# WINTER OPERATION OF ROAD TUNNELS IN QUÉBEC
# THE VILLE-MARIE AND LOUIS-HIPPOLYTE–LAFONTAINE TUNNELS

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## ABSTRACT

In Montreal, approximately 10 km of urban highway passes through tunnels such as the Louis-Hippolyte–Lafontaine Tunnel, which runs under the St. Lawrence Seaway, and the Ville-Marie and Viger Tunnel, an underground interchange that passes through the heart of downtown Montreal. These tunnels, built in the 1960s and 1970s, allow road users to circulate safely and comfortably in a well-lit, scrupulously monitored environment that is sheltered from harsh weather conditions such as snowstorms, freezing rain, strong winds and blowing snow. However, the operation of such tunnels in a northern environment, surrounded by a significant water table and subject to severe weather conditions (major fluctuations and intense cold), poses many operational challenges, and requires a wide range of extra equipment that is not found in other road tunnels. This equipment must be kept operational and periodically maintained.

The case of the Ville-Marie and Louis-Hippolyte–Lafontaine tunnels will be used to illustrate problems related to the winter management of tunnels and their various systems. First, we will provide a description of the equipment and methods needed to maintain an optimal level of safety in the winter operation of the tunnels and their systems. The winter management of a tunnel will be also described. We will discuss standard winter maintenance activities, inspection procedures for the various systems, and all questions related to the logistics of icicle removal interventions, with all the inconveniences this can cause in terms of traffic flow. Second, we will present a number of problems related to the winter operation of tunnels, and we will be discussing the corrective measures implemented. The presence of a significant water table generates considerable water infiltration, and adds to the operating problems by causing the formation of ice patches on the roadway and icicles on the tunnel roof and walls, especially around expansion joints. One of the solutions that has been implemented is the use of reaming techniques and repairing connections under the curbs, which has yielded very encouraging results.

## KEYWORDS

ROAD TUNNEL / OPERATION / MAINTENANCE / WINTER / INFILTRATION / DRAINAGE / ICE / ICICLE / EXPANSION JOINTS

## 1. BACKGROUND

Without a doubt, the Ville-Marie and Louis-Hippolyte–Lafontaine tunnels represent the most significant accomplishments in Québec in terms of constructing concrete engineering structures. They have made it possible to ensure the mobility of hundreds of thousands of motorists in the Montréal Metropolitan Area. Infrastructures of this scale require continuous efforts to ensure user safety, efficient operation, and periodic maintenance. Two control posts dedicated exclusively to these tunnels provide continuous remote surveillance of the traffic lanes and control the various electromechanical systems, such as ventilation, pumping, lighting, the electrical power supply, incident detection, and alarms indicating extreme temperatures and the condition of equipment.

Every year, Montréal is plunged into winter with the arrival of the first snowfall, experiencing typical monthly temperatures ranging from -6.3°C to -10.2°C (Table 1), with frequent extremes as low as -25 °C in January and February. In addition, we have experienced wider ranges between the daily highs and lows during the last six (6) years, with the highs often reaching the freezing point, which causes freeze-thaw cycles and the resulting formation of icicles in the tunnels.

*Table 1. Normal temperatures and record extremes (Montréal, 1971-2000)*

| | Dec. | Jan. | Feb. | March |
|---|---|---|---|---|
| Normal maximum temperature (°C) | -2.2 | -5.7 | -3.9 | 2.2 |
| Normal minimum temperature (°C) | -10.4 | -14.7 | -12.9 | -6.7 |
| Normal mean temperature (°C) | -6.3 | -10.2 | -8.4 | -2.3 |
| Days with maximum ≤ -15°C | 8 | 14 | 11 | 2 |
| Consecutive days with maximum ≤ -15°C | 5 | 6 | 10 | 2 |
| Days with minimum ≤ -20°C (record) | 15 | 19 | 14 | 6 |
| Consecutive days with minimum ≤ -20°C | 7 | 11 | 11 | 6 |

*Source: Centre de ressources en impacts et adaptation au climat et à ses changements [Resource centre on climate and climate change impacts and adaptation]*

These conditions, combined with mean annual accumulations of approximately 200 cm of snow (Table 2), represent a constant challenge for maintaining the road network, and especially for winter management of a tunnel and its various systems and equipment, in a context that more closely resembles an industrial manufacturing plant operating in extreme climate conditions than a roadway segment that requires snow removal.

