Vibration, confined space, and little leeway for improvement

Addressing the challenges posed by the Montréal subway operator workstation

A collaborative approach grounded in the real work context

R-722

irsst

ABSTRACT

This document is intended for occupational health and safety professionals, ergonomists, engineers, and any other persons concerned with making improvements to a workstation that currently offers very little leeway for change.

It provides a brief description of both the technical process and collaborative approach used to improve the workstation of Montréal subway operators, who experience discomfort caused by their seat, confined work space, and vibration. Based on this study, modifications were made to the operator cab, and a seat prototype offering the best possible compromises to improve the situation was proposed.

These solutions were achieved through the collaborative efforts of researchers from the Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST), decision makers and employees of the Société de transport de Montréal (STM), representatives of the union of subway operators, and a specialist in seat adaptations.

The process of improving the subway operator workstation and of designing a seat prototype also included documenting the problem and carrying out simulations and tests grounded in the real work context.

The approach used reconciled the interests and needs of all parties concerned and helped create significant long-term benefits. This experience led STM management and the union to require, in their subsequent call for tenders, that the operator cabs in the newest generation of subway trains be designed using several aspects of this participatory and joint representation process.

A COLLABORATIVE APPROACH GROUNDED IN THE REAL WORK CONTEXT

- Interdisciplinarity; active and joint participation of all workplace players
- Progressive design process using simulations and tests grounded in the real work context

The subway operator cab that led to the request.

THE NEEDS

Montréal's subway system was brought into service in 1966, and had 759 motor cars circulating on four lines in 2010. Nearly 300 operators drive the trains from their workstations in the motor car cabs. Initially designed for work to be performed in standing position, the operators' workstation has undergone several transformations over the years, such as the moving of certain controls to facilitate working in sitting position. Due to the confined space in the cabs, a small, minimally adjustable jump seat is used in the MR-73 model of subway cars, which were built in the 1970s. The operators often reported experiencing discomfort, which they attributed notably to the transmission of vibrations by the seat.

In 2002, the STM and the union representing subway car operators joined forces to submit a request to the IRSST, asking it to quantify the level of vibrations to which the workers were exposed and to make recommendations concerning a new seat for the operator cab in MR-73 motor cars. They specified that the seat had to be ergonomic, attenuate vibrations, and be adapted to the confined space available.

A PROBLEMATIC WORKSTATION

- Whole-body vibrations
- Confined space
- Inadequate seat
- Design dating from the 1970s

The confined space and the seat location resulted in uncomfortable positions for the operators' legs.

THE GAME PLAN

and the players involved

A PARTNERSHIP PROCESS

- Researchers
- Decision makers
- Users
- Union
- Designer
- Other parties

The IRSST's research team, comprising ergonomists and vibration specialists, proposed a three-part study.

The first part was an ergonomic study whose aim was to contextualize the occupational health and safety issues involved in the subway operators' workstation, and to assess the possibilities for retrofitting the operator cab. The second part was a vibration study whose aim was to quantify operator exposure. Optimum design criteria for the operator's seat were also defined by means of these two studies. The aim of the third part of the process, which was carried out on an interdisciplinary basis, was to design and test a seat prototype.

Given the challenge to be met, it was necessary from the outset to mobilize the decision-making authorities and the skills of STM personnel in a joint participation dynamic involving representatives of both management and workers.

First, a steering committee was formed to guide and facilitate the project, and to link the research to the workplace's needs. Second, a working group was formed in order to gain a thorough understanding of the needs and constraints of each department involved and to identify concrete solutions appropriate to the work context.

