CRD503 · WEEK 1

Why Model Crowds

From real disasters to a computer model you can actually trust. No prior simulation knowledge needed — every word and every number explained.

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What this field is, in one sentence

Crowd dynamics simulation is the science of using a computer to predict how groups of people move — so engineers can make buildings safer before anyone is hurt.

Everything in this course is detail underneath that one sentence.

Part 1 · First, the words

Seven terms. Learn these and the rest is easy.

The everyday words

Crowd
Many people sharing a space at the same time.

Density
How crowded a spot is: people per square metre.

Simulation
A computer imitation of reality, used to test ideas safely.

Ground truth
The real, correct answer you check a guess against.

> You don't have to memorise these — each comes back in context. This slide is a reference you can point back to.

The two tools we use

JuPedSim — a free, open-source **pedestrian crowd video-game engine**. You give it a floor plan and a set of walkers with destinations; it computes, step by step, where each person walks.

PedPy — a companion tool that **reads the walking paths** JuPedSim produces and reports two plain numbers per moment: how crowded it was (density) and how fast people moved (speed).

🎮 Think of **JuPedSim as a tiny, realistic crowd video game**, and **PedPy as the scoreboard** that watches the game and writes down the density and speed.

Two terms we’ll meet later — defined now

Fundamental diagram — the curve showing how **walking speed changes as a space fills up**. As density rises, speed falls. It is the single most important pattern in this field.

Voronoi — a way of splitting a floor so that **every point belongs to its nearest person**. Each person ends up owning a patch of floor. (We draw this in Part 4.)

Both words look intimidating and both are simple. You will see each one built up from an everyday picture before any maths appears.

Part 2 · Why bother?

What’s the point of modelling a crowd at all?

Crowd deaths are physics, not panic

Reports often blame "panic" or a "stampede." The science says otherwise.

THE MISDIAGNOSIS

"Panic" points blame at individual people — as if the crowd chose to be dangerous.

WHAT ACTUALLY HAPPENS

Past a critical density, small involuntary body movements pass **force from person to person**. People lose their footing; the pressure behind them cannot be resisted by will alone.

A crowd can become a lethal physical system no single person intended.

Three disasters, three questions

Hillsborough — 1989

- **96 fatalities** on a standing stadium terrace
- A bounded pen over-filled in the first minutes of the match
- The hazard was **local density**, not total stadium capacity
- Pressure in a packed crowd is a lethal force on its own

> **Question to a simulator:**
> At what *local* density does a bounded section become lethal?

Inflow to a pen

↓

Local density rises

↓

Force chains form

↓

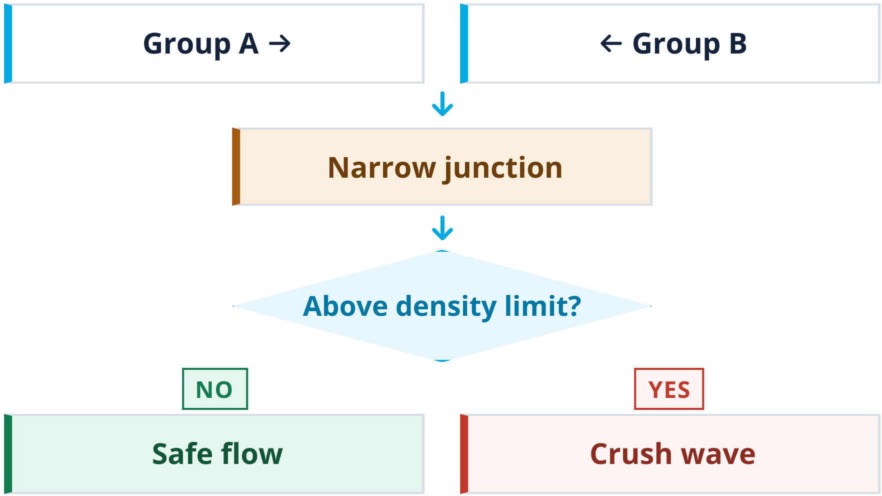
People lose footing

↓

Crush injuries

Mecca Hajj — 2015

- **> 2,000 fatalities** (independent estimates) near the Mina Jamarat Bridge
- Two crowds met head-on at a narrow junction
- Catastrophes recurred at the *same* site (1990, 1994, 1998) despite redesign
- Rebuilding the geometry alone did **not** remove the hazard