*Table 2. Normal precipitation and record extremes (Montréal, 1971-2000)*

| | Dec. | Jan. | Feb. | March |
|---|---|---|---|---|
| Normal rainfall (mm) | 35.1 | 27.2 | 19.8 | 35.8 |
| Normal snowfall (cm) | 48.3 | 52.5 | 43.3 | 36 |
| Normal total precipitation (mm) | 81.3 | 78.3 | 61.5 | 73.6 |
| Maximum 24-hour snowfall (cm) | 30.5 | 37.8 | 35.8 | 39.4 |
| Maximum 48-hour snowfall (cm) | 41.9 | 52.8 | 39.4 | 57.9 |
| Maximum 72-hour snowfall (cm) | 1.9 | 58.9 | 45 | 57.9 |

*Source: Centre de ressources en impacts et adaptation au climat et à ses changements [Resource centre on climate and climate change impacts and adaptation]*

The Louis-Hippolyte–Lafontaine tunnel opened in March 1967. It is the older of the two tunnels, and runs beneath the St. Lawrence River. It is a 1.8-km long underwater gallery comprising 7 concrete components that were built in dry dock and then towed, submerged, and assembled on the riverbed. The tunnel consists of two (2) traffic tubes with three lanes each and a central section that is used for services and rescue purposes.

The Ville-Marie Viger tunnel complex is more recent. It is a concrete structure that was constructed in a trench in an ancient riverbed, and subsequently covered over. It entered into operation in several stages: the Ville-Marie tunnel in 1974; the Viger tunnel in 1986; and more recently, three buildings that comprise the Quartier international de Montréal were constructed in 2002 and 2003. The complex now constitutes an underground freeway interchange totalling 6.8 km of traffic tubes varying from one to five traffic lanes, along with several kilometres of evacuation corridors that criss-cross underground Montréal.

*(a) Dry dock at the Lafontaine Tunnel* *(b) Trench at the Ville-Marie Tunnel*

*Figure 1. Construction sites for the Lafontaine and Ville-Marie tunnels*

In recent years, we have observed that intense cold spells are becoming less common, winter warm spells are more frequent, and although they are less frequent, winter storms have become more severe. These observations are in keeping with the principles set out in climate change predictions. These new meteorological conditions complicate winter management of road tunnels and contribute to accelerated wear and tear on the systems. More frequent freeze-thaw cycles intensify the process of water infiltration resulting from deformation of expansion joints and the formation of icicles and ice patches. On the one hand, these situations represent a risk for users, and on the other hand, they contribute to damaging the ceramic tiles that line the walls of the tunnels, exposing bare concrete. In addition, the expected increase in precipitation levels will necessitate increased use of road salts, with the ensuing environmental impacts.

## 2. ROAD TUNNEL EQUIPMENT (MAINTENANCE AND DURABILITY)

Tunnels are considered to be road infrastructures, consisting of asphalt pavement along with structural and drainage components, but they are also complex industrial installations, with hundreds of systems and sub-systems that must operate under extreme weather conditions. This is particularly true of the mechanical and hydraulic systems (fans, motorized louvers, pumps, motorized valves, compressors, elevators, hoists, winches, etc.), the electrical and electronic systems (circuit breakers, isolating switches, cables, generators, batteries, UPS systems, motors, transformers), the lighting and dynamic signalling systems (traffic lights, variable message signs, illuminated signs), the heating systems (heating cables, coils, radiators, thermostats), and the surveillance and safety systems (cameras, fire protection, gas detectors, telephones).

Some systems, specifically including electronic equipment, are very sensitive to such an aggressive and corrosive environment, and require particular attention. Others systems are better suited to tunnels in a northern environment, where they are exposed to extreme winter temperatures.