A THREE-PART PROCESS

PART 1
ERGONOMIC STUDY

PART 2
VIBRATION STUDY

PART 3
DESIGN, TESTING, AND IMPROVEMENT OF A SEAT PROTOTYPE

THE STEERING COMMITTEE

A joint commitment to the smooth running of the project

The mandate of the steering committee, which met at pivotal points during the project (start-up, results presentation, strategic decision making) was to ensure that the project addressed the needs and concerns of the workplace and that its results would have concrete and useful benefits tailored to the real work context. It undertook to do everything possible to promote the successful execution of the research project by, for example:

- authorizing the release of staff and rendering available the equipment needed for testing purposes;
- agreeing to major changes, such as moving the handbrake handle;
- mandating an outside company to build the prototype in accordance with the criteria defined.

The members of the steering committee also approved the building of two replicas of the seat prototype so as to facilitate testing in the real work context. In addition, they supported the logistical deployment required, the involvement of employees from various departments, and the recommendations made by the working group.

A representative of the joint sector-based association for the occupational health and safety of the municipal business sector (APSAM)[1] was invited to sit on the committee to represent this sector.

THE STEERING COMMITTEE

- **The team of researchers**
- **The department directors**
  - Operations
  - Engineering
  - Maintenance
  - Occupational Health and Safety
- **The union of subway operators**
- **The joint sector-based association**

[1] The mission of the Association paritaire pour la santé et la sécurité du travail du secteur des affaires municipales (APSAM) is to facilitate the management of prevention efforts by the workplace, and thus to create and promote the means necessary to protect the health, safety, and physical well-being of persons working in municipalities and the related organizations, throughout Québec.

THE WORKING GROUP

The mandate of the working group was to identify appropriate and concrete solutions. It's members met approximately 15 times. These meetings provided ideal opportunities for identifying the problems jointly and pooling their respective skills in order to find possible solutions.

This dynamic produced a common understanding of each issue under study and ensured that the requirements and constraints of all parties represented were addressed. It also meant that choices and decisions were based on common ground and were adopted as the project progressed, thus preventing the need to backtrack, which is costly in both time and energy.

The group's validation of the minutes of each meeting was used to ensure this common understanding.

THE WORKING GROUP

- Researchers specialized in ergonomics
- Researchers specialized in whole-body vibrations
- Head of operations
- Subway operators, including one union representative
- Rolling stock engineer
- Maintenance supervisor
- OHS adviser
- External designer

COORDINATION – STAYING ON COURSE TO ACHIEVE THE OBJECTIVES WITH FULL TRANSPARENCY

To ensure successful implementation of the game plan, the ergonomist on the research team was given the responsibility of coordinating and overseeing the project. In such a process, the coordinator's role is to guide the players involved through the different steps and ensure that the planned actions are carried out, mainly by promoting communication, calling and chairing meetings, drafting the minutes, and passing on all relevant information.

In the context of this study, the coordinator constantly interacted with an employer representative and a union representative, whose role was to make the decisions and take the actions under their authority. Between meetings, all information about the research progress and the results obtained was passed on to them, ensuring a transparent and joint participation process.

Overview of the occupational health and safety issues affecting subway operators, the work context, and retrofitting options

The researchers began by analyzing the employment injury data provided by the STM, and by conducting a survey of all STM subway operators for the purpose of documenting their health problems. This step brought to light the importance that efforts be made to improve the operators' driving postures so that those experiencing health problems would not see a worsening of their problems. The researchers also accompanied the operators on the job to observe them under their real driving conditions, and interviewed them to gain a thorough understanding of their work and how it was organized. Finally, discussions were held with the heads of operations.

Through this ergonomic analysis, it was possible to identify the work requirements that had to be taken into account in the retrofitting of the cabs and the development of a new seat.
For example:

- In manual driving mode, the operator controls the train's speed using a controller handle. He or she also has to be able to reach this handle easily.
- The operator's driving position has to provide a clear view of the tracks, the dials on the control console, and the mirrors on the passenger loading platforms.
- In addition to driving, subway operators sometimes have to act quickly to handle technical or human incidents. They must be able to see the dials readily, access the controls easily, apply the handbrake and use their radio. They must also be able to move around in the cab and disembark easily to perform certain troubleshooting tasks outside.
- Once the operators have reached the terminus, they must change trains, a process which takes place every 20 minutes on one of the lines. They must therefore be able to adjust their seat easily.