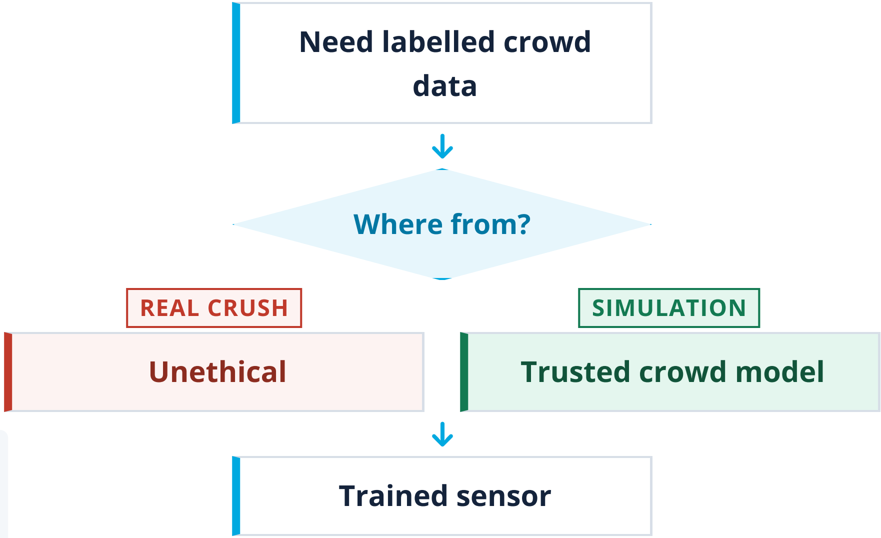


Question to a simulator:
Can pilgrims be re-routed *before* density crosses the lethal threshold?

