Hours of service regulations in road freight transport: an optimization-based international assessment

Thibaut Vidal

Seminar, Universidade Federal Fluminense, March 15th, 2013
Context of this research

- Joint work with
  - Asvin GOEL, Jacobs University, Bremen, Germany

  and also:
  - Teodor Gabriel CRAINIC, Université de Québec à Montréal, Canada
  - Michel GENDREAU, Ecole Polytechnique, Montréal, Canada
  - Christian PRINS, Université de Technologie de Troyes, France

  (routing aspect)

  (scheduling aspect)
Assessing the impact of hours of service (HOS) regulations on the travelling distance, duration and risk.

I) First discuss on optimization methods for vehicle routing.

II) Some preliminary computational experiments.

III) Have an efficient method for generating high-quality itineraries in presence of different regulations.

IV) Compare these itineraries and simulate risk.
Vehicle routing problems

- Capacitated vehicle routing problem:
  - INPUT: \( n \) customers, with locations & demands. All-pair distances. Homogeneous fleet of \( m \) capacitated vehicles located at a central depot.
  - OUTPUT: Least-cost delivery routes (at most one route per vehicle) to service all customers.

- NP-Hard problem
- Exact resolution impracticable for most problem instances of interest (≥ 200 customers).
- “Scopus” facts: 2007-2011 = 1258 articles with the key vehicle routing.
- Massive research effort on heuristics.
Vehicle routing problems

- **Capacitated vehicle routing problem:**
  - Combinatorial optimization problem, for a problem with \( n = 100 \) customers and a single vehicle, the number of possible solutions is:

\[
n! = 933262154439441526816992388562667004907159682643816 \\
2146859296389521759999322991560894146397615651828625369 \\
7920827223758251185210916864000000000000000000000000000 \approx 10^{158}
\]

- Even with a grid of computers which...
  - Contains as many CPU as the estimated nb atoms in the Universe: \( n_{\text{CPU}} = 10^{80} \)
  - Does one operation per Planck time: \( t_p = 5.39 \times 10^{-44} \) s

\[
T = 10^{158} \times 5.39 \times 10^{-44} / 10^{80} = 5.39 \times 10^{34} \text{ s}
\]

Compare this to the estimated age of Universe: \( 4.33 \times 10^{17} \) s ...
Vehicle routing “attributes” : Supplementary decisions, constraints and objectives which complement the problem formulations

- Modeling the specificities of application cases, customers requirements, network and vehicle specificities, operators abilities...
- E.g. Time windows, Multiple periods, multiple depots, heterogeneous fleet, 2D-3D loading, time-dependent travel times...

- Multi-Attribute Vehicle Routing Problems (MAVRP)
  - Challenges : VARIETY of attributes
  - Challenges : COMBINATION of attributes
  - Plethora of attribute-specific methods in the literature, but no unified approach.
Optimization methods for VRPs

- **ASSIGNMENT**: assignment customers and routes to days and depots
  - Take into account Periodic, Multi-Depot, Heterogeneous Fleet problems

- **SEQUENCING**: create the sequence of visits to customers

- **ROUTE EVALUATION**: Evaluate each route generated during the search
  - Time windows, Time-dep. travel time, Loading constraints, HOS regulations Lunch breaks, Load-Dependent costs...
Unified genetic search with advanced diversity control

General HGA Methodology:

Evolve a population of solutions with genetic operators: selection, crossover and mutation.

Simulate a survival-of-the-fittest scheme to achieve high-quality solutions.

- Unified genetic search with Advanced Diversity Control (HGSADC):
  - Solution Representation *without trip delimiters* (Prins 2004)
  - High-performance local search-based *Education* procedure
  - Management of penalized infeasible solutions in two subpopulations
  - *Diversity & Cost objective for individuals evaluations*
Unified genetic search with advanced diversity control

- Solution Representation, *without trip delimiters*, (Prins 2004), one giant tour per (depot/day):

  ![MDPVRP solution](image.png)