THE FOCAL POINT: THE SUBWAY OPERATORS AND THEIR WORK

- **Documenting their health problems**
  - Analyzing employment injury data
  - Administering a questionnaire
- **Understanding the work, needs, and constraints**
  - Observing the real work context
  - Conducting interviews
- **Evaluating the retrofitting options available for the operator cab and determining the desired characteristics of the seat**
  - Uncovering the physical components of the operator console
  - Performing computer simulations and simulations using a full-scale model

The location of the operator seat in the cab and the limited space available for the operators to slide their legs under the console causes them to adopt sitting positions that are often uncomfortable for their lower limbs. As a result, when they are driving, the majority of the operators alternate between standing and sitting positions to shift the discomfort around.

A 3D computer simulation showed that it was impossible for a man of average height to adopt a comfortable manual driving position, given the current confines of the cab and the console configuration. In automated driving mode, even if the situation is slightly improved because the operator does not have to hold the controller handle, the clearance area under the console remains limited and is not aligned with the seat, which places constraints on the position of the operator's legs.

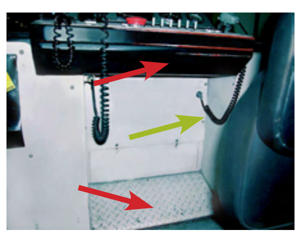
In order to assess the possibility of gaining space to improve the situation, the working group met around a subway cab, where representatives of the STM engineering and maintenance departments removed the metal sheeting covering the control console and the other equipment. Everyone present could see that the equipment in place was bulky, which left little leeway for improvement.

Nonetheless, a few improvements were subsequently made to all the cabs: a space for the right foot was provided under the console; the corner of the console was moved a few centimetres to allow for better positioning of the right leg; and a flip-up footrest was installed to allow shorter operators to raise their seat and obtain a better view of the track. Moreover, a pivotal decision (also involving the steering committee) was made, namely, to move the handbrake handle that was located behind the seat in order to free up a little space and make room for a slightly bigger seat.

All these proposed modifications were first tested by the operators, using a full-scale model of the cab, to verify their real benefits. These simulations also made it possible to determine the basic characteristics of the seat prototype to be created. It became evident that it was important for operators to be able not only to adjust their seat height, but also to move the seat laterally and backward and forward, and to be able to rotate it to the right, all through simple, fast adjustments.

[The metal sheeting covering the control console was removed to see whether any space could be gained.

Green arrows: gain possible
Red arrows: no gain possible



Simulations on a full-scale model of the operator cab made it possible to test the proposed modifications and to set the basic criteria for the seat prototype.

A model of the control console was built, incorporating the desired modifications as well as the rear partitions delimiting the cab space.

Operators selected: Around a dozen operators of different heights and weights (2.5 to 97.5 percentiles) and with varying years of experience were selected.

Seats used: A small chair on castors and a second chair used in the other subway car trains (i.e. not the MR-73 type) served as a basis for determining the desired adjustment ranges needed for the new model (the tests were repeated using the seat prototype created).

Instructions given to operators: The operators were told to choose the seat position(s) most comfortable for them for each type of seat and for each driving mode (automated driving mode and manual driving mode). They were free to use or not the footrest provided.

Information collected: Each seat position was noted (position of the operator's seat cushion and hips relative to the cab floor). By superimposing all positions on the computer, it was possible to determine the ranges of adjustment required. For each position, the possibility of opening the cab door, getting up easily from the seat, and moving around in the cab was verified. The viewing distance on the running track was estimated and the postures adopted were described. The analysis process was facilitated by referring to the videotapes of the tests. The operators' satisfaction levels were noted, particularly with regard to the postures adopted, the presence of discomforts, the possibility of performing the required tasks, and the benefits gained due to the changes made to the control console and seat.

Simulations on a full-scale model of an operator cab.

The control consoles have been modified according to recommendations made by the working group.

