting, recreation, and fitness, is arguably more important than ever before. In addition, designing and building infrastructure suitable for pedestrian and bicyclists can also alleviate the problem of unemployment, by creating jobs for engineers, construction workers, and workers who produce the asphalt, signs, and other construction materials (Ahmed et al., 2010).

Two factor of temperature and humidity have substantial impacts on the pedestrian volume. Extreme temperatures (very cold or very hot temperatures) decrease pedestrian volume drastically with a non-linear pattern which makes pedestrian travel behavior more complicated. For instance, weather condition is responsible for about 30% of variation of pedestrian volume during noon, or precipitation reduces the volume by 13% and winter weather causes 16% of reduction in the same measure (Ahmed et al., 2010).

There are numerous studies addressing weather condition such as precipitation or changes in temperature on cycling. Both Phung et al (2007) and Richardson (2000) explored how weather variations affect bicycle ridership in Melbourne, Australia. Rain was identified as the most influential weather parameter which significantly decreased commuting cyclist volumes. These two researches, found that rainfall has a non-linear effect. Richardson (2000) identified that daily rainfall of around 8 mm, reduces cyclist volumes by about 50% compared to days when there is no rain. On the other hand, Phung et al (2007) found that light rain (defined as daily rainfall less than 10 mm) prohibit between 8 and 19% of all cyclists from using this mode of transportation while heavy rain (defined as daily rainfall greater than 10 mm) prohibit about one-third more (13 to 25%). Air temperature has been identified to have a non-linear and non-symmetrical relationship with commuter cyclist volume. By reviewing multiple studies in this area, a conclusion can be made that perfect temperature for riding is between 25°C and 28°C.In addition, based on these studies as temperature rises above the perfect temperature, cyclist volume decreases drastically.

Active mode of transportation is the most exposed mode compared to other means of transportation. This makes wind and wind speed another factor that affect walking and cycling behavior. For example, ridership on the Bay Trail, that locates near the coast of Port Phillip Bay, was the most sensitive to wind change. Strong wind (defined as 40-62 kph) reduced the volume of commuter cyclist by between 11 and 23% (Phung and Rose, 2007).

3.3 Mitigation to Climate Change

Mitigation can be defined as strategies, regulations, policies and actions to reduce greenhouse gas emissions (Pew Center on Global Climate Change, 2009). There are different sets of mitigation strategies for different modes of transportation like energy efficiency techniques, land use changes aligned with smart growth, use of renewable energy such as wind, solar, geothermal, or hydropower. There are different mitigation strategies for each mode of transportation.

3.3.1 Road Mitigation

One of the most effective methods of reducing greenhouse gas emissions is encouraging public transport like buses, trains, and active mode of transport (walking and cycling). Increasing the price of car ownership or fuel. Anable et al (2005) stated that a 10% increase in fuel price leads to 1-3% reduction in travel. Also, increase in tolling is another way of encouraging drivers to shift from travelling their own cars to use of public transportation (Chapman, 2007). These sets of strategies will decrease road congestion which is known as one of the reasons of increasing emissions. Another aspect of surface transportation generating CO_2 emissions is freight movement. Dependence of freight transportation on trucks and heavy duty vehicles is one of the factors that exacerbates the environmental condition of this industry. The slow movement of heavy vehicles leads to more congestion which is identified as a reason of increasing emission. According World Business Council for Sustainable Development study on the world mobility and its sustainability, freight movement is responsible for 43% of all the energy consumed in transportation. This proves the importance of mitigation in this area. In recent years, manufacturers have made significant progress in improving vehicles' engine performance and vehicles' design leading to 20% improvement in fuel efficiency of freight movement (Chapman, 2007). Exploiting new routing and scheduling software program is also effective in making freight transport more environmental friendly (McKinnon, 1999).

3.3.2 Air Mitigation

Air transport is the second more pollutant mode of transportation after vehicles using diesel as fuel (Chapman, 2007). One of the most effective way of making aviation more sustainable is through enacting policies in order to increase tax which lead to shift to other modes of transportation that are more sustainable. Use of alternative fuels or low carbon fuels for aircraft can be considered as a mitigation strategy in this area which is improving due to recent technologies.

3.3.3 Other Mitigation Strategies

Shifting the movement of passenger and freight by car and aircraft to other modes of transportation such as ships, buses, rail, and active transportation is one of the methods of mitigation that is widely accepted (Chapman, 2007). Shipping is known as a sustainable mode of good movement especially to overseas. However, shipping can still become more environmental friendly by exploiting modern engines which works with the latest technology, and more efficient hulls. These methods can lower the CO2 emissions by 50%. Rail is considered as one the most sustainable modes of transport. Although encouraging people to use trains and manufacturer to move their products by rail rather than cars will have substantial effect of reducing GHG emissions, is a difficult mission. Active mode of transportation is called zero-carbon transportation. Walking and cycling is not only a mitigation factor but also making society more physically, and psychologically healthy.

3.4 Adaptation to Climate Change

Although mitigation efforts are necessary to decrease the amount of emissions and reduce the rate of global warming and climate change, currently the consequences of years of GHG production during last century is tangible throughout the world. Therefore, to live with these consequences adaptation to different climate change stressors should be done.