  Individual in the genetic algorithm:

  a) Pattern chromosome

  \[
  \begin{array}{cccccccccccc}
  \text{Cust} & i & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
  \text{Pat} & \pi_i(P) & \{1,2\} & \{1,2\} & \{1,2\} & \{2\} & \{1\} & \{1,2\} & \{1,2\} & \{1,2\} \\
  \end{array}
  \]

  b) Depot chromosome

  \[
  \begin{array}{cccccccccccc}
  \text{Cust} & i & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
  \text{Dep} & \delta_i(P) & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
  \end{array}
  \]

  c) Giant tour chromosome

  \[
  \begin{array}{cccccccccccc}
  & \nu_{01}(P) & & & & & & & & & \\
  & 4 & 6 & 3 & 2 & & & & & & \\
  & \nu_{02}(P) & & & & & & & & & \\
  & 3 & 2 & 4 & 5 & 9 & 7 & 8 & & & \\
  & \nu_{11}(P) & & & & & & & & & \\
  & 9 & 7 & 8 & 5 & & & & & & \\
  & \nu_{12}(P) & & & & & & & & & \\
  & 8 & 9 & & & & & & & & \\
  \end{array}
  \]

- A polynomial “Split” algorithm based on a shortest path can be used to obtain the trip delimiters.
- Selection by binary tournament.
- New periodic crossover with insertions: inherits customer-to-day assignments and subsequences from the two parents.
Unified genetic search with advanced diversity control

- **Education replaces mutation**
  - Two-level local search:
    - Route-improvement (RI) : insert, swap, 2-opt, 2-opt* for each (day, depot) separately.
    - Pattern-improvement (PI) : changing customer-to-days assignments.
    - Called in Sequence PI-RI-PI
Unified genetic search with advanced diversity control

- Speed-up techniques and memories
  - Granular search (Toth and Vigo 2003): Testing only moves in RI involving correlated nodes (X% close in terms of distance)
  - Memories for moves and for insertion costs in any route.

- Repair = Increase penalties and use education
- The effect of route-constraints relaxations (load and duration) during local search...

- Helps transitioning between structurally different feasible solutions:

- Adaptation of penalty coefficients.
Biased Fitness is a tradeoff between ranks in terms of penalized cost $\text{fit}(I)$, and contribution to the diversity $dc(I)$, measured as a distance to others individuals.

$$BF(I) = \text{fit}(I) + \left(1 - \frac{\text{nbElit}}{\text{nbIndiv} - 1}\right) \times dc(I)$$

- Used during selection of the parents
  - Balancing strength with innovation during reproduction, and thus favoring exploration of the search space.
- and during selection of survivors:
  - Removing the individual $I$ with worst $BF(I)$ also guarantees some elitism in terms of solution quality.
Computational Experiments on VRP instances

- Extensive computational experiments on 26 structurally different VRP variants and 39 sets of benchmark instances.
  - A total of 1008 problem instances.

- Comparing UHGS with the best problem-tailored method for each benchmark and problem. 10 runs on each problem.

- In the following, we indicate for each method:
  - % Gap to the best known solution (BKS) of an average run (out of 10 for UHGS).
  - % Gap to the BKS of a best run (out of 10 for UHGS).
  - Computational effort (total work time) for an average run
  - Type of processor used.
## Computational Experiments on VRP instances

<table>
<thead>
<tr>
<th>Variant</th>
<th>Bench.</th>
<th>( n )</th>
<th>Obj.</th>
<th>State-of-the-art methods</th>
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Computational Experiments on VRP instances

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Computational Experiments on VRP instances

- Matching or outperforming the current best 180 problem-dedicated algorithms from the literature for 29 problems and 38 benchmark instance sets !!!

- BKS has been found or improved on 954/1008 problems
- Strictly improved on 550/1008 problems.
- All known optimal solutions have been retrieved !!
- Run time of a few minutes for average-size instances (n = 200-300)
- Standard deviation below 0.1%

- Suitable as an optimization method to generate routes for our HOS regulations assessment.
Thank you for your attention!

- For further reading, and follow-up works:
  - These papers + some others + slides can be found at [http://w1.cirrelt.ca/~vidalt/](http://w1.cirrelt.ca/~vidalt/)
Hours of Service Regulations in Road Transport

Fatigue

Truck driver fatigue is internationally recognized as a significant factor in 15-50% of all commercial road transport accidents. To improve road safety, governments worldwide are tightening truck driver regulations. Some regulatory initiatives also limit the number of hours a driver can work, as illustrated in the diagram. This helps reduce the risk of accidents caused by fatigued drivers.

Truck Driver Scheduling

Problem: Given a sequence of customer locations to be visited within a given time frame and a schedule of available time slots, the objective is to optimize the truck driver’s route while ensuring he completes his tasks. This is illustrated in the diagram, where a feasible time schedule is calculated for a given number of tasks and time frame.