The area beneath the control console before and after the modifications.

Improved positioning of the right leg due to the modifications made to the control console in the cab.

SMALL BUT SIGNIFICANT GAINS IN SPACE

- **To allow for better positioning of the right leg and less contact between the operators' knees and the metal sheeting:**
  - Certain structures were moved
  - An opening was created under the console
- **To allow for the installation of a larger seat:**
  - The handbrake handle was moved
- **To allow smaller operators to sit higher:**
  - A flip-up footrest was added

ERGONOMIC CRITERIA

A SEAT THAT CAN BE ADJUSTED TO SUIT THE DIFFERENT DRIVING MODES AND OPERATORS' NEEDS

- Seat position must be adjustable: height-wise, and able to rotate and move both laterally and forward/backward
- Adjustments must be simple and quick to make
- Backrest must have adjustable tilt
- Must be possible to flip up the seat cushion
- Must respect the maximum dimensions defined for the seat, seat cushion and backrest
- Must respect the zone defined for securing the seat base to the floor
- Seat cushions can be moulded but subtly only
- Seat upholstering must be made of fabric
- Must be suitable for operators weighing from 50 kg to 130 kg, and measuring from 1.52 m to 1.88 m tall

Vibrations were measured in the real work context in two different MR-73 motor cars. The researchers installed sensors on the jump seat in the cab to measure the operator's exposure to whole-body vibrations and on the floor to characterize the vibration environment. They also collected measurements on the axles and on other components of the motor cars in order to evaluate the behaviour of the axle suspension. Lastly, they studied the profile of the subway running tracks.

In the motor car model under study, the highest vibration magnitudes were observed in the vertical axis, at a vibration frequency of 2.4 Hz, corresponding to the vibration mode of the cab. Another peak value, but of smaller amplitude, appeared at around 6 Hz, a frequency associated with the vibration mode of the bogie[1] and to which the human body is particularly sensitive. The vibration magnitude was accentuated at this frequency when the speed of the train exceeded 60 km/h. The researchers calculated that the daily level of MR-73 subway car operators' exposure to whole-body vibrations was around the level of the health guidance caution zone defined in the 1997 ISO 2631-1 standard.

It would appear that the unevenness of the running tracks is very minor and therefore has very little impact on the vibrations felt by the operators. However, the existing jump seats amplify rather than attenuate the vibrations. Due to cost factors, the option of attenuating the vibrations by adding shock absorbers to the suspension, between the bogie and the cab, was not retained. The use of a suspension seat whose natural vibration frequency would be 1.7 Hz or less was regarded as the simplest and most feasible means of attenuating the vibrations.

EVALUATION OF WHOLE-BODY VIBRATIONS: MANY VARIABLES TO CONSIDER

- Speed of the train
- Condition of the running track
- Condition of the tires – ovalization
- Vibration behaviour of the motor car
- Seat transmissibility

VIBRATION CRITERIA

A SEAT THAT ATTENUATES WHOLE-BODY VIBRATIONS

- Priority frequencies to attenuate: 2.4 Hz and 6 Hz
- Main vibration axis to attenuate: vertical
- Natural vibration frequency sought for the seat: 1.7 Hz or less

[1] Bogie : Truck (a swiveling carriage consisting of a frame with one or more pairs of wheels and springs to carry and guide one end (as of a railroad car) in turning sharp curves) (http://www.merriam-webster.com/dictionary/truck)

The ergonomic and vibration criteria determined in the first two parts of the study were detailed in the technical specifications. Thanks to the contribution made by the working group, the requirements of the various departments of the STM – engineering, maintenance, operations, OHS and procurement – and of the union were added to the specifications.

