ICU Congestion:
the impact on patient flows

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*Based on joint work with Galit Yom-Tov (Columbia University), Hailey Kim (Columbia University), Marcelo Olivares (Columbia Business School), Gabriel Escobar (Kaiser Permanente)

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Capacity-Constrained Hospitals

- Growing demand for healthcare
- Pressure to cut costs

→ Congested units

→ Need to use resources efficiently
  - Quantitative analysis of operational data
  - Work with doctors and nurses involved in critical decisions

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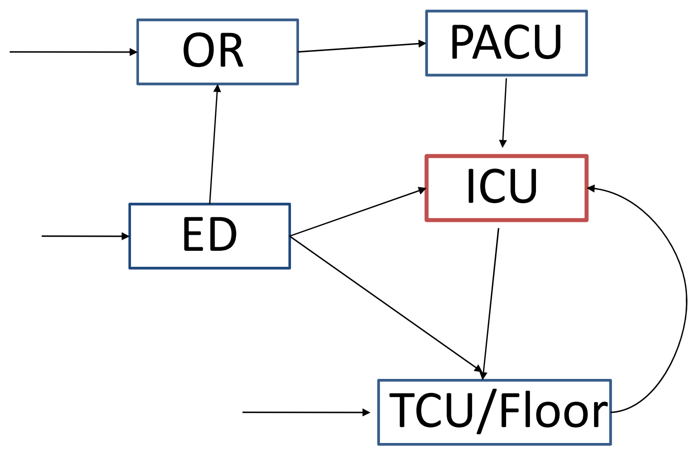
ICU flows



Provision of ICU Care

- ICUs provide highest level of care
  - 1 nurse for every 1 or 2 patients
- 20% of hospital costs, only 10% of beds
- Often operating at/near capacity

Congestion Effects in Hospitals

- Adaptive Mechanisms
  - Delays and Boarding [Chalfin et al 07], [Price et al 11]
  - Speedup [Kc and Terweisch 09], [Dobson et al 10], [Anderson et al 11], [Chan et al 11]
  - Admission Control [Azoulay et al 01], [Escher et al 04], [Shmueli et al 05]
  - Surgery Cancellation [Cady, Mattes and Burton 95]
  - Blocking [Allon, Deo and Lin 11]
- Limited standards on how to utilize these options
- Best practices typically 'philosophical'
- How to deal with congestion
  - Control and mitigate flow *in* and flow *out*

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Data Setting: Kaiser Permanente

- Integrated healthcare delivery system
- Northern California KP
  - Covers 30% of insured population
  - 3.3million members
  - 21 hospitals
  - 17million outpatient and ED visits/year
  - 250,000 hospitalizations/year
  - Division of Research (Oakland, CA)
  - 2006-2010, deployed EMR system in all hospitals/clinics

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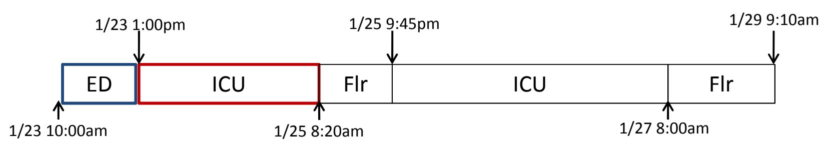
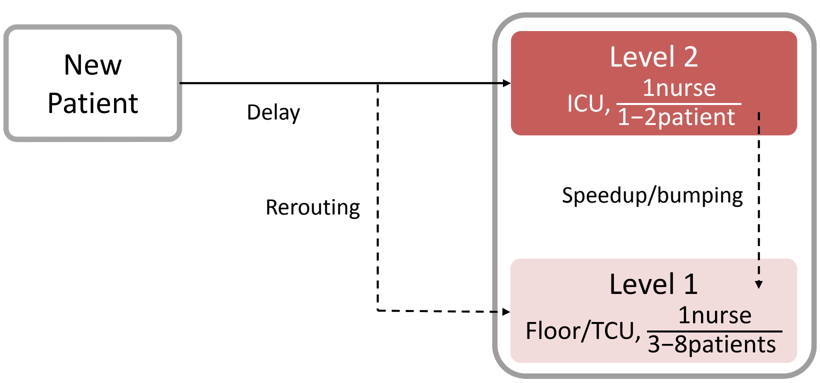
Patient Data

