

Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006.

| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|--------------------------------------|--|--|---|---|
| <i>Temperature Increase</i> | | | | |
| Increased Summer Temperatures | Highway asphalt rutting | | Proper design/construction, milling out ruts, more maintenance, overlay with more rut resistant asphalt | 1) Wooler, Sarah. 2004. 2) Andrey and Mills. 2003. 3) Hass, et al. 2006. 4) Black, William. 1990. 5) Meyers, Michael. 2006. 6) Barrett, et al. 2004. 7) Marbek Resource Consultants Ltd. 2003. 8) Kerr, Andrew, et al. 1999. 9) Warren, et al. 2004. 10) Entek U.K. Limited. 2000. 11) Entek U.K. Limited. 2004. 12) Lockwood, Steve. 2006. 13) Kinsella, Y. and McGuire, E. 2005. 14) Mills and Andrey. 2002. |
| | Rail buckling | Speed restrictions could increase travel time | Speed restrictions, reducing frequency of some services, better air conditioning for signals | 1) Wooler, Sarah. 2004. 2) Eddowes, M.J., et al. 2003. 3) Kerr, Andrew, et al. 1999. 4) Warren, et al. 2004. 5) Entek U.K. Limited. 2000. 6) Land Use Consultants, et al. 2002. 7) Smyth, et al. 2002. 8) Kerr, Andy. 2001. 9) Entek U.K. Limited. 2004. 10) Rossetti. 2002. |
| | More airport runway length and fuel needed because of less dense air | | New planes designed to takeoff more efficiently | 1) Wooler, Sarah. 2004. 2) Andrey and Mills. 2003. 3) Irwin and Johnson. 1990. 4) Warren, et al. 2004. 5) Entek U.K. Limited. 2000. 6) Smyth, et al. 2002. 7) Entek U.K. Limited. 2004. |
| | Heat/Lack of ventilation on London Underground | Overcrowding, failed, or delayed service will only compound the problem. Could cause passengers to avoid taking public transportation (mode shift) | Install better ventilation systems | 1) Wooler, Sarah. 2004. 2) Greater London Authority. 2005. |
| | | | | |

Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)

| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|---|--------------------------------------|---|---|--|
| <i>Temperature Increase (continued)</i> | | | | |
| | Low water levels on inland waterways | Increased shipping costs; shift to other modes (rail, truck) | Changes to navigation, dredging of channels, flow augmentation | 1) Wooler, Sarah. 2004. 2) Andrey and Mills. 2003. 3) Olsen, et al. 2005. 4) Black, William. 1990. 5) Irwin and Johnson. 1990. 6) U.S. Federal Highway Administration Office of Environment and Planning. 1998. 7) U.S. Department of State. 2002. 8) Institute for Water Resources, U.S. Army Corps of Engineers. 2004. 9) Sousounis, Peter J. and Jeanne M. Bisanz, Eds. 2000. 10) National Assessment Synthesis Team. 2000. 11) Marbek Resource Consultants Ltd. 2003. 12) D'Arcy, Pierre. 2004. 13) Warren, et al. 2004. 14) Entek U.K. Limited. 2000. 15) Ministry of Housing, Spatial Planning, and the Environment, The Netherlands. 2001. 16) Ruth, Matthais. 2006. 17) Quinn. 2002. |
| | Thermal expansion of bridges | Frequent detours, traffic disruptions | Increased ongoing maintenance | 1) Cohen, Susan, Soo Hoo, Wendy K., and Sumitani, Megumi. 2005. |
| | Overheating of diesel engines | | Adaptation of cooling systems | 1) Entek U.K. Limited. 2000. |
| | Increased vegetation – leaf fall | Ineffective braking of rail cars, visual obstruction | Vegetation management, plant low-maintenance vegetation as buffer | 1) Wooler, Sarah. 2004. 2) Eddowes, M.J., et al. 2003. 3) Land Use Consultants, et al. 2002. 4) Smyth, et al. 2002. 5) Kerr, Andy. 2001. 6) Entek U.K. Limited. 2004. 7) Kinsella, Y. and McGuire, E. 2005. |
| | Changes to landscape/biodiversity | Highway agency owns many medians. Increased pest management. Impact on wetlands commitments | Different types of vegetation may have to be considered | 1) Wooler, Sarah. 2004. 2) Kinsella, Y. and McGuire, E. 2005. 3) Mortenson and Bank. 2002. |