OTHER CRITERIA

A SEAT THAT MEETS THE REQUIREMENTS OF THE DIFFERENT DEPARTMENTS

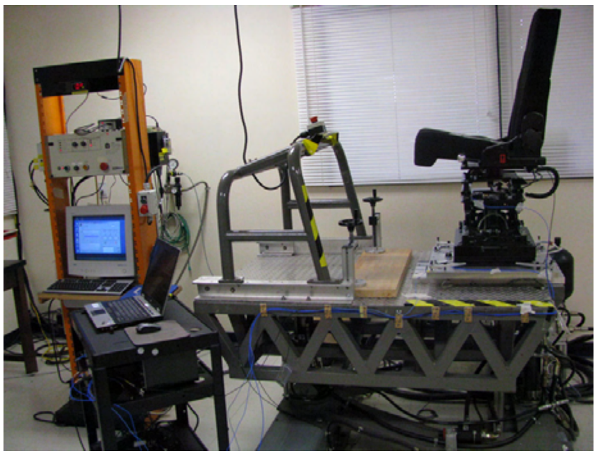
- **ENGINEERING**
  - Source of power feeding the suspension
  - Mechanical resistance, robustness
  - Fire-resistance
- **MAINTENANCE**
  - Ease of installation, assembly and disassembly
  - Frequency of maintenance operations
  - Durability of components
- **PROCUREMENT**
  - Long-term availability of parts
  - Replacement cost
- **SAFETY**
  - No sharp edges, protruding parts, risks of jamming or colliding

One of the key criteria was that the seat prototype had to be built with existing components in order to minimize the development time and uncertainties about the resistance and availability of parts. The designer recruited by the STM to build the prototype therefore had to be able to supply the proper components and adapt them to respond optimally to the specified criteria. Several test cycles involving the operators, study sessions and discussions with the working group, and work sessions to improve the prototype were necessary between the first proposal made and the final prototype.

A COOPERATIVE AND ITERATIVE CREATION PROCESS

- Tests involving numerous operators:
  - Laboratory (tests on a vibration simulator and static tests)
  - Full-scale model of the operator cab
  - Actual operator cab
- Simultaneous data collection through measurements, observations and questionnaires
- Assessment by the working group
- Changes made to the prototype by the designer
- Evaluation in the real work context

One of the biggest challenges faced was finding efficient seat suspension that was also sufficiently compact so as not to occupy too much space, either on the floor or behind the backrest. In order to determine the efficiency of the different types of suspensions, a series of tests were first performed in the laboratory on a platform mounted on hydraulic jacks used to reproduce the vertical vibrations in accordance with the 1992 ISO 10326-1 standard.



Laboratory evaluation of the vibrations transmitted to the seat cushion.

Other characteristics of the suspensions were also detailed: their dimensions, adjustment range, ease of use, and the possibility they offered of flipping up the seat cushion to facilitate movement in the cab. The working group also debated the advantages of pneumatic suspension versus those of mechanical suspension, and verified feasibility in terms of additional maintenance and of a pneumatic power supply versus an electric power supply from the train.

To meet all the requirements to the fullest extent possible, the researchers and the designer proposed exploring creative, unconventional solutions to resolve the suspension problem; these solutions were rigorously tested. For example, in order to free up the space needed to allow for movement around the cab, pneumatic suspension was installed under the seat cushion at a 90-degree angle compared to its usual axis.

Tests performed on the vibration simulator and in a real operator cab made it possible to determine, in light of the space available, the location where the suspension should be secured under the seat cushion so as to minimize pitching. The designer also reinforced the suspension to provide resistance to mechanical stresses. Since the dynamic behaviour of the subway trains does not involve shocks, it was possible to remove the shock absorber from the suspension to further attenuate the low-frequency vibrations. Tests showed that the suspension could be used to adjust the seat height and simultaneously attenuate the vibrations, which in turn simplified the adjustments. The adjustment stops limiting the travel distance of the suspension were also adapted to accommodate the adjustment range required.