In order to prevent freezing, the water-supply lines for the fire-protection system, the gutter expansion joints, the wall drains, the drains under the pavement, and the various trenches and culverts are heated by electrical cables to prevent ice clogging and promote drainage. Rigid copper cables encased in a plastic material are used in the Louis-Hippolyte–

Lafontaine tunnel. The heating cables in the Ville-Marie Viger tunnel are made of neoprene covered with a rubber material. These have proven to be less resistant than expected, and in some cases, have been replaced by the same type that is used in the Louis-Hippolyte–Lafontaine tunnel. The heating cables serve as a partial mitigation measure for the problem of icicle formation, which is mainly caused by infiltration through the expansion joints, especially specific joints that have been known to be susceptible to this since the tunnels were opened. In addition, all of the fire cabinets have heaters in order to prevent freezing of the fire protection equipment, including the valves, ducts, extinguishers, and other equipment, such as extinguishing foam for hydrocarbons. This equipment is constantly monitored by temperature sensors, which trigger alarms when necessary. In February 2009, a defective heating cable caused water to freeze in a drain under the pavement, resulting in damage to the foundations and the formation of a hump in the pavement, which necessitated intermittent closure of the traffic lanes for almost two weeks.

A large number of equipment items are installed in the tunnels for the purpose of remote surveillance and monitoring. In addition to detection equipment, including sampling gas analyzers, there are surveillance cameras installed in pressurized climate-controlled housings in order to prevent contamination by salt spray. The most recent cameras even have washer-wiper systems.

With respect to static and dynamic traffic signals, such as lane signals, illuminated signs, and variable message signs, the gradual introduction of LED (light emitting diode) technology has allowed us to improve the visibility of signals in winter conditions. This same technology could also be used for lighting traffic lanes and evacuation corridors in the tunnels, replacing the sodium lamps that are currently in use. In addition to reducing costs, LED lighting allows for the adjustment of illumination levels at the tunnel entrances at night or during storms that cause reduced visibility. Finally, the major advantage of LED lighting arises from the service life of the equipment (four times longer than conventional lamps), with the key factors being lower maintenance costs and a reduced number of outages.

## 3. WINTER MAINTENANCE ACTIVITIES

In general, there are two types of road maintenance in Québec: summer maintenance and winter maintenance. In addition to the seasonal distinction, the summer maintenance refers to routine and periodic maintenance of a preventive nature, while winter maintenance refers to all winter maintenance activities. These activities are required in order to keep roadways clear and safe following weather disruptions, including snowstorms or extreme temperatures that reduce tire grip. Although primarily preventive in nature, routine maintenance can also include a remedial component involving minor repairs or replacing equipment.

In tunnels, summer-type maintenance is carried throughout the year. Much of this work is cyclical and repetitive. The methods, tools, and intervention frequencies vary as a function of a number of factors, including winter maintenance activities and weather conditions.

The purpose of the preventive maintenance program is to ensure the safety of users by keeping the tunnels and their systems at their planned safety level and in compliance with design standards. The various activities include the following:

- Cleaning (walls, signalling devices, light standards, drainage, cameras, etc.);

- Replacing parts (lamps, filters, and other hardware);
- Changing fluids (motors, pumps, fans);
- Lubricating and tightening connections (motors, louvers, vents, etc.);
- Calibrating sensors and alarm levels (detection, probes, etc.)

in the context of urban tunnels in a northern environment, the challenges that must be met are numerous and of greater complexity, because these tunnels are used very heavily and are exposed to very difficult conditions, including an aggressive road environment and extreme temperatures within the humid environment that is characteristic of underground locations.

In light of the fact that these are urban tunnels, every intervention has a major impact on traffic flow. As a mitigation measure, work is scheduled during off-peak hours. In addition, taking into account the particular context of visibility in tunnels, work can only be carried out when the traffic tube is completely or partially blocked over its entire length, because lane changes are not permitted inside the traffic tube.

In winter, these maintenance activities are required at extremely variable intervals. The logistics and intervention methods required are quite different from those during the summer. For example, wall cleaning cannot be carried out using a brush-truck, because these vehicles are taken off the road from December to March. When there is a warm spell, the walls, the signage, and the traffic signals are cleaned manually or using a water jet (Figure 2).