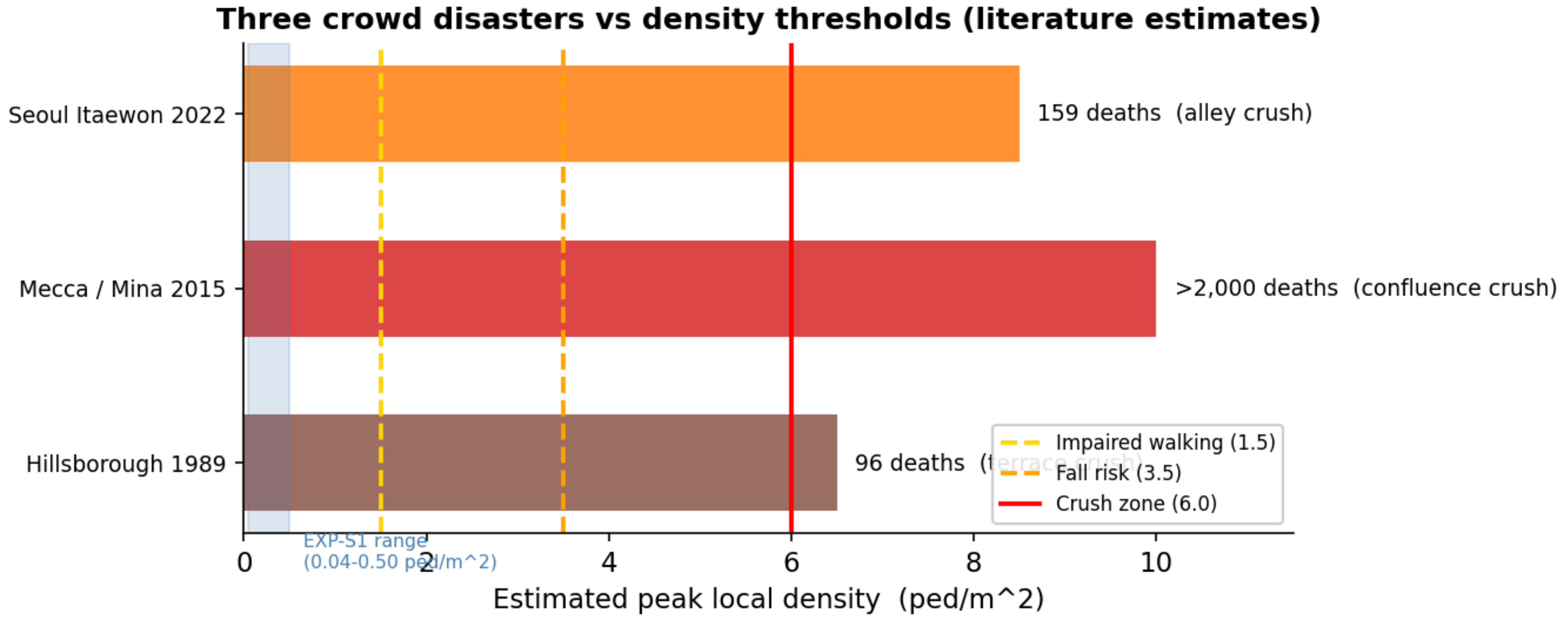
Seoul Itaewon — 2022

- **159 fatalities** in a Halloween crowd crush
- No event organiser; no crowd management at all
- Revellers funnelled into a narrow sloping lane from several directions
- It was an **outdoor street network**, not a stadium with one gate

Question to a simulator:
How do we build a sensing system to warn us *before* the next festival?



Where the danger lives — and where we test



Peak densities are **literature estimates**, not measurements. The lab's own runs (blue band) sit deliberately in the safe range — about ten times less crowded than the lowest lethal estimate.

Part 3 · One model, three jobs

The same simulator gets used in three very different ways

Three uses of a crowd model

SAFETY ASSESSMENT

Check whether a venue can hold its crowd **without dangerous spots**. Needs the density and pressure physics to be *qualitatively* right.

FACILITY DESIGN

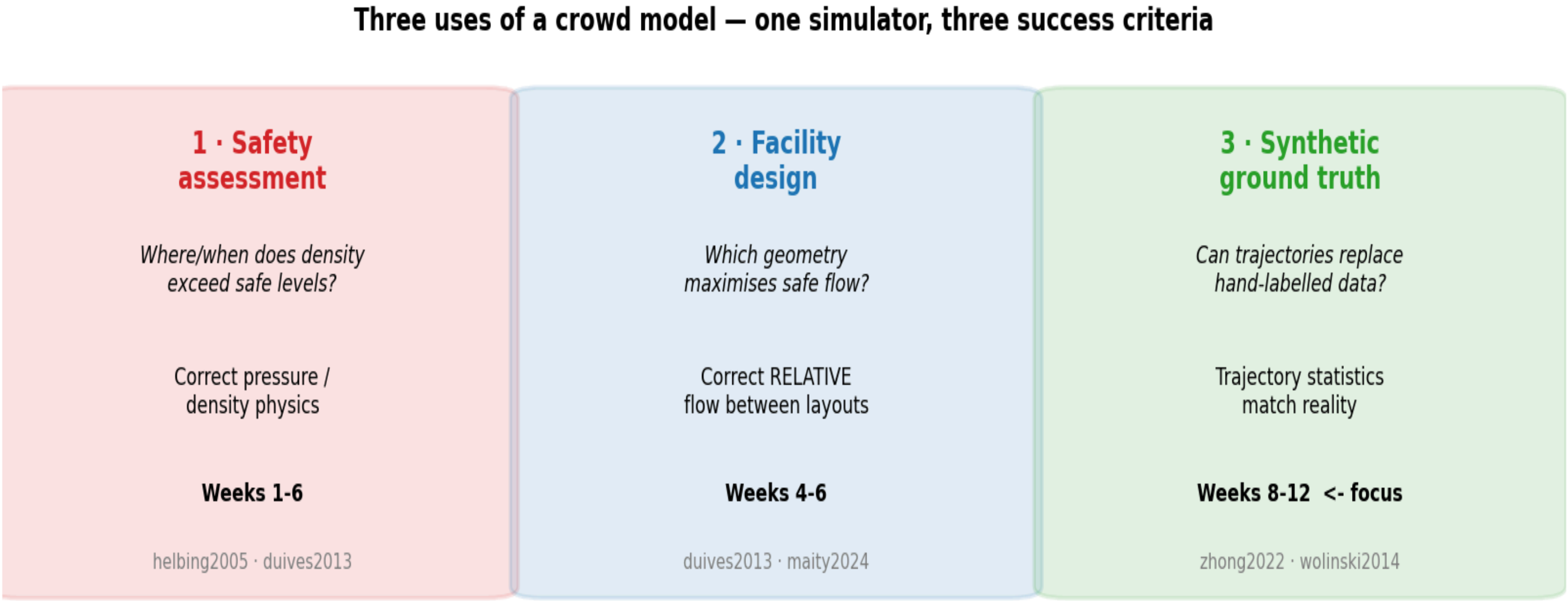
Improve a layout — wider doors, a column upstream of a bottleneck. Needs the **relative flow** between designs to be right.