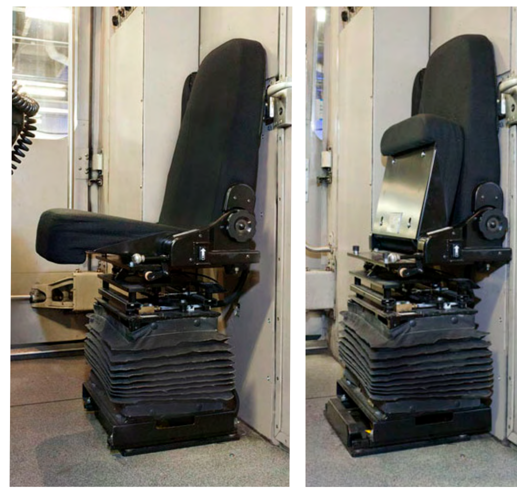
EXPLORATION OF UNCONVENTIONAL OPTIONS

- Suspension installed under the seat at a 90-degree angle compared to its usual axis
- Removing the shock absorber to reduce the vibration frequency of the suspension
- Moving the suspension stops to allow for greater travel distance
- Using the suspension to make adjustments to the seat height
- Using the flipped-up seat cushion as a buttocks support
- Making a combination of adjustments to the seat position by means of a single handle

Given the limited space available, each centimetre matters and can compromise the possibility of, for example, pivoting the seat, tilting the backrest, or moving around the cab. Each modification proposed therefore had to be verified in an environment that approximated the reality as closely as possible. A series of tests led to changes being made in the seat prototype. These tests involved the operators and were performed in the laboratory on the vibration simulator, in the full-scale cab model, and in an actual cab. The dimensions of the seat cushion, the location and type of handle for adjusting the seat position, the location where the seat base was secured to the floor, and the length of the rails available for adjusting the seat position were all verified with the input of the working group and numerous operators.

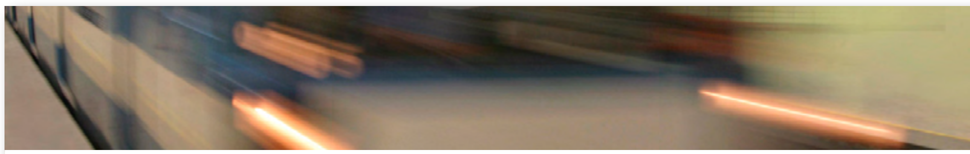
After carrying out these successive improvement steps, the prototype, which was then deemed satisfactory and safe, was tested in the real work context with the participation of nearly 20 operators.

These tests, which required the deployment of considerable logistics on the part of the STM, were carried out over 11 days. The operators' activities, which were filmed, were then subject to ergonomic analysis. In addition, a detailed questionnaire administered to the operators provided information on their perception of the seat characteristics, mainly with respect to comfort and their ability to carry out their work. The researchers also measured the vibrations on both the seat and the floor, using accelerometers.



The new seat.

The prototype, deemed satisfactory and safe, was tested in the real work context.



19 operators of varying heights and weights (2.5 to 97.5 percentiles) and with varying lengths of work experience were selected.

Prototype of the seat installed in a modified cab: The operators were familiarized with the seat prototype, and the prototype was then used and evaluated (approximately three hours in sitting position).

Instructions given to the operators during the evaluation: They were told to choose the seat positions most comfortable for driving the subway for at least 10 interstations (i.e. the track section running between two adjacent stations) in automated driving mode, 10 interstations in manual driving mode, and 10 other interstations in the mode of their choice.

Information collected: Vibrations were measured on the floor and seat cushion while the subway car was moving. At each station, the operators' perceptions of the vibration-related discomforts and of the ease of accessing the necessary visual information in the loading platform mirrors were evaluated. After the tests, a questionnaire was administered regarding overall discomfort, localized discomforts, seat characteristics associated with the discomforts, assessment of the seat characteristics (e.g. adjustment range, ease of adjustments, backrest, seat cushion, suspension), impact of the seat on work and safety (e.g. ability to see and reach the controls, move around the cab, and stand up quickly). Their postures were analyzed (filmed continuously during the tests). The use made of the seat (adjustment ranges used) was described. The operator's viewing distance on the running track was estimated. The results were compared with the initial situation (old jump seat with no changes made to the cab).