Asvin Goel, Thibaut Vidal
Seminar UFPB, 15 March 2013

Regulatory Impact Analysis

We assume that center looks to minimize total costs. This means using hybrid genetic search. Analyze solutions regarding total costs and road safety. Fatigue: Risk factors: Speed, hours of service, and work environment. See http://www.aaa.org/research/hours/8414.html

Vehicle Routing

In many applications we need to reduce hours of service regulations when optimizing vehicle routes. This is illustrated in the diagram, where a route optimization algorithm is used to minimize total travel time while adhering to regulatory constraints.
Hours of Service Regulations in Road Transport

Fatigue

- Fatigue is a significant factor in up to 30% of all commercial road transport accidents.

Truck Driver Scheduling

- A sequence of customer locations to be visited with given start and end times, subject to the constraints of service regulations such as the number of hours a driver can work.

Regulatory Impact Analysis

- To minimize costs and maximize safety, regulations must be analyzed for their impact on costs and safety.

- Analysis of a truck driver's schedule for fatigue.

Vehicle Routing

- In many applications, we need to consider hours of service regulations when optimizing vehicle routes.
Asvin Goel, Thibaut Vidal

Seminar UFPB,
15 March 2013
Fatigue

Truck driver fatigue is internationally recognised as a significant factor in 15-20% of all commercial road transport crashes.

To improve road safety governments worldwide are adopting stricter hours of service regulations for truck drivers.

Some regulations introduce a "chain of responsibility" so that dispatchers can be made liable for unrealistic schedules.
Hours of Service Regulations in Road Transport

Fatigue

Truck driver fatigue is internationally recognized as a significant factor in 55-70% of all commercial road transport accidents.

The importance of fatigue legislation is growing. European legislation, for example, includes a "Factor of Reservable Duty" so that drivers can use it to plan their休息 activity.

Regulatory Impact Analysis

No research has been done to determine total costs

Vehicle Routing

In many applications we must consider hours of service regulations when optimising vehicle routes.

Truck Driver Scheduling

Problem: Given a sequence of customer locations to be visited with a given time window, find the optimal route that minimizes the total distance traveled.

Surer et al. (2013) proposed a mixed integer linear programming solution to this problem.

Asvin Goel, Thibaut Vidal

Seminar UFPB, 15 March 2013
United States

- Rest periods must have a duration of at least 10 hours
- At most 11 hours of driving between rests
- No driving if 14 hours or more have elapsed since the end of the last rest period
- From July 2013: No driving if 8 hours or more have elapsed since the end of the last rest or break period of at least 30 minutes
Canada

- Rest periods must have a duration of at least 8 hours
- At most 13 hours of driving between rests
- No driving if 14 hours of on-duty time are accumulated
- No driving if 16 hours or more have elapsed since the end of the last rest period
- Every day at least 10 hours of off-duty time including 2 hours of break which may be taken in blocks of no less than 30 minutes
European Union

- Rest periods must have a duration of at least 11 hours
- At most 9 hours of driving between rests
- A break of 45 minutes must be taken after 4½ hours of driving
- Rest periods must be completed 24 hours after end of previous rest
- Breaks may be split in a first part of 15 minutes and a second part of 30 minutes
- Rests may be split in a first part of 3 hours and a second part of 9 hours
- Three times in a week a rest may be reduced to 9 hours
- Two times in a week driving between rests can be extended to 10 hours
Australia
(Standard Hours)

- Rest periods must have a duration of at least 7 hours
- In any period of 5½ hours a driver must not work for more than 5¼ hours
- In any period of 8 hours a driver must not work for more than 7½ hours
- In any period of 11 hours a driver must not work for more than 10 hours
- In any period of 24 hours a driver must not work for more than 12 hours
- In any period of 24 hours a driver must have a rest
Australia
(Basic Fatigue Management)

- Rest periods must have a duration of at least 7 hours
- In any period of 6¼ hours a driver must not work for more than 6 hours
- In any period of 9 hours a driver must not work for more than 8½ hours
- In any period of 12 hours a driver must not work for more than 11 hours
- In any period of 24 hours a driver must not work for more than 14 hours
- In any period of 24 hours a driver must have a rest
Regulations in Road Transport

Truck Driver Scheduling

Problem:
Given a sequence of customer locations to be visited within given time windows, find a schedule complying with applicable hours of service regulations such that each customer is visited within the respective time window.

Solution Approach

Vehicle Routing

Asvin Goel, Thibaut Vidal
Seminar UFPB,
15 March 2013
Truck Driver Scheduling

Problem:
Given a sequence of customer locations to be visited within given time windows, find a schedule complying with applicable hours of service regulations such that each customer is visited within the respective time window.

