Measuring and Modelling Crowd Flows - Fusing Stationary and Tracking Data

Martin Treiber  TGF 15, Nootdorp, Holland
Rennsteiglauf (a German Marathon)
Inline-skating event (Dresden)
Pedestrian streams at the Hajj
"Stationary Detector Data" (SDD)

- Each athlete has an RFID chip
- When passing the starting line, the start time will be recorded
- When passing stations (refreshments), split times are taken
- At the finish, the final time is recorded

=> Passage times (and some socioeconomic data and the starting wave) are known at fixed locations xDet_i
Speed distributions (Vasaloppet 2012)

Between stations 1 and 2: Gaussian

Between stations 2 and 3: the slowest wave 10 is not Gaussian: evidence for congestion!
Live GPS-Tracking for Events

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New York City Marathon

November 1, 2015
Simulation approach I: dedicated, fully microscopic multilane model

► Time: about 1 minute

► Time: about 10 minutes

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Simulation approach II: macroscopic hybrid dispersion-transport-LWR model

► Fast athletes remain fast, and slow remain slow: dispersion-transport equation instead of diffusion-transport equation

► Speed distribution of each block k is Gaussian:

\[ V_k \sim N(\mu_k, \sigma_k^2) \]

► If traffic demand (athletes per second) exceeds the local capacity, traffic breaks down and congested traffic is described by a LWR model with a triangular fundamental diagram

► In jams, everybody is equal – there are no longer block differences
Simulation approach III: effectively 1d microscopic model: IDM with flow-conserving bottlenecks
Pedestrian stop-and-go traffic in the IDM

bottleneck
Determining the flow-conserving bottleneck: characteristics of the track

- Vertical profile
- Width profile
- Local capacity

Detector station S1, S2, S3, S4, S5, S6, S7

w [lanes]

K [athletes/s]

bottleneck 1
Model-based jam detection/prediction using the LWR with diagonal fundamental diagram

3 parameters: select three from $V_0$, $c$, $T$, $\rho_{\text{max}}$, and $Q_{\text{max}}$

Usage I: Congested component of the macroscopic hybrid crowd-flow model

Usage II: Real-time jam detection and short-term prediction

=> check on vehicular flow data: proof of robustness

=> apply to pedestrian/athlete SDD and FAD generated by the IDM: proof of concept for the application to crowd flow
Real-time determination/short-term prediction of the upstream jam front

Flow (and density):

\[ Q(x, t) = \begin{cases} 
Q_d(x, t) & \text{free traffic (demand)} \\
Q_s(x, t) & \text{jam due to a bottleneck (supply)} 
\end{cases} \]

Front propagation:

\[ \frac{dx_{up}}{dt} = \frac{Q_s(x_{up}, t) - Q_d(x_{up}, t)}{\rho_s(x_{up}, t) - \rho_d(x_{up}, t)} \]

Congested flow and density:

\[ Q_s(x, t) = K \left( x_B, {t-(x-x_B)} \right), \]
\[ \rho_s(x, t) = \left( 1 - \frac{Q_s(x,t)}{K(x)} \right) \rho_{max}(x) \]

Jam dissolution:

\[ \frac{dx_{up}}{dt} > 0, \quad x_{up} = x_B \]

Estimation method:

\[ Q_s(x, t) = Q_{D2} \left( \frac{t-(x-x_{D2})}{c} \right), \quad Q_d(x, t) = Q_{D1} \left( \frac{t-(x-x_{D1})}{V_0} \right) \]
Schematic dynamics

Shockwave formula: \( c_{12} = \frac{(Q_1 - Q_2)}{(\rho_1 - \rho_2)} \) plus propagation velocities \( V_0 \) and \( c \)
Application to vehicular traffic flow: calibrating the parameters

Data: only one-minute flows from stationary detectors

- parameters: $Q_{\text{max}}$, $V_0$, and $c$

- objective function: 1-norm of positional errors of front
Validation: Apply calibrated model to another congestion on the other direction

Congestion on the A5-South with LWR prediction as calibrated by the A5-North jam of the previous slides
Application to an athlete crowd flow, e.g., Marathon, cross-country ski, inline skating
Calibration using six FA trajectories