CONCLUSION

AN IMPROVED SUBWAY OPERATOR WORKSTATION

The numerous validation efforts made during the course of the project to factor in the real work context successfully minimized unwanted surprises during the final evaluation of the prototype, and ultimately yielded a solution that improved the operators' comfort. The modifications made to the cab slightly enlarged the space available for their legs. The seat prototype attenuated the vibrations, offered better body support, and was easily adjustable, providing the operators with various posture options. However, this last improvement was the result of a compromise, given that the space in the cab is still too small for an operator's legs and it is still hard to access the controller handle. There are therefore few possibilities available for adopting a posture that is comfortable simultaneously for the neck, back, and legs, and for the arm that operates the controller handle.

With a view to future implementation of the seat prototype, the researchers submitted recommendations to the STM, notably, that it carry out more long-term tests, allow the operators time to familiarize themselves with the new seat adjustment options, and encourage them to change their posture regularly.

The STM, which wanted to install a new seat fairly quickly, continued the work. Two replicas of the prototype were tested over a one-year period and elicited positive comments from the operators. The mechanical problems noted during the test period were rectified. Ten seats of the new design type were installed first, and for a one-week period, underwent the tests imposed by the STM's Engineering Department. Large-scale implementation began in the summer of 2011, at the rate of around five seats a week.

AN APPROACH TO BE RETAINED

Over and above the improvements made to the operator workstation, one of the successes of the research project as a whole was the introduction of this collaborative partnership approach involving interdisciplinarity and joint participation. To be effective, this approach requires time and availability, the commitment of decision makers, and the involvement and open-mindedness of all parties. If these winning conditions are in place, not only can the needs and interests of all parties concerned be reconciled, but significant long-term benefits can be obtained.

The STM found the collaborative approach used in this research project to be highly beneficial. In fact, both management and the union recognized the major contribution made by the collaborative and joint participation approach, and, commencing with the call for tenders phase, required that the next generation of subway trains be designed using the same approach. They required that a working group participate in the different steps of designing a subway operator workstation and that a full-scale model be built and tested by several operators.

The approach has been effective in reconciling the needs and interests of all parties concerned and will provide significant long-term benefits.

In manual driving mode, the seat prototype can be moved toward the controller handle, thus providing the operator's body with better support.

AN IMPROVED OPERATOR WORKSTATION

- The possibility of choosing and varying postures
- Better body support
- Vibrations attenuated
- Simple and fast to adjust
- Improved positioning of the operator's legs
- Seat appreciated by the operators

In automated driving mode, operators can pivot the seat prototype to free up their legs, while at the same time, keep their backs well supported.

AN APPROACH TO BE RETAINED

- Participatory
- Collaborative
- Interdisciplinary
- Joint participation (management/worker)

TO LEARN MORE

The research publications of the IRSST can be downloaded free of charge from our Web site. www.irsst.qc.ca

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ABOUT THE IRSST

Established in Québec since 1980, the Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST) is a scientific research organization known for the quality of its work and the expertise of its personnel.

The collaborative approach described here clearly illustrates the framework of practice espoused by the IRSST, which places value on ongoing interaction between researchers and the users of the results of any given study throughout the entire research process. The active participation of these partners commencing with the project development phase ensures that the project will meet their needs, be grounded in the real work context, and have concrete benefits for the workplace involved. This dynamic reflects the principles of joint participation (management/worker) that form the basis of occupational health and safety action in Québec.

MISSION

To contribute, through research, to the prevention of industrial accidents and occupational diseases as well as to the rehabilitation of affected workers.

To offer the laboratory services and expertise necessary for the activities of the public occupational health and safety prevention network.

To disseminate knowledge, and to act as scientific benchmark and expert.

Funded by the Commission de la santé et de la sécurité du travail, the IRSST has a board of directors made up of an equal number of employer and worker representatives.

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