A DMAIC-based methodology for improving urban traffic quality with application for city of Montreal

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Abstract: Traffic congestion is a severe problem in cities. Drivers spend hours going through the traffic. This results not only in driver fatigue but also vehicular emissions, noise and pollutants into the environment. Controlling the situation of congestion in cities is of vital importance to city transport organisations and traffic decision-makers. In this paper, we propose a DMAIC-based methodology for improving the quality of urban traffic. The proposed methodology comprises of three steps. In Step 1, we conduct a survey study to collect traffic congestion data in the city. In Step 2, DMAIC methodology is applied to analyse the survey data collected from Step 1. The techniques used are Descriptive statistics, Pareto analysis, Cause–Effect Diagram, Factor Analysis, and Control Charts (Individual and Multivariate). In the third step, we generate recommendations for reducing traffic congestion and ameliorating transportation service quality in cities based on results of Steps 1 and 2. The proposed work is novel and has practical applicability in managing the situation of traffic congestion in cities. An application of the proposed approach for city of Montreal is provided.

Keywords: traffic congestion; DMAIC; critical to quality; factor analysis; cause and effect diagram; control charts; six sigma.


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Anjali Awasthi is currently working as an Associate Professor at Concordia Institute for Information Systems Engineering (CIIESE), in Concordia University, Montreal. She received a PhD in industrial engineering and automation from INRIA Rocquencourt & University of Metz, France. She has several years of industry and research experience in areas of automated transportation, sustainable mobility solutions, city logistics and applied
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operations research. She is the author of several journal and conference papers on these topics. She is also a senior member of American Society for Quality (ASQ) and co-counsellor for its Montreal universities student branch.

1 Introduction

Congestion is a commonly occurring phenomenon in modern cities. Sustained rapid urbanisation and social activities have led to high levels of traffic congestion in cities. This is becoming of great concern to government and private organisations, especially in centralised metropolis. Traffic congestion has been defined in several ways. Transport planners define the occurrence of congestion as a phenomenon resulting whenever a volume of traffic or modal split generates demand for space greater than the available road capacity. The general public perceives congestion in terms of level of service which can be described in terms of average travel speed, delays encountered during travel, etc. Thresholds of acceptability are set for these measures and exceeding these thresholds results in congestion (Laetz, 1990). A number of circumstances cause or aggravate congestion. It may result due to reduction of capacity of a road at a given point or over a certain length, or increase in the number of vehicles with respect to road capacity. About half of traffic congestion occurring in modern cities is recurring, and result of growing volumes of traffic; most of the rest can be attributed to traffic incidents, road works and weather events. Speed and flow can also impact network capacity leading to congestion (Cambridge Systematics, 2005; LaPlante, 2007).

City of Montreal, ranked as the sixth largest city overall across Canada and the USA, has a well-established transportation network including three Trans-Canada highways, four major highways and six second highways (Figure 1). The island of Montreal is a hub for the Quebec Autoroute system, and is served by Quebec Autoroutes A-10 (known as the Bonaventure Expressway on the island of Montreal), A-15 (aka the Decarie Expressway south of the A-40 and the Laurentian Autoroute to the north of it), A-13 (aka Autoroute Chomedey), A-20, A-25, A-40 (part of the Trans-Canada Highway system, and known as ‘The Metropolitan’ or simply ‘The Met’ in its elevated mid-town section), A-520 and A-720 (aka the Ville-Marie Autoroute). Many of these Autoroutes are frequently congested at rush hour. To alleviate congestion, government has put in place several measures. One such example is the extension of Quebec Autoroute 30 on Montreal’s south shore, which will serve as a bypass (Transports Québec, 2008). As the requirement of economic development and immigration population is expanding in Montreal, to keep the transportation system work effectively will be a challenge.

In Montreal, several studies on traffic congestion have been carried by MTQ (Gouvril and Joubert, 2004; Les Conseillers ADEC Inc., 2009). According to their report, traffic congestion is widely present in roads in Montreal region. Figure 2 shows the situation in 1998 and Figure 3 shows the situation in 2003. It can be seen from Figures 2 and 3 that this problem is still severe with traffic congestion growing over years, even though the government has implemented many countermeasures to reduce congestion. Therefore, it is necessary that we should review this problem and explore a new attempt to improve it.
Figure 1  Transportation network in Montreal