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| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|---|--|---|---|--|
| <i>Temperature Increase (continued)</i> | | | | |
| Increased Summer Temperature and Decreased Precipitation | Less rain to dilute surface salt may cause steel reinforcing in concrete structures to corrode (Australia) | | Better protect reinforcing in saline environments | 1) Norwell, Gary. 2004. |
| Increased Winter Temperatures | Reduction in cold weather rail maintenance | Fewer broken rails, excessive wheel wear, and frozen switches | | 1) Andrey and Mills. 2002. |
| | Longer construction season | Drier and warmer days | | 1) Andrey and Mills. 2003. 2) Kinsella, Y. and McGuire, E. 2005. |
| Thawing Permafrost (U.S., Canada, China) | Road, rail, airport, pipeline embankments will fail and shallow pile foundations could settle | Potential for fewer construction problems in long run | Crushed rock cooling system, insulation/ground refrigeration systems, rehabilitation, relocation, mechanically stabilize embankments against ground movement, remove permafrost before construction | 1) Instanes et al.. 2005. 2) Brown, Jeff. 2005. 3) Cheng, Guadong. 2005. 4) Hass, et al. 2006. 5) Black, William. 1990. 6) Irwin and Johnson. 1990. 7) U.S. Arctic Research Commission Permafrost Task Force. 2003. 8) Weller, Gunter, et al. 1999. 9) Grondin et al. 2005. 10) Wright, Fred. 2001. 11) Warren, et al. 2004. 12) Ruth, Matthais. 2006. 13) Smith and Levasseur. 2002. 14) Caldwell et al. 2002. |
| Reduction of Freezing Season for Ice Roads (Arctic) | Roads unusable during certain seasons | Shorter shipping season, higher maintenance costs, higher life-cycle costs, seasonal mode shift | Reconstruction of severely damaged infrastructure with less frost-susceptible foundation (geosynthetic barrier), retrofitting road side drains | 1) Instanes et al.. 2005. 2) Lonergan, et al. 1993. 3) Andrey and Mills. 2003. 4) Hass, et al. 2006. 5) Weller, Gunter, et al. 1999. 6) Marbek Resource Consultants Ltd. 2003. 7) Clayton et al. (and Montufar). 2005. 8) Warren, et al. 2004. 9) Lockwood, Steve. 2006. |

Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)

| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|---|---|---|--|--|
| <i>Precipitation Increase</i> | | | | |
| Increased Winter Precipitation – Rain/Snow | Flooding of roads/airport runways/bikeways and walkways (frequency and magnitude will increase) | Infrastructure deterioration (quicker with acid rain), impacts on water quality | Seek alternative routes, improve flood protection, risk assessment for new roads, emergency contingency planning, ensure bridge openings/culverts sufficient to deal with flooding, improve drainage, improved asphalt/concrete mixtures, perform adequate maintenance, and minimize repair backlogs | <ol style="list-style-type: none"> 1) Wooler, Sarah. 2004. 2) Andrey and Mills. 2003. 3) Irwin and Johnson. 1990. 4) U.S. Department of State. 2002. 5) Kirshen, Paul H. and Matthais, Ruth. 2004. 6) Intergovernmental Panel on Climate Change. 2001. 7) Sousounis, Peter J. and Jeanne M. Bisanz, Eds. 2000. 8) Wilkenson, Robert. 2002. 9) Meyers, Michael. 2006. 10) Barrett, et al. 2004. 11) Kerr, Andrew, et al. 1999. 12) Warren, et al. 2004. 13) Entek U.K. Limited. 2000. 14) Land Use Consultants, et al. 2002. 15) Smyth, et al. 2002. 16) Kerr, Andy. 2001. 17) Entek U.K. Limited. 2004. 18) Norwell, Gary. 2004. 19) Kinsella, Y. and McGuire, E. 2005. 20) Rossiter, Lisa. 2004. 21) Smith, Orson. 2006. |
| | Flooding of rails | Service disruption | Engineering solutions | <ol style="list-style-type: none"> 1) Wooler, Sarah. 2004. 2) Irwin and Johnson. 1990. 3) Eddowes, M.J., et al. 2003. 4) Entek U.K. Limited. 2000. 5) Smyth, et al. 2002. |
| | Bridge scour | | Speed restrictions, closure to traffic, new materials, better maintenance | <ol style="list-style-type: none"> 1) Wooler, Sarah. 2004. 2) Hass, et al. 2006. 3) Kirshen, Paul H. and Matthais, Ruth. 2004. 4) Meyers, Michael. 2006. 5) Eddowes, M.J., et al. 2003. 6) Smith, Orson. 2006. |
| | Flooding of underground transit systems | Drowned passengers | Pumping systems | <ol style="list-style-type: none"> 1) Wooler, Sarah. 2004. 2) Zimmerman, 2002a and 2002b. |
| | River flooding | Interruptions of river navigation | | <ol style="list-style-type: none"> 1) Intergovernmental Panel on Climate Change. 2001. 2) Ning, Zhu H., et al. 2003. |