Climate change adaptation is defined by the IPCC (2007) "as the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects which moderates harms or exploits beneficial opportunities".

The adaptation process requires significant preparation in regards to the following areas (Pew Center on Global Climate Change, 2009):

- Risk assessment
- Prioritization of projects
- Solution development and implementation
- Information sharing
- Decision-support tools
- Collaboration across agencies, sectors, and geographic boundaries
- Creativity in design
- Funding and allocation of both financial and human resources

An example of an adaptation strategy in response to rising sea level is shore protection. Construction of dikes, bulkheads, and beach nourishment can prevent the impacts of sea level rise such as flooding, eroding beaches, and inundation of low-lying coastal properties. Another adaptation effort against sea level rise is relocating infrastructures instead of investing to the maintenance of existing ones. The adaptation strategy should be selected based on its associated costs and benefits.

3.5 Summary of the Chapter

As Environmental Protection Agency reported, transportation is responsible for about one-third of carbon dioxide emissions in the United States. Also, transportation is responsible for the emissions of other greenhouse gases. Five types of climate change impacts that have the most influence on transportation are increases in very hot days and heat waves, increases in arctic temperatures, rising sea levels, increases in intense precipitation events, and increases in hurricane intensity.

Surface transportation is affected by these climatic stressors in different ways. Sea level rise will cause more frequent interruption of roadway traffic and railroads, and inundation of roads, rail lines and tunnels in low-lying regions. Intense precipitation causes increase in travel time due to congestion. As it was thoroughly explained in this chapter one the most important stressors that affects infrastructure is increase temperature. Also, it has a great influence on travel behavior for different modes of transportation.

Air transportation has a reciprocal relation with climate change meaning that it contributes to the production of greenhouse gases which cause global warming and it is impacted by the consequences of climate change. Climate change has two most important effects on avian transportation. First, it results in damage and deterioration of facilities such as runways. Second, it causes disruption in airport's services due to various weather extremes such as storms. Maritime transportation is another mode that has the same relationship with climate change which is discussed in this chapter.

Non-Motorized transportation or in other word active transportation is defined as walking or cycling. Sidewalks, walkways, bike lanes, and trails can be addressed as facilities for this mode of transport. Climate change has drastic effects on this mode since pedestrian and cyclists are more exposed to weather extremes. Temperature, humidity, and precipitation are identified as weather measures that has the most effects on pedestrian and cyclists' travel behavior.

The practice of reducing the amount of emissions is defined as mitigation. There are different sets of mitigation strategies for different modes of transportation like energy efficiency techniques, land use changes aligned with smart growth, use of renewable energy such as wind, solar, geothermal, or hydropower. In this chapter, a summary of mitigation strategies for road transportation and other modes are provided. Although these strategies will cause reduction in the production of greenhouse gases and alleviate the climate change, the impacts of climate change are already tangible all around the world. Thus, adaptation strategies are required to live with these impacts for example road elevation is one method of surviving against sea level rise. Several adaptation strategies are discussed in this chapter.

Chapter 4

METHODOLOGY

4.1 Identified Climate Change Stressors in the State of Delaware

In this research the three most important climate change stressors that affect surface transportation in general and trail and bike routes in particular are identified. Sea level rise, flooding due to increase in storm surges and more frequent intense precipitation, and increase in mean temperature along with heat waves are climate change stressors that their effects on non-motorized transportation are significant. Since Delaware has a long coastal line and several number of trails and bike routes locate near coast the effect of rising sea level is considerable in this state. Although the other two derivatives of climate change (more frequent flooding, and increased temperature) have their own effects on non-motorized transportation facilities, this research's focus is on the influence of sea level rise on these facilities.

4.2 Descriptions of Analyzed Data

To evaluate future sea level rise risks on transportation infrastructure in Delaware, a Geographic Information System (GIS) was used to perform quantitative spatial analysis. The input data used in the analysis consisted of roadway geospatial data, topographic data, and sea level rise projections.

4.2.1 Trails and Bike Routes Geospatial Data

The geospatial data of existing trails in the state is directly obtained from Delaware Department of Transportation (DelDOT). In this inventory, each trail is associated with an ID. Trail's name, management, county where the trail locates, and type of operation (pedestrian, bicyclists, pedestrian and bicyclists) are provided in the data set. In order to, proceed with the Geographic Information Systems (GIS) analysis geometric attributes of trails such as distance were added to the current inventory.

Bike routes are defined as roadways that are considered safe for bicyclist. The geospatial data of bike routes is obtained from a self-service Enterprise Geographic Information System organization called “Firstmap”. The inventory of bike routes is classified based on the type of roadway which could be statewide, regional, or connector. Statewide bike routes are the ones that that run the length of the State of Delaware from north to south. Regional bike routes run mainly east to west across the state. Finally, connector bike routes connect the regional and statewide bike routes. This inventory was completed by adding geometric attributes of the features.