Solution Approach
- All on-duty periods are scheduled as early as possible and with minimal duration.
- All off-duty periods are scheduled as late as possible and with minimal duration.
- Duration of off-duty periods is only increased if beneficial.

Example:

This schedule can be generated as follows:
- Work
- Drive
- Rest
- Drive
- Rest
- Work
- Drive
- Rest
- Work

Duration of on-duty periods:

Duration of off-duty periods:
of service regulations such that each customer is visited within the respective time window.

\[ t_{1}^{\text{min}} = t_{1}^{\text{max}} \]

\[ [t_{2}^{\text{min}}, t_{2}^{\text{max}}] \]

\[ [t_{3}^{\text{min}}, t_{3}^{\text{max}}] \]
Truck Driver Scheduling

Problem:
Given a sequence of customer locations to be visited within given time windows, find a schedule complying with applicable hours of service regulations such that each customer is visited within the respective time window.

\[ t_{\text{min}} = t_{1}^{\text{max}} \quad \left( t_{2}^{\text{min}}, t_{2}^{\text{max}} \right) \quad \left( t_{3}^{\text{min}}, t_{3}^{\text{max}} \right) \]

Diagram:
- All on-duty periods are scheduled as early as possible and with minimal duration.
- All off-duty periods are scheduled as late as possible and with minimal duration.
- Duration of off-duty periods is only increased if beneficial.

Example:
For the given schedule:

1. Drive 1 hour, rest 6 hours, drive 1 hour.
2. Rest 10 hours, drive 1 hour, rest 1 hour.
3. Drive 1 hour, rest 6 hours.

This schedule can be generated as follows:
- Period 1: Drive (1-2)
- Period 2: Rest (3-12)
- Period 3: Drive (13-14)
- Period 4: Rest (15-16)
- Period 5: Drive (17-18)
- Period 6: Rest (19-20)
- Period 7: Drive (21-22)
- Period 8: Rest (23-24)

Ensure all constraints are met.
Solution Approach

- All on-duty periods are scheduled as early as possible and with maximal duration
- All off-duty periods are scheduled as late as possible and with minimal duration
- Duration of off-duty periods is only increased if beneficial

Example:

\[ t_{1}^{\text{min}} = t_{1}^{\text{max}} \]

\[ [t_{2}^{\text{min}}, t_{2}^{\text{max}}] \]

\[ [t_{3}^{\text{min}}, t_{3}^{\text{max}}] \]

This schedule can be generated as follows:

\[ ((\text{WORK}, 1). (\text{DRIVE}, 6). (\text{IDLE}, 1). (\text{WORK}, 1). (\text{DRIVE}, 5) \cdot (\text{REST}, 10) \cdot (\text{DRIVE}, 6) \cdot (\text{REST})^2) \cdot (\text{WORK}, 1). \]

Minimal duration
Duration of rest is increased to avoid waiting time
Tree Search

$S_1$ $S_2$ $S_3$ $S_4$

$S_{11}$ $S_{21}$ $S_{31}$ $S_{41}$

$S_{11}$ $S_{22}$ $S_{32}$ $S_{42}$

$S_{11}$ $S_{22}$ $S_{33}$ $S_{43}$

$S_{11}$ $S_{22}$ $S_{34}$ $S_{44}$
Removal of dominated schedules
Heuristic removal of schedules
Truck Driver Scheduling

Problem:
Given a sequence of customer locations to be visited within given time windows, find a schedule complying with applicable hours of service regulations such that each customer is visited within the respective time window.

Solution Approach

- All on-duty periods are scheduled as early as possible and with minimal duration.
- All off-duty periods are scheduled as late as possible and with minimal duration.
- Duration of off-duty periods is only increased if beneficial.

Example:

This schedule can be generated as follows:

- Work (1), Drive (2), Rest (3), Work (4), Drive (5), Rest (6), Work (7), Drive (8), Rest (9), Work (10), Drive (11), Work (12), Drive (13), Work (14).
Vehicle Routing

In many applications we must consider hours of service regulations when optimising vehicle routes.
Vehicle Routing

In many applications we must consider hours of service regulations when optimising vehicle routes.
Hybrid Genetic Search

Population
- Survival of the fittest

Reproduction
- Binary tournament

Education
- Local search
Population

Survival of the fittest

- Individuals are represented as giant tours without trip delimiters
- Fitness value is based on (penalised) costs and diversity
Reproduction