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| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|--|--|-------------------------------------|---|--|
| Precipitation Increase(continued) | | | | |
| Increased Precipitation and Increased Summer Temperatures | Highway, rail, and pipeline embankments at risk of subsidence/ heave | Landslides | Fill cracks and carry out more maintenance | 1) Wooler, Sarah. 2004. 2) Instanes et al.. 2005. 3) Cohen, Susan, Soo Hoo, Wendy K., and Sumitani, Megumi. 2005. 4) Wilkenson, Robert. 2002. 5) Weller, Gunter, et al. 1999. 6) Eddowes, M.J., et al. 2003. 7) Konuk, Ibrahim. 2005. 8) Marbek Resource Consultants Ltd. 2003. 9) Kerr, Andrew, et al. 1999. 10) Warren, et al. 2004. 11) Entek U.K. Limited. 2000. 12) Land Use Consultants, et al. 2002. 13) Smyth, et al. 2002. 14) Entek U.K. Limited. 2004. 15) Kinsella, Y. and McGuire, E. 2005. 16) Rossiter, Lisa. 2004. 17) duVair et al. 2002. |
| | Concrete deterioration | | | 1) Wooler, Sarah. 2004. 2) U.S. Department of State. 2002. |
| | More frequent and larger slush-flow avalanches (Arctic) | | Incorporate potential risk into planning process for new settlements, detection systems, temporary closures | 1) Instanes et al.. 2005. 2) Marbek Resource Consultants Ltd. 2003. 3) Warren, et al. 2004. 4) Stethem, Chris, et al. 2003. |
| | Altered runoff patterns (Arctic) | Disruption of the ice-water balance | | 1) Instanes et al.. 2005. |
| Glacial Melting/Thermal Expansion of Oceans | | | | |
| Sea Level Rise | Erosion of coastal highways | | Construction of sea walls | 1) Wooler, Sarah. 2004. 2) Black, William. 1990. 3) U.S. Federal Highway Administration Office of Environment and Planning. 1998. 4) Marbek Resource Consultants Ltd. 2003. 5) Norwell, Gary. 2004. 6) Kinsella, Y. and McGuire, E. 2005. 7) Ruth, Matthais. 2006. 8) Hyman, William, et al. 1989. 9) Titus, 2002. |

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| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|--|---|-----------------------------------|---|---|
| <i>Glacial Melting/Thermal Expansion of Oceans (continued)</i> | | | | |
| | Higher tides at ports/harbor facilities | | | 1) Wooler, Sarah. 2004. 2) Black, William. 1990. 3) U.S. Department of State. 2002. 4) Kirshen, Paul H. and Matthais, Ruth. 2004. 5) Smyth, et al. 2002. 6) Ministry of Housing, Spatial Planning, and the Environment, The Netherlands. 2001. 7) Caldwell et al. 2002. |
| | Deeper water | Permit greater ship drafts | | 1) Andrey and Mills. 2003. 2) Kerr, Andrew, et al. 1999. 3) Titus. 2002. |
| | Low-level aviation infrastructure at risk | | Relocation or protection of facilities | 1) Andrey and Mills. 2003. 2) Committee on Engineering Implications of Change in Relative Mean Sea Level. 1987. 3) Warren, et al. 2004. 4) Ruth, Matthais. 2006. 5) Hyman, William, et al. 1989. |
| | Less bridge clearance | | | 1) Cohen, Susan, Soo Hoo, Wendy K., and Sumitani, Megumi. 2005. 2) Committee on Engineering Implications of Change in Relative Mean Sea Level. 1987. 3) Norwell, Gary. 2004. 4) Hyman, William, et al. 1989. |
| | | More search and rescue operations | Obtain more vessels with emergency towing capabilities, better weather forecasting, change seasonal classifications of waters around coast, change ship/boat design | 1) Wooler, Sarah. 2004. 2) Marbek Resource Consultants Ltd. 2003. |

Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)

| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|------------------------------|--|---|---|---|
| <i>Storm Activity</i> | | | | |
| Storm Surges | Coastal road flooding | Increased VMT and VHT; increased number of road accidents | Seawalls, build more redundancy into system, support land use policies that discourage development on shoreline, design and material changes, pumping of underpasses, raise roads | 1) Choo, Kristin. 2005. 2) U.S. Federal Highway Administration Office of Environment and Planning. 1998. 3) Intergovernmental Panel on Climate Change. 2001. 4) Suarez, Pablo et Al. 2005. 5) Rosenzweig, Cynthia and Soleki, William. 2001. 6) Wilkenson, Robert. 2002. 7) National Assessment Synthesis Team. 2000. 8) Meyers, Michael. 2006. 9) Committee on Engineering Implications of Change in Relative Mean Sea Level. 1987. 10) Greater London Authority. 2005. |
| | Railway flooding | | Seawalls, raising rails | 1) Black, William. 1990. 2) Committee on Engineering Implications of Change in Relative Mean Sea Level. 1987. 3) Kerr, Andrew, et al. 1999. 4) Greater London Authority. 2005. |
| | Subway flooding | | Flood barriers | 1) Choo, Kristin. 2005. 2) Black, William. 1990. 3) Greater London Authority. 2005. 4) Ruth, Matthais. 2006. 5) Zimmerman, 2002. |
| | Port flooding/damage | | Reduce “cope” level at ports to reduce likelihood of water flowing across docks; construct flood defense mechanisms | 1) ABP Marine Environmental Research Ltd 2004. 2) Committee on Engineering Implications of Change in Relative Mean Sea Level. 1987. 3) Entek U.K. Limited. 2000. 4) Land Use Consultants, et al. 2002. |
| | | | Closures of roads, railways, airports; emergency evacuations | 1) Instanes et al.. 2005. 2) Smyth, et al. 2002. 3) Ruth, Matthais. 2006. |
| | Damage to seaports/airports | Travel delays | | 1) Intergovernmental Panel on Climate Change. 2001. |
| Increased Wind Speeds | Bridges, signs, overhead cables, tall structures at risk | | Design structures for more turbulent wind conditions, build with better material, use “smart” technologies to detect abnormal events | 1) Wooler, Sarah. 2004. 2) Meyers, Michael. 2006. 3) Eddowes, M.J., et al. 2003. 4) Kerr, Andrew, et al. 1999. 5) Kerr, Andy. 2001. 6) Kinsella, Y. and McGuire, E. 2005. |

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| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|--|---|---|--|---|
| <i>Storm Activity (continued)</i> | | | | |
| Lightning/Electrical Disturbance | Disruption to transportation electronic infrastructure, signaling, etc. | Unknown | Unknown | 1) Wooler, Sarah. 2004. 2) Eddowes, M.J., et al. 2003. |
| Fewer Winter Storms | Less snow/ice for all modes | Improved mobility/safety, reduced maintenance costs, less pollution from salt, decrease in vehicle corrosion | | 1) Andrey and Mills. 2003. 2) Black, William. 1990. 3) Irwin and Johnson. 1990. 4) Intergovernmental Panel on Climate Change. 2001. 5) Barrett, et al. 2004. 6) Marbek Resource Consultants Ltd. 2003. 7) Kerr, Andrew, et al. 1999. 8) Warren, et al. 2004. 9) Entek U.K. Limited. 2000. 10) Land Use Consultants, et al. 2002. 11) Entek U.K. Limited. 2004. 12) Wooler, Sarah. 2004. 13) Kinsella, Y. and McGuire, E. 2005. 14) Hyman, William, et al. 1989. 15) Pisano et al. 2002. |
| <i>Ice Melting</i> | | | | |
| Reduced Ice Cover (Canada, Alaska, Great Lakes) | Reduced ice loading on structures, such as bridges or piers | | | 1) Instanes et al.. 2005. |
| | New northern shipping routes | Shorten shipping distance and delivery time, security concerns, environmental risks, law-diplomacy issues, Inuit unease | Develop a "transit management regime" for area | 1) Instanes et al.. 2005. 2) Johnston, Douglas. 2002. 3) Brigham, Lawson and Ben Ellis, Eds. 2004. 4) Office of Naval Research, Naval Ice Center, Oceanographer of the Navy. 2001. 5) National Assessment Synthesis Team. 2000. 6) Marbek Resource Consultants Ltd. 2003. 7) Warren, et al. 2004. 8) Smith and Levasseur. 2002. 9) Caldwell et al. 2002. |
| | | Lengthened season for float planes | | 1) Black, William. 1990. 2) Irwin and Johnson. 1990. |

Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)

| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|---|---|-----------------------------|--|---|
| <i>Ice Melting (continued)</i> | | | | |
| | | Longer shipping season | | 1) Wooler, Sarah. 2004. 2) Andrey and Mills. 2003. 3) Black, William. 1990. 4) Irwin and Johnson. 1990. 5) U.S. Federal Highway Administration Office of Environment and Planning. 1998. 6) Sousounis, Peter J. and Jeanne M. Bisanz, Eds. 2000. 7) National Assessment Synthesis Team. 2000. 8) Warren, et al. 2004. 9) Ruth, Matthais. 2006. 10) Caldwell et al. 2002. |
| | Multi-year ice, in low concentrations, will be hazard to ships and naval submarines | | New ship/submarine design or modifications | 1) Brigham, Lawson and Ben Ellis, Eds. 2004. 2) Office of Naval Research, Naval Ice Center, Oceanographer of the Navy. 2001. |
| Earlier River Ice Breakup (U.S., Canada) | Ice-jam flooding risk | | | 1) Instanes et al.. 2005. 2) Hass, et al. 2006. 3) Smith and Levasseur. 2002. |