SYNTHETIC GROUND TRUTH

Generate fake-but-realistic crowd data to train sensors. Needs the **trajectory statistics to match reality** — the strictest test.

One simulator, three jobs — three different meanings of "correct."

The three jobs, pictured



This course's primary target is the green box — synthetic ground truth for sensing.

Part 4 · The lab’s first numbers

Before any theory — let’s just look at three measurements

What "EXP-S1" means

> **EXP-S1** — short for **Experiment Series 1**: the lab's reference pedestrian-flow dataset. It is the same little experiment we return to almost every week, so we give it a short name.

THE SETUP

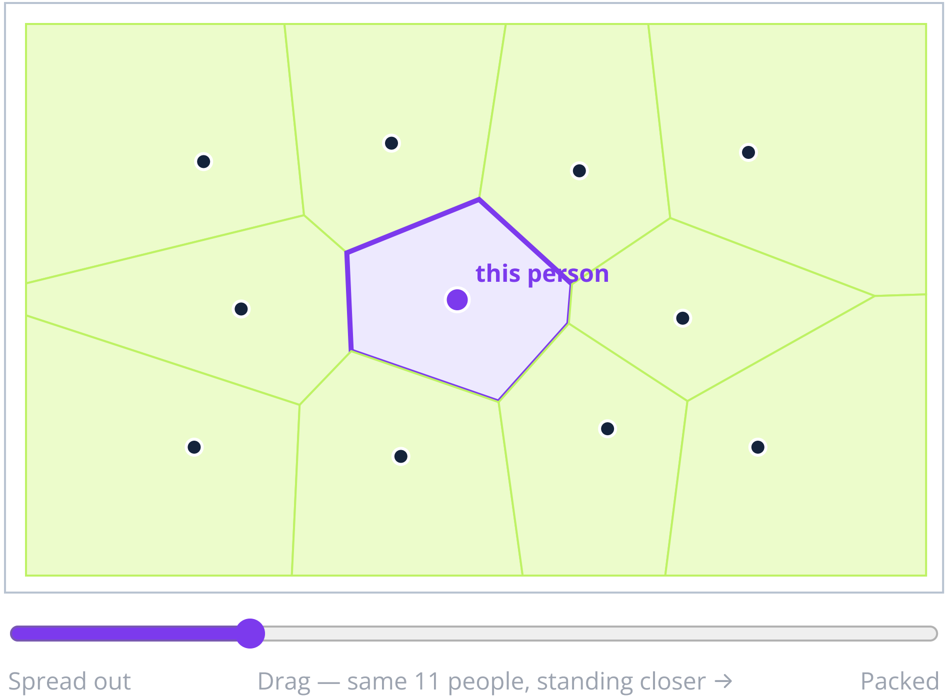
A **96 m² seminar room** (8 m × 12 m). Walkers loop around a closed path so the crowd never empties out.

WHAT WAS RECORDED

The lab ran it at **three crowd sizes** and recorded **180 seconds** of steady walking at each. That gives three density-and-speed measurements.

What we need before reading the numbers

🗺️ Split the floor so **every point belongs to its nearest person** — each person owns a patch. **Smaller patch = more tightly packed**, so a person's local density is just **one divided by their patch area**.



$$\varrho_i = \frac{1}{|A_i|}$$

Person **i**'s density **ρ** ("rho", people/m^2) = **1** ÷ the area **$|A_i|$** of their patch.