Figure 2  Congestion roads during 6:00–9:00 am in Montreal Region (1998) (see online version for colours)
In literature, several metrics have been proposed to measure traffic congestion, namely roadway Level of Service (LOS), average traffic speed, and average congestion delay compared with free-flowing traffic (Litman, 2001; Litman, 2009; TRB, 1997), etc. Laetz (1990) proposed six measures for measuring level of service, namely (1) traffic density, (2) average travel speed, (3) maximum service flow rate, (4) a ratio of traffic volume to road capacity (V/C), (5) average daily traffic volume, and (6) daily vehicle miles of travel. Service levels are based on an ordinal scale ranging from A to F, with level of service A representing the best operating conditions of free-flowing traffic and level of service F representing the worst condition of a breakdown in traffic flow. In this paper, we will evaluate congestion in terms of the waiting times or delays experienced by the drivers/users while travelling on roads. Four levels of congestion are considered, namely ‘No congestion’ (that is 0–6 minutes jam in 1 hour driving), ‘Slight Congestion’ (7–15 minutes jam in 1 hour driving), ‘Moderate Congestion’ (16–30 minutes jam in 1 hour driving), and ‘Extreme Congestion’ (>31 minutes jam in 1 hour driving).

The rest of the paper is organised as follows. In Section 2, we present the problem definition. Section 3 presents the solution approach. In Section 4, we present application of the proposed approach on city of Montreal. Finally in Section 5, we present the conclusions and future work.

2 Problem definition

Traffic congestion is a severe problem in cities. Drivers spend several hours a day passing through congested roads of the city. With the rise in the number of vehicles that are expected to occupy city roads over the coming years, the problem is going to become
even more complex. It is a constant challenge before the city administrations, public and private transport organisations to control congestion in cities to improve travel conditions, reduce waiting times, conserve fuel and minimise the impact of vehicular emissions on city residents and their environment.


During the literature review, we found that most of these studies are qualitative in nature and provide general solutions for alleviating congestion. The use of historical data for generating customised solutions based on congestion situation of the city on a real-time basis is lacking. In this paper, our focus is to investigate the problem from a statistical point of view and propose a solution approach that allows monitoring and control of traffic congestion on a real-time basis. The goal is to continually improve the traffic situation and take proactive actions in order to avoid delays and congested conditions on city roads.

3 Solution approach

Our solution approach for managing traffic congestion in cities comprises of following three steps:

1. Data collection on traffic congestion using a questionnaire survey.
2. Application of DMAIC to analyse survey responses.
3. Propose recommendations for mitigating congestion in cities based on results of Steps 1 and 2.

These steps are explained in detail as follows.

3.1 Step 1: data collection using questionnaire survey

The first step involves conducting questionnaire study to collect data about the situation of traffic congestion in the city. Questionnaires are used to collect the information that researchers need for problem investigation. Questionnaire development should follow the regulation of design (Brace, 2008) and contain questions that are compact and understandable in order to avoid impatience of respondents. In order to frame questions for our questionnaire, we first identified causes that lead to traffic congestion in cities. Figure 4 presents our cause and effect diagram.
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Figure 4  Cause and effect diagram for traffic congestion

It can be seen in Figure 4 that poor road facilities, road management, types of vehicles, people driving behaviour and environmental conditions like weather, presence of incidents, etc., are the main causes that lead to traffic congestion in cities. For each of these causes, we identified the Critical-to-Quality (CTQ) parameters that can help improve the situation of traffic congestion in cities. Figure 5 presents the CTQs. Four main CTQs that can improve the situation of traffic congestion are good management of transportation system, well-organised drivers and passengers, good transportation environment, and good facilities for transportation. The CTQs have relevant sub-factors which can be seen at lower levels of the tree diagram in Figure 5.

Figure 5  CTQ tree for improving traffic congestion in cities (see online version for colours)
Using the results of cause–effect diagram (Figure 4) and CTQs (Figure 5), we prepared questions for the survey instrument. The questions sought following information from users:

- What is your experience with the congestion in Montreal?
- When is the most congested time in a day/week?
- Which are the most congested roads?
- What is your one-way driving distance?
- How long is your driving time?
- What is your average waiting time when you are driving?
- How do the road facilities affect traffic congestion?
- How does the transportation environment affect traffic congestion?
- How do the management factors affect traffic congestion?
- How do the operators’ factors affect traffic congestion?

The complete questionnaire is attached in Appendix A.

### 3.2 Step 2: application of DMAIC to analyse survey responses

The second step involves application of DMAIC to analyse survey responses obtained from Step 1. It is well known that six sigma is an effective business process quality management approach that seeks to identify and eliminate the causes of defective, non-conforming and production errors, reduce cycle duration and cost of operations, improve productivity and process reliability, better meet customer expectations, and achieve higher asset utilisation and returns on business finance strategy in manufacturing and service processes (Evans and Lindsay, 2005). We have chosen DMAIC or six sigma for traffic congestion monitoring in our study since it is a continuous quality improvement technique and our goal is to identify long-term solutions to manage and continually improve the situation of traffic congestion in cities.