(a) Cleaning the signage


(b) Cleaning lane signals

*Figure 2. Cleaning in the Ville-Marie tunnel using a water jet in winter*

The main goal of winter maintenance in tunnels is to restore the safety level road of the road in the tunnel and its approaches after a specific meteorological event (mild weather or intense cold) or after a major storm. The constraints imposed by the impact on traffic are significant. However, the urgency of these interventions means that they must be carried out quickly. Among other things, this applies to the following activities:

- Snow and ice removal at tunnel entrances;
- Removal and hauling of snow at the portals; and
- Removal of icicles and ice patches resulting from infiltrations.

Snow and ice removal operations are initiated on the basis of monitoring weather conditions and forecasts. During precipitation events, performance criteria specify a maximum tolerance of 5 to 7 cm of snow. Traffic lanes must be completely cleared within 3 to 5 hours after the end of the precipitation event. Tunnel entrances and exits are critical areas that require special attention (Figure 3). When precipitation is heavy, these zones represent areas of sudden change in terms of both visibility and road surface conditions (snow accumulation). In light of this, these areas receive particular attention in terms of snow removal and salt spreading. The use of abrasives (e.g.: sand) is no longer allowed inside tunnels. Experience has shown that sand blocks the drainage system and impacts the visibility inside tunnels and through the cameras, which affects user safety.

*(a) Accumulation of snow at the portal* *(b) Snow and ice removal inside a tunnel*

*Figure 3. Winter maintenance in the Ville-Marie tunnel*


*(a) Accumulation of snow at the entrance* *(b) Snow removal at the exit*

*Figure 4. Winter maintenance in the Louis-Hippolyte–Lafontaine tunnel*

Removal and hauling of snow at tunnel portals is carried out after the storm, and requires the complete closure of the tunnel. This operation has a substantial impact on the free traffic flow of the Metropolitan area and is carried during the night on the day after a storm (Figure 4). It involves picking up the snow that has accumulated at the entrances, because tunnels do not have any space to contain the accumulation of snow at the portals. With this in mind, it would be quite beneficial to plan for such a space at entrances during the design stage for tunnels in northern environments.

Finally, monitoring and removal of icicles and ice patches resulting from infiltrations is an operation that is carried out on a continuous basis, governed by clearly defined intervention criteria. The Louis-Hippolyte–Lafontaine tunnel is inspected at 1:00 a.m. and 1:00 p.m. every day. In order to facilitate this inspection to ensure the absence of icicles, one or two lanes are blocked in mobile roadwork mode. There is only one daily inspection At the Ville-Marie Viger tunnel, at 1:00 a.m. If icicles or ice patches on the pavement are detected, a team is mobilized in order to intervene as soon as possible and ideally before the morning rush hour, which starts around 5:00 a.m., or the evening rush hour, which starts around 3:30 p.m. This urgent intervention often has a major impact on traffic. However, "operation icicles" is widely known and well understood by both the media and the public.

*(a) Ice patches on pavement* *(b) Removal of icicles*

*Figure 5. Formation and removal of ice in tunnels*

## 4. REHABILITATION AND REMEDIAL MAINTENANCE OF THE DRAINAGE SYSTEM

Significant leakage has developed due to the aging of the tunnels and the intense hydraulic pressure that they are subjected to. This leakage damages the tunnel structure and hinders use of the tunnel due to the formation of icicles. These phenomena are caused by a range of factors, which vary from one tunnel to the next:

- Leaking of construction joints and cast joints.
- Poor quality concrete, resulting in honeycombing.
- The formation of microcracks in the slabs and walls.
- Contraction of concrete caused by low temperatures (freeze-thaw cycle).
- The presence of a significant water table.

Beginning with the first years of operation, efforts have been made to stop the leakage at the source and to maximize the water-tightness of the tunnels.