Parents

Binary tournament

Ordered crossover

Offspring
Education

Local search
- 2-opt, 2-opt*, cross

Change of representation

Evaluation of routes
- Distance (straight forward)
- Precedence capacity violations (straight forward)
- Precedence (interferences)
- Number of service regulations must be considered with
- If a customer cannot be visited within time windows, only those schedules with interval obey are kept
- Use some optimization techniques to reduce computational effort
Change of representation

**INDIVIDUAL REPRESENTATION**

1 3 7 8 2 4 6 5

**SOLUTION REPRESENTATION**

0 1 3 0 0 7 8 2 4 0 0 6 5 0

Diagram: 1 -> 3 -> 7 -> 8 -> 3

- **SPLIT**: Placement of depot visits
- **REMOVAL**: Removal of depot visits
Evaluation of routes

- Distance (straight forward)
- Penalised capacity violations (straight forward)
- Penalised lateness
  - Hours of service regulations must be complied with
  - If a customer cannot be visited within time windows only those schedules with minimal delay are kept
  - For some regulations heuristic scheduling methods are used to reduce computational effort
Education

Local search
- 2-opt, 2-opt*, cross

Change of representation

Evaluation of routes
- Distance ( Straight forward)
- Prevents capacity violations ( straight forward)
- Prevents interference
- Means of service regulations must be considered
- If a customer cannot be visited within time windows
  only those schedules with minimal delay are kept
- Due to large problem size, heuristic scheduling methods
  are used to reduce computational effort
Hybrid Genetic Search

Population
- Survival of the fittest
- Individuals are represented as genetic codes without triplications
- Fitness value is determined by the code's costs and diversity

Reproduction
- Binary tournament
- Parents
- Ordered crossover
- Offspring

Education
- Local search
- Local search is applied to the offspring
Computational Experiments

- Tested on 56 instances based on well-known VRPTW instances by Solomon
- Compared with best-known solutions for European Union regulations

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<th>Prescott-Gagnon et al. (2010)</th>
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Avg. CPU: 11 min (OPT 2.3 Ghz)  
Avg. CPU: 54 min (XE 2.83 Ghz)

51/56 best-known solutions, 29/56 new best solutions

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<tr>
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Avg. CPU: 88 min (OPT 2.3 Ghz)  
Avg. CPU: 228 min (XE 2.83 Ghz)

52/56 best-known solutions, 43/56 new best solutions
Vehicle Routing

In many applications we must consider hours of service regulations when optimising vehicle routes.
Regulatory Impact Analysis

- We assume that carrier seeks to minimise total costs
- Optimise routes for different regulations using hybrid genetic search
- Analyse solutions regarding total costs and road safety
- Fatigue/Risk Index Calculator provided by Health and Safety Executive - UK (http://www.hse.gov.uk/research/rrhtm/rr446.htm)
## Total costs

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Hours of Service Regulations in Road Transport

Fatigue

Truck driver fatigue is internationally recognized as a significant factor in 15-30% of all commercial road transport accidents. To improve road safety, governments worldwide are adopting stricter hours of service regulations for truck drivers. Some regulations introduce a “rule of reasonable duty” so that dispatchers can be more flexible for non-essential schedules.

Regulatory Impact Analysis

- No consensus on what causes to minimize total costs
- Possible options for different regulations using hybrid genetic search
- Analyse solutions regarding total costs and road safety
- Fatigue Risk Index Calculated by Health and Safety Executive – UK

http://www.hse.gov.uk/manufacturing/0164.html

Truck Driver Scheduling

Given a sequence of customer locations to be visited within given time windows, find the best (in cost) solution that satisfies the constraints of hours of work regulations such that each customer is visited only once in the respective time window.

Asvin Goel, Thibaut Vidal
Seminar UFPB, 15 March 2013

Vehicle Routing

In many applications, we need to model hours of service regulations when optimising vehicle routes.

- Vehicle Routing Complexities
- Graph Theory Concepts
- Solution Methodologies
Thank you very much for your attention!!

For further reading:


• A. Goel and L. -M. Rousseau, Truck Driver Scheduling in Canada (2012), in: Journal of Scheduling (to appear)

• A. Goel and L. Kok, Truck Driver Scheduling in the United States (2012), in: Transportation Science (to appear)


• A. Goel, Truck Driver Scheduling in the European Union (2010), in: Transportation Science, 44:4(429-441)

• A. Goel, Vehicle Scheduling and Routing with Drivers' Working Hours (2009), in: Transportation Science, 43:1(17--26)