Six sigma is based on a five-step methodology called DMAIC (Define, Measure, Analyse, Improve and Control). In the ‘Define’ step, we define the problem under investigation. In our case, the problem is congestion monitoring and control. The ‘Measure’ step involves measurement of data related to congestion problem under study. In the ‘Analyze’ step, we investigate the collected data and identify causes for poor performance/quality. The ‘Improve’ step involves development of solution measures based on analysis of collected data for improvement. In the fifth and the last step called ‘Control’, we establish control measures for the process to prevent defects from occurring in future. Figure 6 shows the five-step DMAIC methodology used in six sigma projects.

The survey responses obtained from Step 1 are subject to DMAIC in Step 2. The techniques used in the five phases of DMAIC are presented in Table 1. These techniques were chosen based on their ability to analyse the traffic congestion data collected in Step 1.
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3.3 Step 3: generate recommendations based on DMAIC results

The third step involves generation of recommendations for reducing traffic congestion based on results obtained from Step 1 (questionnaire) and Step 2 (DMAIC). Our goal is to provide long-term solutions that can continually help improve the situation of traffic congestion in cities and the quality of travel on city roads.

4 Case study: city of Montreal

In this section, we present the application of the proposed approach on city of Montreal. The proposed questionnaire (Appendix A) was used to measure the situation of traffic congestion in the city. The questionnaire was administered at random to 42 drivers in different areas in Montreal. The areas are in Montreal Island and cover Central-Ville, Montreal-Nord, Montreal-East, Saint-Laurent, Rosemont, Lachine, Pierrefonds, Pointe-Claire, LaSalle/Verdun and South-Shore. Out of 42 drivers, 35 drivers replied to our questionnaire (83.33% response rate). Figure 7 presents the distribution of living areas of the respondents.

On analysing the survey responses we found, that not all questions were answered by the drivers. Some of them partially attempted the questions. Therefore, we will analyse the response of each of the questions individually in this paper. The distribution of survey responses is presented in Figure 8.

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**Table 1**

<table>
<thead>
<tr>
<th><strong>DMAIC step</strong></th>
<th><strong>Technique used</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Define (D)</td>
<td>Descriptive statistics</td>
</tr>
<tr>
<td>Measure (M)</td>
<td>Pareto Analysis</td>
</tr>
<tr>
<td>Analyse (A)</td>
<td>Multivariate Factorial Analysis</td>
</tr>
<tr>
<td>Improve (I)</td>
<td>Cause and Effect Diagram</td>
</tr>
<tr>
<td>Control (C)</td>
<td>Control Charts</td>
</tr>
</tbody>
</table>

**Figure 6**

Six sigma and DMAIC

**Figure 7**

Business Performance Strategies

<table>
<thead>
<tr>
<th>Good Quality</th>
<th>High Productivity</th>
<th>High Reliability</th>
<th>Good Cost Controlled</th>
<th>High Profitability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
From the survey responses, we found that majority of the respondents were male (79.41%), age category 30–50 (79.41%), mixed professions (Manager, Technician, Student, Service, Retired, Others, etc.), average travel duration 1–2 hours (85.7%), used private cars for travel (75%) and performed travel every day (65.38%). The one-way travel time from the origin to the destination was less than an hour (91.66%) and trip distance was less than 30 kilometres (97.05%). The DMAIC methodology was applied on the survey data and the results obtained are explained as follows.
4.1 Define

In the define phase, we used descriptive statistics (mean values). To indicate the congestion levels on city roads, we used a weighted congestion score matrix. The weighted congestion matrix contains congestion levels weighted according to location sources. To compute the weighted congestion levels, the aggregated sum of product of weights of the location sources and their contribution to the whole congestion level of the city was used. The weights and contribution values were provided by the respondents (Table 2). For example, for Highways weight = 28.63%, Exits of Highway = 21.37%, Intersections = 20.99%, Main Roads = 19.08%, Other/Local Roads = 9.92%, etc. Respondent 1 provided a score of 3 for Highways and Exits of Highways. Therefore, the weighted congestion level provided by Respondent 1 is given by 0.2137*3 + 0.2099*3 + 0.1908*0 + 0.0992*0 = 1.5. Likewise, weighted congestion levels for all the 30 respondents are calculated. These values can be seen in the last column of Table 2. It can be seen that the traffic congestion level varies from level 1 to 4. The average congestion is highest on highways followed by exits of highways, intersections and main roads. The average congestion level for Montreal = 1.9036 (last row, Table 2) which takes into account weighted congestion levels of all location sources.

Table 2  Weighted congestion score matrix

<table>
<thead>
<tr>
<th>Respondent</th>
<th>Weighted Score Contributed to Whole Congestion Level of the City</th>
<th>Weighted Congestion Level</th>
<th>Evaluation of Congestion</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>Highway</td>
<td>Exits of Highway</td>
<td>Main Road</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Average weighted score of traffic congestion for Montreal: 2.0000
4.2 Measure

In this phase, we measure the questionnaire responses on different factors associated with congestion. Table 3 shows the results for various factors associated with congestion. It can be seen that majority of respondents believe that vehicle type, peak hours and management of roads are main causes of congestion. To analyse Table 3 responses in detail, we performed Pareto analysis. Pareto analysis is widely used for problem-solving in many fields, especially in project management in manufacturing industries (Karuppusami and Gandhinathan, 2006). According to Pareto’s rule, under most conditions, 80% of problems are most likely led by 20% of causes which are the so-called significant causes or core causes.