HIGHLIGHTED PERSON · LIGHT

patch $|A|$ = **2.49** m²

ρ = 1 / 2.49 = **0.40** ped/m²

Drag the slider: same headcount, but packing them tighter **shrinks** the patch and ρ **climbs** — the **Voronoi** idea from Part 1, made exact.

EXP-S1 — three crowd levels

The lab's three verified runs, in the 96 m² room

Low density	Moderate density	Crowded
ρ = 0.04 ped/m²	ρ = 0.17 ped/m²	ρ = 0.50 ped/m²
1.17 m/s	**1.14 m/s**	**0.71 m/s**
Free-flow regime	First interactions	Avoidance active
Near normal walking pace	~3% slowdown	39% speed drop

As the room fills up, walking speed falls. Every single time.

What a perfect downward trend looks like

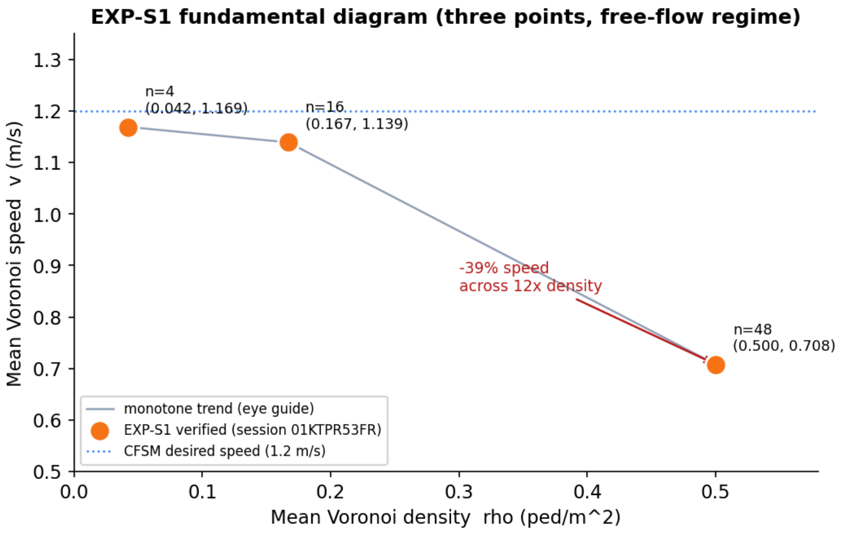
📉 A **correlation score of −1.0** means: **every single time** density went up, speed went down — no exceptions, no wobble. It is the strongest possible "these two move in opposite directions."

Spearman rank correlation — a score from **−1 to +1** for whether two things move together. +1 = always rise together · 0 = no pattern · −1 = one always rises as the other falls.

EXP-S1 RESULT

Across the three runs the score is exactly **−1.0**: speed fell at every step up in density. This is the defining signature of the fundamental diagram.

The three points, as measured



- These are the **raw measured points** — no fitted line yet
- Speed falls every step: **1.17 → 1.14 → 0.71 m/s**
- A **12× density** rise costs **≈ 39%** of free-flow speed
- All three sit in the **free-flow / light-congestion** range of the small room

> Don't draw a curve through them today. Deriving the curve is Week 2.

Why we quote a steady-state number

🚿 Turn on a shower and the temperature swings for a few seconds before **settling**. You quote the settled temperature, not the wild first moment. A crowd is the same: it takes a little while to **settle into its steady flow**.