### *a. Joint Injection Campaigns*

Less than 1 year after the Louis-Hippolyte-La Fontaine tunnel opened, a letter from its designers reported leakage of water in joints running perpendicular to the tunnel’s axis, particularly at the last two special joints. These joints had been concreted in the springtime, rather than in the winter, altering the tunnel’s stress environment and producing tension in the joints during winter cold spells. The joints had originally been designed to permit movement without leakage. To prevent such leakage, a chemical substance that swells on contact with water was injected during the winter, while the joint was under maximum tension. Over the past three years, encouraging results have been observed, with a substantial decrease in leakage from the joints. The remainder of the water is drained off into culverts that are heated by electric cables. Although the issues of ice accumulation and icicle formation persist, they have been reduced significantly.

Similar problems were encountered in the Ville-Marie tunnel. The slightest imperfection in the concrete or the manner in which sealants were installed results in sweating or slight leakage. A number of campaigns were carried out to inject cement and polyurethane grout starting in the first few years of operation. These injection methods yielded only partial and temporary results. Repeated freezes combined with the quality of the concrete resulted in the development of microcracks, which spread over time, permitting additional leakage. In light of this, another solution was considered and adopted. Rather than trying to stop the leakage, this water was redirected to the drainage system, conditional upon the tunnel maintaining its full design capacity in terms of hydraulics.

### *b. Drainage Rehabilitation Campaigns*

A 2005 inspection of the drainage system for the Ville-Marie tunnel revealed that many of its pipes were blocked. This blockage ranged from 15% to 97% in the 150 mm pipes (Figure 6). Stagnant water mixing with accumulated sediment creates a sludge that ultimately hardens and blocks the drains.

*(a) 55% blocked drain* *(b) 97% blocked drain*

*Figure 6. Sediment adhering to the walls of drainage pipes*

A study of samples taken from these deposits reveals that the obstructions consist of 64% calcium carbonate and 19% silica. These deposits are generated by a chemical reaction that releases minerals from the water when exposed to heat from the heating cables. The presence of silica explains the hardness of the deposits on the drain walls, and why it is so difficult to remove these deposits using conventional methods.

As the tunnels have aged, annual maintenance using pressurized water trucks (up to 20,000 kPa of pressure) was no longer sufficient to clear these deposits and keep the drainage system working. The magnitude of the obstructions suggested that, if a method were found to restore the design hydraulic pressure in the tunnel, much of the leakage would be adsorbed, and the formation of icicles would be eliminated. A non-structural reaming process was used to rehabilitate the drains in the Ville-Marie tunnel following tests on a few drains that yielded conclusive results (Figure 7).


(a) Reaming Nozzle with Chain Head

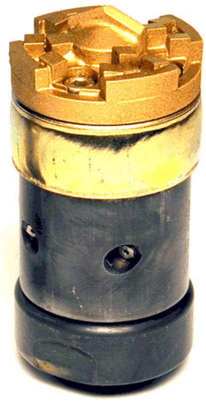
(b) Reaming Nozzle with Cutting Head

*Figure 7. Selected Reaming Technique*

The selected reaming technique employs heads that are driven longitudinally and vertically by water. The longitudinal jet of water propels the head forward, while the transverse jet propels it at an angle, producing rotation that enables the teeth to dislodge deposits and enables the chains (Figure 7a) to deploy radially in order to restore the initial diameter of the drain. In the case of harder deposits, such as concrete residues that have set, a reaming nozzle with a cutting head (Figure 7b) is used to bore a passage in the appropriate pipe. Once the passage has been bored, the reaming nozzle with the chain head is used to remove the deposits from the walls. Reaming time varies considerably from one pipe to another, depending on the length of the pipe, the percentage of obstruction, and the hardness of deposits. An inspection camera is vital for determining the type of obstruction and selecting the appropriate head.

Overall results have been conclusive. The reaming and drilling of the drains, combined with connections under the curbs, has restored the original hydraulic capacity in the Ville-Marie tunnel. Work to inject chemicals into problematic joints continues at the Louis-Hippolyte-La Fontaine tunnel. We have begun to see encouraging results over the past two years, with a significant decrease in leakage through the joints. The remainder of the water is drained off into culverts that are heated by electric cables. Although the issues of ice accumulation and icicle formation persist, they have been reduced significantly.

## 5. CONCLUSION AND RECOMMENDATION

This article discusses the complexity of winter maintenance activities in urban road tunnels. These activities are strategic and critical in terms of road safety, and they entail a number of problems and challenges.