Table 3  Traffic congestion factors indicated by respondents

<table>
<thead>
<tr>
<th>Respondents</th>
<th>Responded Congestion Factors: Use ✓ to show respondents emphasised this factor in questionnaire</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>Vehicle</td>
</tr>
<tr>
<td>1</td>
<td>✓</td>
</tr>
<tr>
<td>2</td>
<td>✓</td>
</tr>
<tr>
<td>3</td>
<td>✓</td>
</tr>
<tr>
<td>4</td>
<td>✓</td>
</tr>
<tr>
<td>5</td>
<td>✓</td>
</tr>
<tr>
<td>6</td>
<td>✓</td>
</tr>
<tr>
<td>7</td>
<td>✓</td>
</tr>
<tr>
<td>8</td>
<td>✓</td>
</tr>
<tr>
<td>9</td>
<td>✓</td>
</tr>
<tr>
<td>10</td>
<td>✓</td>
</tr>
<tr>
<td>11</td>
<td>✓</td>
</tr>
<tr>
<td>12</td>
<td>✓</td>
</tr>
<tr>
<td>13</td>
<td>✓</td>
</tr>
<tr>
<td>14</td>
<td>✓</td>
</tr>
<tr>
<td>15</td>
<td>✓</td>
</tr>
<tr>
<td>16</td>
<td>✓</td>
</tr>
<tr>
<td>17</td>
<td>✓</td>
</tr>
<tr>
<td>18</td>
<td>✓</td>
</tr>
<tr>
<td>19</td>
<td>✓</td>
</tr>
<tr>
<td>20</td>
<td>✓</td>
</tr>
<tr>
<td>21</td>
<td>✓</td>
</tr>
<tr>
<td>22</td>
<td>✓</td>
</tr>
<tr>
<td>23</td>
<td>✓</td>
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<tr>
<td>24</td>
<td>✓</td>
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<tr>
<td>25</td>
<td>✓</td>
</tr>
<tr>
<td>26</td>
<td>✓</td>
</tr>
<tr>
<td>27</td>
<td>✓</td>
</tr>
<tr>
<td>28</td>
<td>✓</td>
</tr>
<tr>
<td>29</td>
<td>✓</td>
</tr>
<tr>
<td>30</td>
<td>✓</td>
</tr>
</tbody>
</table>

Figure 9 presents the Pareto diagram for the causes of congestion indicated by respondents. It can be seen that environment factor is most important (44%) followed by vehicles/people factor, and management factor. These three factors together contribute to 89% of congestion. For each of these factors, we developed second-level Pareto diagrams (Figures 10–12).
Figure 9  High-level Pareto analysis of congestion factors (see online version for colours)

Figure 10 presents the Pareto analysis for sub-factors of environment factor. It can be seen that work peak hours and construction contribute to 89% of the environment factors.

Figure 10  Pareto analysis of environment factors (see online version for colours)
Figure 11 presents the Pareto analysis for sub-factors of environment factor. It can be seen that vehicles contribute to 81% of the operator factors.

**Figure 11** Pareto analysis of operator factors (see online version for colours)

![Pareto analysis of operator factors](image)

Figure 12 presents the Pareto analysis for sub-factors of management factor. It can be seen that roads management and traffic indicators contribute to 94% of the management factors.

**Figure 12** Pareto analysis of management factors (see online version for colours)

![Pareto analysis of management factors](image)
Figure 13 indicates the frequency of congestion observed by the respondents. It can be seen that 55.17% of respondents often encountered traffic congestion, whereas 13.79% of total respondents indicated that they encountered traffic jam very often.

**Figure 13**  Congestion frequency (see online version for colours)

Figure 14 presents the responses for general congestion level in Montreal Island. It can be seen that 73.33% of respondents considered there is traffic congestion problem in city of Montreal. 60% of total respondents indicated moderate congestion and 13.33% indicated extreme congestion.

**Figure 14**  Congestion degree indicator (see online version for colours)
Figures 15–16 present the days and times at which congestion was experienced. It can be seen in Figure 15 that congestion was encountered more on weekdays than on weekends. From Figure 16, we can say that congestion occurred mostly during peak periods (7–9 am, 5–6 pm).