4.2.2 Topographic Data

A LiDAR-derived digital elevation model (DEM), with a horizontal accuracy of 1 meter, was obtained from the National Oceanic and Atmospheric Administration (NOAA). This digital elevation model (DEM) is a part of a series of DEMs produced for the National Oceanic and Atmospheric Administration Coastal Services Center's Sea Level Rise. The DEMs created for this project were developed using the NOAA National Weather Service's Weather Forecast Office (WFO) boundaries. The DEM includes the best available Lidar known to exist at the time of DEM creation that met project specifications for the Philadelphia WFO, which includes the coastal counties of Delaware. These DEMs serve as source datasets used to derive data to visualize the impacts of inundation resulting from sea level rise along the coastal United States and its territories.

The DEM was used to estimate the elevation of trails and bike routes centerlines throughout the study area. This was done by using a mask operation in

ArcGIS where the DEM raster cells that intersected the trails and bike routes centerline retained their value but all raster cells not intersecting these facilities' centerline were set to NoData. The resulting raster dataset included elevation values only along the centerlines.

4.2.3 Sea Level Rise Projections

As it was thoroughly explained in the literature review, rise of sea level till the end of this century is significant however there are uncertainty around the height of rise because of different reason. For instance, if developing countries start the mitigation process the amount of greenhouse gas emissions produced by different industrial sectors will definitely decrease which have a tremendous positive effect on global warming and climate change. Thus, political decisions can be count as one of the sources of this uncertainty around climate change and sea level rise.

Therefore, National Oceanic and Atmospheric Administration (NOAA) developed a model for sea level rise. In this model three scenarios, low, medium and high are proposed for the sea level rise by 2100. The lowest scenario suggests that there will be 2 (ft) rise in the sea level by the end of this century. The highest scenario which represents the worst situation estimates that there will be 6 (ft) of sea level rise by 2100 and the amount of sea level rise for the medium scenario recommended by NOAA is 4 (ft).

4.3 GIS-Based Analysis

In this research, a GIS model of sea level rise has been developed which include several layers. The inventories containing trails and bike routes in the State of Delaware were imported to the model. The sea level rise model containing three projection developed by NOAA was added to the GIS-based model. By applying the intersection tool of the ArcMap (a GIS platform), the interactions between different layers were identified. In this step of the analysis, number of trails and bike routes that will be affected by three different scenarios of sea level rise.

Each facility is investigated separately. The distance of inundation (distance of trails and bike routes that will be under water) is estimated by the analysis done using ArcMap. The maximum depth of water on each affected facility is determined using the GIS-based analysis. By these two variables (distance of inundation and maximum depth of inundation), a rank is allocated to a facility showing vulnerability of that facility against sea level rise. If the distance of inundation is minor and the maximum depth of water is low for a certain facility, the facility (trail or bike route) can be maintained and saved by a low-cost adaptation strategy. In this situation, the facility acquires a high rank. On other hand, a facility that loses a considerable length due to land inundation and the maximum depth of water is significant needs tremendous budget for adaptation. In this case, the facility will acquire a low ran showing that the management of the facility should allocate considerable funding to save it.

4.4 Vulnerability Assessment

The core goal of this research is assessing the vulnerability of trails and bike routes in the State against different scenarios of sea level rise (low, medium, and high). The assessment is based on two factors: first the distance of the facility that will be under water due to rising sea level, and second the maximum depth of water on each facility. The depth of water is important because the possibility of rehabilitation and maintenance depends on it. Based on these two measures, level of service for each trail under different scenarios is decided. As it was mentioned earlier, the vulnerability assessment of each facility is presented by the suggested level of service under different sea level rise scenarios. The level of service is determined by the following tables based on the inundation mileage of the facility and maximum depth of water on that facility. A facility could obtain a level service A to F based on different measures for different sea level rise scenarios.

The result of this vulnerability assessment can be used by the State DOT or other organizations which are responsible for trails and bike routes management. For example, if a trail's level of service is determined to be F, the management corporation could shut the trail down and invest in building a new trail in a location that will not be in danger of rising sea level.

Table 4.1: Level of service estimation based on depth of water and length of inundation for low SLR scenario

			Inundation Distance (%)					
			0-10	**10-30**	**30-50**	**50-70**	**70-90**	**90-100**
Sea Level Rise Projection	**Low (2ft)**	**Maximum Depth of Water less than 1 (ft)**	LOS A	LOS A	LOS B	LOS D	LOS E	Out of Service
		Maximum Depth of Water More than 1 (ft)	LOS A	LOS B	LOS C	LOS D	LOS F	Out of Service
	Medium (4ft)	**Maximum Depth of Water less than 2 (ft)**	LOS A	LOS B	LOS D	LOS E	LOS F	Out of Service
		Maximum Depth of Water More than 2 (ft)	LOS B	LOS C	LOS D	LOS F	LOS F	Out of Service
	High (6ft)	**Maximum Depth of Water less than 3 (ft)**	LOS A	LOS C	LOS D	LOS F	LOS F	Out of Service
		Maximum Depth of Water More than 3 (ft)	LOS B	LOS C	LOS E	LOS F	LOS F	Out of Service