V_0 = 9 km/h
\( c = -4.5 \text{ km/h} \)
Q_{max} = 2300/h
Validation to another simulated jam

\( V_0 = 9 \text{ km/h} \)
\( c = -4.5 \text{ km/h} \)
\( Q_{\text{max}} = 2300/\text{h} \)
Dynamic calibration 1 using the second FA trajectory

V0 = 9 km/h
\( c = -4.0 \text{ km/h} \)
Qmax = 2300/h
Dynamic calibration 2

\[ V_0 = 9 \text{ km/h} \]
\[ c = -4.0 \text{ km/h} \]
\[ Q_{\text{max}} = 2350/\text{h} \]
Dynamic calibration 3

\[ V_0 = 9.5 \text{ km/h} \]
\[ c = -4.2 \text{ km/h} \]
\[ Q_{\text{max}} = 2420/\text{h} \]
Conclusions

- Unidirectional crowd flow (running, cross-country skiing, and inline-skating) including jam formation can be simulated macroscopically by a **simple dispersion-transport-LWR model** and microscopically by the **reparameterized IDM with flow-conserving bottlenecks**.

- The complete LWR model with tridiagonal FD and location-dependent local capacity can be applied to **detect and short-term predict** jam fronts of crowd and vehicular flow by using two stationary counting detectors.

- The detection algorithm can be **calibrated in real-time** by **Floating-Athlete (FA) trajectories** e.g., taken by smartphones. A few athletes/vehicles per hour is sufficient.
Passage time distributions: Dispersion-transport model

\[ f_T^k(T|x) = \frac{x f_v^k \left( \frac{x}{T} \right)}{T^2}, \]

\[ f_v^k(v) \propto \exp \left[ \frac{(v-\mu_k)^2}{2\sigma_k^2} \right] \]

Rennsteig Half Marathon 2012 at finish
Between stations 1 and 2: skewness > 0

Between stations 2 and 3: evidence for congestion!
Traffic demand as predicted by the dispersion-transport model

► Partial flow and density of block k at distance x and time t after the start of this block:

\[ Q_d^k(x, t) = n_k f_T^k(t | x), \]
\[ \rho_d^k(x, t) = \frac{Q_d^k(x, t)}{x/t} \]

► Total demand and density (free flow):

\[ Q_d(x, t) = \sum_k Q_d^k(x, t - \Delta t_k) \]
\[ \rho_d(x, t) = \sum_k \rho_d^k(x, t - \Delta t_k) \]
Breakdown to congested traffic

- Local capacity:

\[ K(x) = K_{\text{spec}}(\alpha(x)) \, w(x) \]

- Breakdown condition:

\[ Q(x, t) > K(x) \]

- The bottleneck location \( x = x_B \) is the position where the breakdown condition is satisfied for the first time:

K [athletes/s]

[Diagram showing local capacity with three bottlenecks]
II What Can a Traffic Flow Modeler Do?

► 1. Optimize the spatial configuration of the starting field
Thank you for your attention!

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Overview

- “Traffic Jams” in Mass Sports Events
- What Can a Traffic Flow Modeler Do?
- A Macroscopic Model
- Simulation of Three Events
- Discussion
II What Can a Traffic Flow Modeler Do?

1. Optimize the spatial configuration of the starting field, part II

No blocks
(athletes can take positions by self-assessment)
III. Modelling

**Geometrical Class**

- **Unidirectional and lane-based:**
  Vehicular traffic, cross-country skiing
  (classic style)

- **Unidirectional and non-lane-based:**
  Vehicular traffic in developing countries
  (mixed traffic), cross-country skiing
  (skating style), running, inline skating,
  pedestrian traffic with a definite target

- **Neither unidirectional nor lane-based:**
  Pedestrian traffic in city centers

**Model Class**

- micro, macro
- micro, macro
- only micro!
Jizerska Padesatka (Czech Republic)
Optimize the temporal course of action in the starting phase

- simultaneous mass start
- Block/wave start

Wave 2: Delay 5 minutes
Wave 3: Delay 10 minutes
Wave 4: Delay 15 minutes
Wave 5: Delay 20 minutes