**Figure 15** Congestion across days of a week (see online version for colours)

![Graph showing congestion across days of a week](image)

**Figure 16** Congestion times in a day (see online version for colours)

![Graph showing congestion times in a day](image)

Table 4 presents the driving distance, total driving time and time spent in congestion by the respondents. It can be seen that the average driving time is 72.5 minutes/day for people, average driving distance is 27.43 kilometres and average congestion time encountered is 12.22 minutes. On the question of average stopping times and stopping frequency on various stops and city roads as a result of congestion, majority of the drivers reported waiting (1–10 times) and between (30 seconds to 1.5 minutes) and up to eight traffic lights in general before getting out of congestion. Almost all respondents experienced stress as result of congestion.
4.3 Analyse

In this phase, we analyse the relationship between traffic congestion factors (Xs) and weighted congestion level (Y). That is, do the Xs truly influence the Ys? How do Xs significantly affect Ys? To perform this, we conducted multivariate factorial analysis (Yang and Trewn, 2004). The Xs considered in our study are ‘Volume of Vehicles’, ‘Work Peak Hour’, ‘Construction’, ‘Roads Management’ and ‘Roads Condition’ (Figures 8–11). Table 5 presents the results of the multivariate factorial analysis at significance level \( \alpha = 0.05 \) and degrees of freedom \( n = 32 \). The F-statistic \( F_{0.05,1,32} = 4.1491 \). It can be seen in Table 5 that the factor ‘Roads Construction*Roads Management’ has \( F = 14.01 > F_{0.05,1,32} \), therefore we can say that the interaction between Roads Construction and Roads Management is the most significant factor influencing traffic congestion (Y).
Table 5  Factorial analysis for improving traffic congestion

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum Sq</th>
<th>df</th>
<th>Mean Sq</th>
<th>F</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>0.107</td>
<td>1</td>
<td>0.107</td>
<td>0.95</td>
<td>0.333</td>
</tr>
<tr>
<td>Work Peak Hour</td>
<td>0.720</td>
<td>1</td>
<td>0.720</td>
<td>1.50</td>
<td>0.269</td>
</tr>
<tr>
<td>Road Construction</td>
<td>0.118</td>
<td>1</td>
<td>0.118</td>
<td>0.20</td>
<td>0.653</td>
</tr>
<tr>
<td>Road Management</td>
<td>0.396</td>
<td>1</td>
<td>0.396</td>
<td>0.79</td>
<td>0.376</td>
</tr>
<tr>
<td>Road Condition</td>
<td>0.626</td>
<td>1</td>
<td>0.626</td>
<td>1.39</td>
<td>0.248</td>
</tr>
<tr>
<td>VehicleRoad Peak Hour</td>
<td>0.256</td>
<td>1</td>
<td>0.256</td>
<td>0.50</td>
<td>0.482</td>
</tr>
<tr>
<td>VehicleRoadMode Construction</td>
<td>0.101</td>
<td>1</td>
<td>0.101</td>
<td>0.24</td>
<td>0.629</td>
</tr>
<tr>
<td>VehicleRoadMode Management</td>
<td>0.116</td>
<td>1</td>
<td>0.116</td>
<td>0.26</td>
<td>0.615</td>
</tr>
<tr>
<td>VehicleRoadMode Condition</td>
<td>0.341</td>
<td>1</td>
<td>0.341</td>
<td>0.68</td>
<td>0.429</td>
</tr>
<tr>
<td>Work Peak HourRoadConstruction</td>
<td>0.822</td>
<td>1</td>
<td>0.822</td>
<td>1.83</td>
<td>0.235</td>
</tr>
<tr>
<td>Work Peak HourRoadManagement</td>
<td>0.157</td>
<td>1</td>
<td>0.157</td>
<td>0.34</td>
<td>0.567</td>
</tr>
<tr>
<td>Work Peak HourRoadCondition</td>
<td>0.627</td>
<td>1</td>
<td>0.627</td>
<td>1.47</td>
<td>0.237</td>
</tr>
<tr>
<td>Work Peak HourRoadModeCondition</td>
<td>0.716</td>
<td>1</td>
<td>0.716</td>
<td>1.64</td>
<td>0.213</td>
</tr>
<tr>
<td>Work Peak HourRoadModeManagement</td>
<td>0.338</td>
<td>1</td>
<td>0.338</td>
<td>0.75</td>
<td>0.393</td>
</tr>
<tr>
<td>Work Peak HourRoadModeCondition</td>
<td>0.542</td>
<td>1</td>
<td>0.542</td>
<td>1.24</td>
<td>0.282</td>
</tr>
<tr>
<td>Work Peak HourRoadModeCondition</td>
<td>0.834</td>
<td>1</td>
<td>0.834</td>
<td>1.89</td>
<td>0.232</td>
</tr>
<tr>
<td>Work Peak HourRoadModeCondition</td>
<td>0.540</td>
<td>1</td>
<td>0.540</td>
<td>1.24</td>
<td>0.282</td>
</tr>
<tr>
<td>Total</td>
<td>16.972</td>
<td>30</td>
<td>0.554</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.4 Improve

Cause–effect diagrams were developed in this phase to identify factors that can help improve roads management and roads construction (Table 5) which in turn will improve the situation of traffic congestion in the city. Figures 17–18 present the cause and effect diagrams for improving roads management and roads construction in city of Montreal. It can be seen from these diagrams that better facilities, use of right methods, trained drivers and proper driving environment are vital in reducing traffic congestion in cities.