- electronic systems are sensitive to the aggressive winter conditions;
- heavy duty systems and regular cleaning and maintenance required;
- maintenance requires interruption of the traffic with resulting impact;
- winter cleaning is dependent of the temperatures and the weather;
- use of abrasives blocks the drainage systems and impacts visibility;
- removal of icicles and hauling of snow at the portals is a critical activity.

The systems and sub-systems that are installed in tunnels were described. Many of them are affected by aggressive winter conditions, which reduce their service life and necessitate heavier-duty installations that feature a certain degree of resistance to environmental conditions.

The monitoring activities involving low-temperature alarms were presented. These alarms are critical to maintaining the functionality of the drainage and fire-protection systems. We also described the constraints that affect the carrying out of winter maintenance activities that require blocking traffic and that can sometimes have a serious impact on traffic flow, including snow or ice clearing and snow or icicle removal operations. The methods used to clean tunnel walls and signalling equipment at temperatures below freezing were also presented.

Curative maintenance by joint injection with cement and polyurethane, gave encouraging results in restraining infiltration in La Fontaine Tunnel.

Finally, although the tunnel drainage systems are designed to capture surface and seepage water, the aging of the structure and the obstruction of some pipes by ice and deposit build-ups cause recurring problems. Annual maintenance using pressurized water trucks is no longer sufficient to keep the drainage system working. One of the solutions that were implemented is the use of reaming techniques and repairing connections under the curbs, which has yielded very encouraging results.

In order to avoid more problems in the future, we must change our philosophy with respect to the design of underground structures. The design should entail control and drainage of water outside of the tunnel. Construction joints must be made more watertight, and the materials used must be more impervious and resistant to temperature fluctuations. The use of heavier-duty waterproof membranes or the injection of sealing materials into the fill should be explored.

In terms of winter maintenance, other de-icing materials, then sand and salt, should be explored and regular cleaning and reaming of pipes should be performed, as well as sediment pumping.

## BIBLIOGRAPHIC REFERENCES

DEBS, A., 2009. « Tunnel Management in Quebec - Inspection, Maintenance, Operation and Safety Management in the Ville-Marie and La Fontaine Tunnels », Transport Research Board (TRB), Annual TRB Conference, Washington DC (USA), January 2009.

DEBS, A. & Co., 2008. « Water Infiltration and Ice Formation in tunnels », AIPCR-Québec Road Tunnel Symposium, Workshop 3, Montreal (Quebec), October 2008.

FREIHOLTZ, B., 2008. « Water Infiltration and Ice Formation from the Swedish and Nordic Countries Perspective », AIPCR-Québec Road Tunnel Symposium, Workshop 3, Montreal (Quebec), October 2008.

NORSTRÖM, E., 2008. « Water Infiltration and Ice Problems in Tunnels, the Norwegian Way of Ice and Frost Insulation », AIPCR-Québec Road Tunnel Symposium, Workshop 3, Montreal (Quebec), October 2008.

VIGER, G., 2007, « Infiltration d'eau et formation de glaçons dans le tunnel Ville-Marie », Final Study Project, École des technologies supérieurs, November 2007.

LINTEAU, R., 2006. « Réhabilitation du système de drainage du tunnel Ville-Marie », Ministère des transports du Québec, Montréal (Québec), November 2006.

PALARDY, D., 2004. « Investigation des joints 6/7 et 7/8 du tunnel Louis-Hippolyte-La Fontaine », Rapport client, SNC-Lavalin, Montréal (Québec), 2002.

BALLIVY G. & Co., 2002. «Évaluation de l'état des joints du pont-tunnel Louis-Hippolyte-Lafontaine à l'aide d'essais non-destructifs », Groupe de Recherche sur l'Auscultation des Infrastructures (GRSAI), Université de Sherbrooke, Québec, September 2002.

DEBS, A., 2002. « Gestion et exploitation des tunnels Ville-Marie et Louis-Hippolyte-La Fontaine », Routes et Transports, vol. 31, no 1, AQTR, Montréal (Québec), Winter 2002.