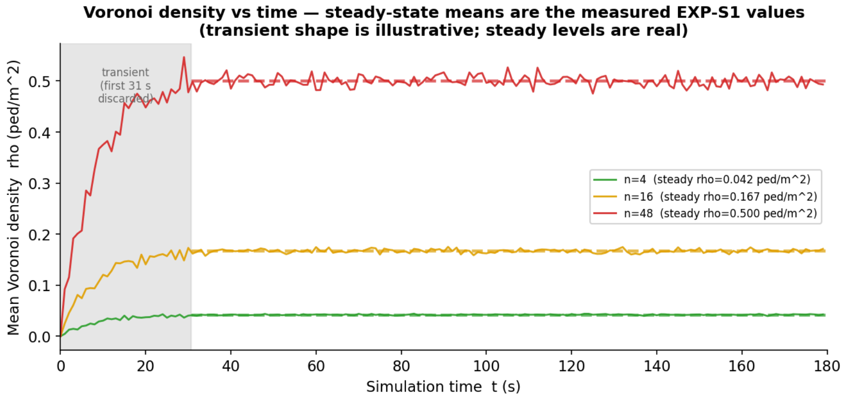
THE SETTLED VALUE

The density and speed we quote are **steady-state means** — averages taken after the crowd has settled, not in the messy first moments.

THE STARTUP WE DISCARD

The lab drops the first **17% of each run** — the first **30.6 seconds** of the 180-second run — before averaging.

Density settling over time



- Each line rises, then **settles** onto its steady value
- The number we quote is that **settled (steady-state) level**
- PedPy measures each person's density as **1 / their patch area**
- Settled levels are the **real measured** values; the rising shape is illustrative

Part 5 · Borrowing the curve

Someone already measured this trend on real people

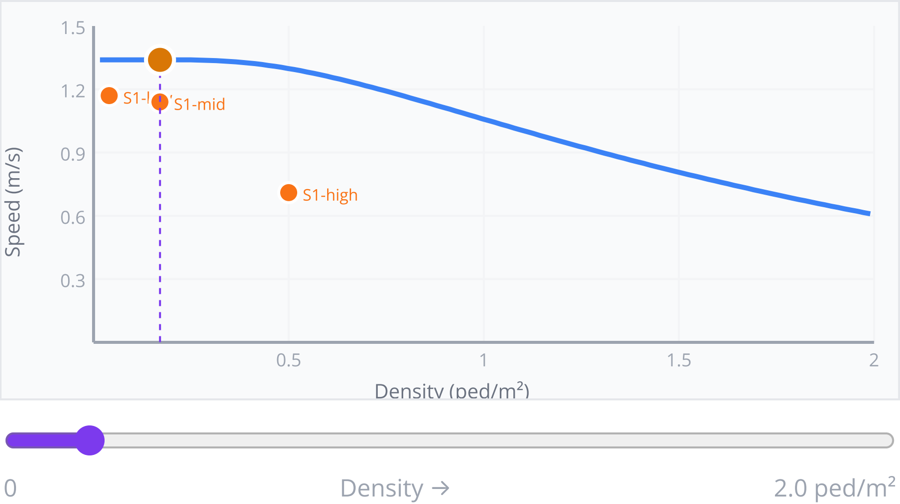
More people, slower walking — the universal law

🚦 On a motorway, **more cars means everyone slows down**; jam-packed means crawling. Crowds do exactly the same — walking **speed drops as the floor fills up**.

Fundamental diagram — the curve of **walking speed versus density**. The traffic-jam picture above *is* the fundamental diagram, drawn for people instead of cars.

Weidmann (1992) — a researcher who **measured this curve on real Swiss pedestrians** and fitted a tidy mathematical line through his data. That fitted line is the **blue reference curve** in the next slide.

Interactive — fundamental diagram explorer



Density
0.17 ped/m²

Speed (Weidmann)
1.34 m/s

Transitional

- The lab's three measured points
- Weidmann (1992) curve — measured on real people

Drag the slider. Do the lab's three points sit on Weidmann's reference curve? What might any gap mean?

Part 6 · The big payoff

Why a trusted simulation can replace real, hand-labelled data

What does "validated" mean?

When can a simulated crowd stand in for a real one?

THE PROMISE

Real labelled crowd data is expensive, ethically fraught, and tied to one building. A simulator could produce unlimited labelled data for free.

THE CONDITION

You may use simulated data **only if** the simulation has been **checked against real measurements** at the conditions you care about. That check is what "validated" means.

🎯 Tuning a simulator to match reality is like **turning knobs on a radio until the station comes in clearly** — you adjust the settings until the output matches the real signal as closely as you can.

The substitution rests on three claims

A simulated crowd path can replace a real one — but only if all three hold.