Figure 17  Cause and effect diagram for improving roads management
4.5 Control

Control process is the last step of DMAIC. It ensures that project improvements can be sustained by tracking key performance measures and CTQs on a regular basis, and taking corrective actions whenever necessary to fix the problems and bring the process back to stable performance. For managing and improving the traffic congestion in city of Montreal, we propose the use of individual (x-bar and R) and multivariate ($T^2$ Hotelling) control charts (Montgomery, 2005).

The individual control chart can be applied to study the congestion level over time. Upper (UCL) and lower control limits (LCL) should be set up to detect out of control points and take appropriate actions. Let us denote the average congestion metric as $\bar{X}$, then the control limits are given by:

\begin{align*}
UCL &= \bar{X} + 3\bar{\sigma} \\
CL &= \bar{X} \\
LCL &= \bar{X} - 3\bar{\sigma}
\end{align*}

Using the data of Table 2 and applying equations (1) to (3), we obtain $\bar{X} = 1.9036$, $\bar{\sigma} = 0.7218$. Therefore, $UCL = 4.096$, $CL = 1.9036$, $LCL = -0.2618$. Since $LCL < 0$, therefore LCL is set equal to 0. Figure 19 shows the individual control chart for monitoring traffic congestion level in city of Montreal. It can be seen that several points are above centre control limits, therefore more actions are required by city of Montreal to reduce congestion.
For correlated variables, we propose the use of $T^2$ Hotelling control chart (Montgomery, 2005). For example, variables like Driving Time, Driving Distance or Waiting Time, will distort the results if considered individually. Phase I of the Hotelling’s $T^2$ statistic, also referred to as Mahalanobis distance, is defined as:

$$T^2 = (x - \mu)S^{-1}(x - \mu)^T$$

where:

$$\mu = (\mu_1, \mu_2, \mu_3)$$

$$\mu_i = \frac{1}{m} \sum_{i=1}^{m} x_i$$

$$S = \frac{1}{m-1} \sum_{i=1}^{m} (x_i - \mu)^T (x_i - \mu)$$

$i$ is from 1 to 30, which means the number of respondents in this case.

Equations (5) and (7) provide the sample mean matrix and covariance matrix, respectively. Equation (6) defines the mean for each variable $x_i \in x$, it is the vector which contains three variables: Driving Time, Driving Distance and Waiting Time. The control limits for $T^2$ Hotelling control chart are given by:

$$UCL = \left(\frac{m-1}{m}\right)^2 \frac{p}{m-p-1} \cdot \frac{1}{\frac{p}{m-p-1} \cdot F_{\alpha/2, p, m-p-1} + \frac{p}{m-p-1} \cdot F_{\alpha/2, p, m-p-1}}$$

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\[ LCL = \left( \frac{m - 1}{m} \right)^{\frac{p}{m}} \frac{1}{m - p - 1} \cdot \frac{m - p - 1}{m - p} \cdot F_{\frac{m - 1}{2}, m - p - 1} \]  \hspace{1cm} (9) \]

where:

\( m \): number of observations, in this case, it is 30 (there are total 30 effective data from respondents).

\( p \): number of variables, in this case, it is four (driving time, driving distance, waiting time, weighted congestion level).

Considering a confidence level \( \alpha = 0.05 \) and applying equations (8) and (9) on Table 4 data, we get UCL = 9.7882 and LCL = 0.5179. The \( T^2 \) control chart is shown in Figure 20. It can be seen that three points are out of control (two violating upper limit and one violating lower limit). This means the data provided by 13th, 14th and 27th respondents cannot objectively reflect the traffic congestion in city of Montreal. May be those respondents are under specific driving conditions or living areas.

Figure 20 \( T^2 \) control chart (see online version for colours)

Therefore, we exclude these out-control points in Phase II and recomputed the limits. After eliminating the out of control points of Phase I, we obtain new data set in Table 6. Equations (10) and (11) are used to compute new limits for Phase II. The new control limits for Phase II are given by:

\[ UCL = \frac{p(m + 1)(m - 1)}{m(m - p)} \cdot F_{\frac{m - 1}{2}, m - p} \]  \hspace{1cm} (10)
Z.H. Zhang and A. Awasthi

\[ LCL = \frac{p(m+1)(m-1)}{m(m-p)} \cdot F_{1-\alpha/2,p,m-p} \]  

(11)

The new data will now be monitored using the control limits of Phase II. If there are still points out of control, then the reasons need to be investigated and appropriate actions required to bring the congestion situation under control.

Table 6  Data in-control (Phase II)

<table>
<thead>
<tr>
<th>Respondents</th>
<th>Total Driving Time per Day (minutes)</th>
<th>Total Driving Distance per Day (km)</th>
<th>Total Time Spending in Congestion (minutes)</th>
<th>Weighted Congestion Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45</td>
<td>14</td>
<td>16</td>
<td>1.5090</td>
</tr>
<tr>
<td>2</td>
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<tr>
<td>3</td>
<td>75</td>
<td>34</td>
<td>14</td>
<td>0.2863</td>
</tr>
<tr>
<td>4</td>
<td>45</td>
<td>34</td>
<td>9</td>
<td>2.6145</td>
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<td>6</td>
<td>75</td>
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<td>20</td>
<td>1.5000</td>
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<td>75</td>
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<td>0.5725</td>
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<tr>
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<td>1</td>
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</tr>
<tr>
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<td>75</td>
<td>34</td>
<td>3</td>
<td>1.1450</td>
</tr>
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<td>11</td>
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<td>14</td>
<td>6</td>
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</tr>
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<td>14</td>
<td>7.5</td>
<td>2.4237</td>
</tr>
<tr>
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<td>20</td>
<td>2.3344</td>
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<tr>
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<tr>
<td>29</td>
<td>45</td>
<td>24</td>
<td>7.5</td>
<td>1.7863</td>
</tr>
</tbody>
</table>

When asked to respondents about whether they think the problem of congestion should be intervened by some departments, majority of them replied ‘Yes’ (29/30). The areas that the government, public and private roads transport organisations need to focus are improving roads management, use of public transport, expansion of roads, offering flexible work schedules, etc. Figure 21 presents the responses in favour of these suggestions.
From the DMAIC study, we found that improving roads management and road construction are crucial to managing congestion (Table 4). Therefore, based on the results of questionnaire survey (Figure 21) and DMAIC (Table 5), we can say that the two results are in agreement with each other, thereby validating the results achieved. The recommendations based on this case study to reduce congestion in the city of Montreal are better management of city roads, construction of roads, use of public transit, expanding roads and offering flexible work schedule.

5 Conclusions and future works

In this paper, we propose a three-step methodology for reducing traffic congestion in cities. In Step 1, we propose a questionnaire study to collect data on the situation of traffic congestion in the city. In Step 2, we apply DMAIC methodology on the survey data collected from Step 1. The techniques used are Pareto analysis, Cause–Effect Diagram, Factor Analysis, and Control Charts (Individual and Multivariate). In Step 3, recommendations for reducing traffic congestion in cities are generated using results obtained in Steps 1 and 2. A practical case study is provided for city of Montreal.

The results of our study identified roads construction and roads management as the most significant factor influencing traffic congestion in city of Montreal. The main improvement suggestions include improving roads management, improving public transportation, offering flexible work schedules, and imposing limits on vehicle movements.

The strength of the proposed work is the innovative application of DMAIC methodology on improving the situation of traffic congestion in cities. The limitation is the small sample size of the respondents which makes generalisation of the results difficult. The findings of the study will change if the number and nature of respondents is changed. Besides, the context of the city will also impact of the nature of the results.
Based on the current work, several future works are possible. Firstly, solutions for different congestion factors identified in the study can be further explored and compared using multi-criteria decision-making techniques. Secondly, the study can be done in different contexts (e.g., size of the city, structure of the city, population, geography, etc.). Thirdly, the impact of different regulatory measures on minimising traffic in cities can be investigated. Fourthly, the results of our study can be compared with other quantitative methods. Lastly, impact of information technology-based proactive congestion mitigation measures such as variable message signs and intelligent route planning can be another critical area of research.

The next step of our work involves conducting Design of Experiments to investigate various congestion mitigation solutions and select the best alternative.

References


Gouvril, L. and Joubert, F. (2004) Évaluation de la congestion routière dans la région de Montréal, Études et recherches en transports, Québec, ministère des Transports du Québec, 123. [In French]


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Appendix A

TRAFFIC CONGESTION SURVEY QUESTIONNAIRE OF MONTREAL

This survey intends to collect the traffic congestion data to analyze and evaluate the land transportation conditions in Montreal island. Please mark the choices that apply to you. You can select more than one response for the same question.

Note: Please feel free to ask me if you need more information about anything on this questionnaire.