1. The simulator reproduces the real **speed-vs-density curve** (the fundamental diagram) for the place and crowding you care about. — Weeks 2–3
2. The simulation's **floor plan and walker settings** match the real building where the sensor will live. — Weeks 4–5
3. The **sensor's signal model** (how radio bounces around the room) is realistic for that geometry. — Weeks 8–9

> Today we begin to discharge **only claim 1** — and only its easiest, necessary part.

The validation equation — in words, then symbols

$$p^{\star} = \arg\min_{p} \ \mathrm{dist}(\mathrm{sim}(p),\ z_{\mathrm{ref}})$$

$\mathbf{z_{ref}}$ = the real reference data · **sim(p)** = what the simulator produces with settings **p** · **dist** = how far apart they are · **p★** = the settings with the smallest gap.

"Turn the simulator's knobs until what it produces looks as close as possible to real data."

> When the reference $\mathbf{z_{ref}}$ is a fundamental diagram, this is exactly the trend a WiFi or Bluetooth sensor would feel — which is why claim 1 reduces to reproducing that curve.

Part 7 · The semester ahead

The 12-week arc

CRD503 twelve-week arc (Week 1 highlighted)

Week	Theme	Advances
1	**Why model crowds**	**Safety - Design - GT**
2	The fundamental diagram	GT
3	Microscopic models I: social force	Safety - GT
4	Microscopic models II	Design
5	JuPedSim scenarios	Design - GT
6	PedPy measurement	GT
7	Voronoi density & the method trap	GT
8	Bottlenecks & the multi-room collapse	Safety - Design
9	Evacuation dynamics	Safety
10	Simulation as synthetic ground truth	GT
11	Validation against real trajectories	GT
12	Capstone: validated evacuation study	Safety - Design - GT

Reproduce it yourself

This week's workbook just reads the three numbers and checks the trend. Three steps:

1. **Type in the three measurements.** Paste the three (people, density, speed) triples — they are listed in the course portal — as plain constants.
2. **Check the trend.** Confirm the Spearman correlation between density and speed is exactly **−1.0** (speed falls at every step).
3. **Plot them.** Draw the three points as a scatter — density across, speed up. No fitted curve yet; that is Week 2.

> Nothing is downloaded this week. You are looking at three points on a curve whose shape you will derive over the next two weeks.

Week 1 recap

- **Crowd disasters are physics, not panic.** Three events — Hillsborough, Mecca, Seoul — each ask a simulator a different question.
- **One model, three jobs:** correct density/pressure physics (safety) · correct relative flow (design) · matching trajectory statistics (synthetic ground truth, the strictest).
- **The lab's three runs:** as density rose 0.04 → 0.50 ped/m^2, speed fell 1.17 → 0.71 m/s — a 39% drop across a 12× density rise, with a perfect −1.0 correlation.
- **Validated simulation can replace real data** — but only if three claims hold. Today began just **claim 1**, the fundamental diagram.
- **Week 2:** derive the speed-vs-density curve from scratch and place these three points against real-world measurements.

Further reading

- **Helbing et al. (2005)** — *Self-organized pedestrian crowd dynamics.* The social-force model and the counter-intuitive design solutions (e.g. a column upstream of a bottleneck). The founding reference for safety-assessment uses.
- **Duives et al. (2013)** — *State-of-the-art crowd motion simulation models.* Compares model families across motion cases and self-organisation phenomena; tells you which model can do which job.
- **Maity et al. (2024)** — *Meshfree particle method for macroscopic pedestrian flow.* Motivates the engineering need for accurate macroscopic crowd simulation in mass-gathering disasters.
- **Wolinski et al. (2014)** — *Parameter estimation and comparative evaluation of crowd simulations.* The validation-as-optimisation framework and the fundamental-diagram metric used all course.
- **Zhong et al. (2022)** — *Data-driven crowd modelling techniques: a survey.* Why both path-level and density-level fidelity are needed; background for the sim-to-real weeks.
- **Haghani et al. (2023)** — *A roadmap for crowd safety research (Swiss Cheese Model).* Documents the Seoul 2022 crush within the broader pattern of recurring crowd fatalities.

CRD503 · Week 1 complete

Next: Week 2 — derive the fundamental diagram and place the lab's three points against real-world measurements.