PART I of IV: INFORMATION ABOUT YOU

1. Please indicate your age:
   - Under 20
   - 20-30
   - 30-40
   - 41-50
   - 51-60
   - Over 61

2. Please indicate your gender:
   - Male
   - Female

3. Please indicate your occupation:
   - Management
   - Sales/Trades
   - Service
   - Driver
   - Work at home
   - Others

4. Please indicate you live area:
   - Central-Montreal
   - Rosemont
   - Montreal-East
   - Montreal-Nord
   - Lachine
   - Saint-Laurent
   - Pierrefonds/DOO
   - Pointe-Claire
   - LaSalle/Verdon
   - Others:

5. Please indicate how often you travel by vehicles:
   - Over 8 hours a day
   - 4-8 hours a day
   - 2-4 hours a day
   - 1-2 hours a day
   - 0.5-1 hours a day
   - Under 0.5 hour a day

6. Please indicate what is your primary commute mode:
   - Drive alone
   - Walk
   - Drive to bus
   - Carpool
   - Drive to rail
   - Vanpool
   - Bicycle
   - Others:
   - Walk to Bus

7. Please indicate the average one-way travel time from your original place to destination:
   - Over 2.0 hours
   - 1.5-2.0 hours
   - 1.0-1.5 hours
   - Less than 1.0 hours

8. Please indicate the average one-way travel distance from your original place to destination:
   - Over 50 km
   - 30-50 km
   - 20-29 km
   - 15-19 km
   - Less than 15 km

9. Please indicate most of the congestion locations and time (Am/Pm: From--To--) where you experienced:
   - Highway: Time: am/pm
   - Main roads: Time: am/pm
   - Roads in your area: Time: am/pm
   - Intersections: Time: am/pm
   - Others 1: Time: am/pm
   - Others 2: Time: am/pm
   - Others 3: Time: am/pm
   - Others 4: Time: am/pm

10. Please select most of the factors you consider important why there are heavy congestion on roads:
   - So many vehicles
   - So many construction
   - Peak hours
   - Aggressive driving
   - Roads’ conditions
   - Lack of traffic signal
   - Bus management
   - Bad weather
   - Others:
   - So many accident

PART II of IV: YOUR EXPERIENCE WITH CONGESTION IN MONTREAL

1. How many total average times (each time >0.5 minute) did you stop on the roads (except traffic lights and traffic signals)?
   - Never stop
   - Stop 1-5 times
   - Stop 6-10 times
   - Stop 11-15 times
   - Over 15 times

2. How long is average time of each stop on the roads (except traffic lights and traffic signals)?
   - Less 30 seconds
   - 30-59 seconds
   - 1.0-1.5 minutes
   - 1.5-2.0 minutes
   - Over 3.0 minutes
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3. How many total traffic lights should you stop to wait for pass through?  
   □ Less 5 traffic lights □ 6-8 traffic lights □ 9-14 traffic lights □ Over 15 traffic lights

4. Please indicate the general congestion level in Montreal island?  
   □ No congestion □ Slightly congested □ Moderately congested □ Extremely congested

5. Please indicate the congestion level by your experience for the following roads:
   □ Highway □ Exit of highway □ Main roads □ Intersections □ Local roadway  
   Level: _______ Which highways: _______ Where: _______  
   Level: _______ Which exits: _______ Where: _______  
   Level: _______ Which roads: _______ Where: _______  
   Level: _______ Which intersections: _______ Where: _______  
   Level: _______ Which areas: _______ Where: _______

PART III of IV: MISCELLANEOUS INFORMATION ABOUT CONGESTION

1. What’s the time of a day when you are driving?  
   □ AM peak: _______ From: _______ To: _______  
   □ PM peak: _______ From: _______ To: _______

2. What are most congestive days of a week when you are driving?  
   □ Monday □ Tuesday □ Wednesday □ Thursday □ Friday □ Saturday □ Sunday

3. How often do you experience stress in your daily commute?  
   □ Always □ Often □ Very often □ Sometimes □ Never

4. Have you noticed an increase in driving related stress over the last year?  
   □ Yes □ No

5. Have you noticed an increase in driving related stress over the last five years?  
   □ Yes □ No

6. What do you see as the thing most responsible for your stress while driving?  
   □ Aggressive driving □ Weather □ Congestion due to road construction □ People who drive too slow  
   □ Congestion due to accidents □ Others __________________________

PART IV of IV: HOW TO DEAL WITH CONGESTION

1. When you are facing on the congestion what you would do?  
   □ Keep waiting □ Change the way □ Change the way tomorrow □ Others __________________________

2. Do you think it should be intervened by some departments when there are congestions?  
   □ Yes □ No

3. What the government should do for the congestion problems?  
   □ Expand the width of roads □ Limit vehicles on road  
   □ Improve roads management □ Improve the effectiveness of public transportation  
   □ Others __________________________

4. What do you hope the companies/organizations should do about the congestion problems?  
   □ Change the office hour for employees □ Move the office  
   □ Stimulate to use public transportation method □ Others __________________________

THANK YOU FOR YOUR ASSISTANCE