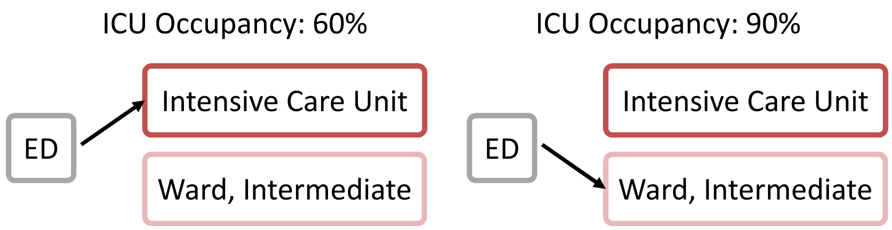
- 19 Hospitals, 212,064 patients over 1 year
  - 7 hospitals with two levels of care (ICU and Floor)
  - 11 hospitals with Transitional Care Unit (TCU)
  - Heterogeneous sizes of Inpatient units.
- Patient Data
  - Age, Sex
  - Admission diagnosis/type
  - Severity scores based on Comorbidities, Lab tests
- Patient Flow



New patient arrives to full ICU



Admission Control



Q1: Effect of ICU congestion on ICU admission

Q2: Effect of ICU admission on patient outcomes

* What is the magnitude of these effects?

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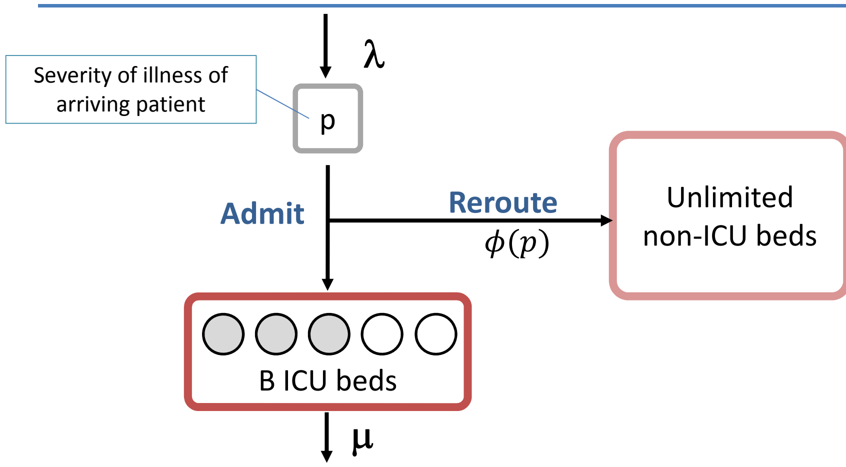
Stylized Model of Inpatient Units



→ Minimize expected long-term rerouting cost

$(\min E[\sum_{t=0}^{T-1} \phi(p_t) \cdot 1\{\pi_t = Reroute\}])$

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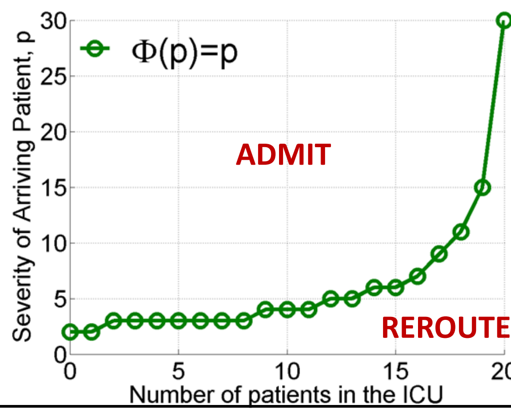
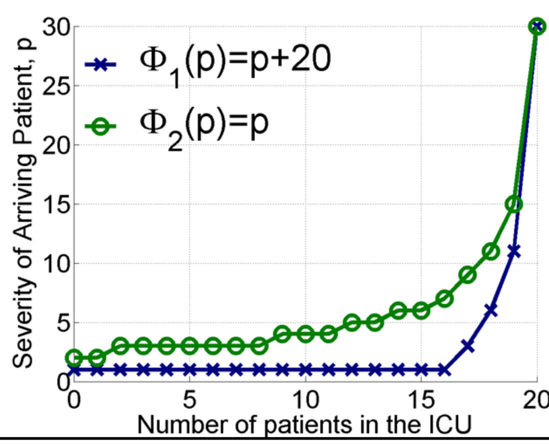
Properties of Optimal Policy

1. Threshold policy
   - $p \geq \kappa^*(x,t)$ → Admit
   - $p < \kappa^*(x,t)$ → Reroute
2. Threshold non-decreasing in # ICU patients, x
   - $x \uparrow$ → $\kappa^*(x,t) \uparrow$

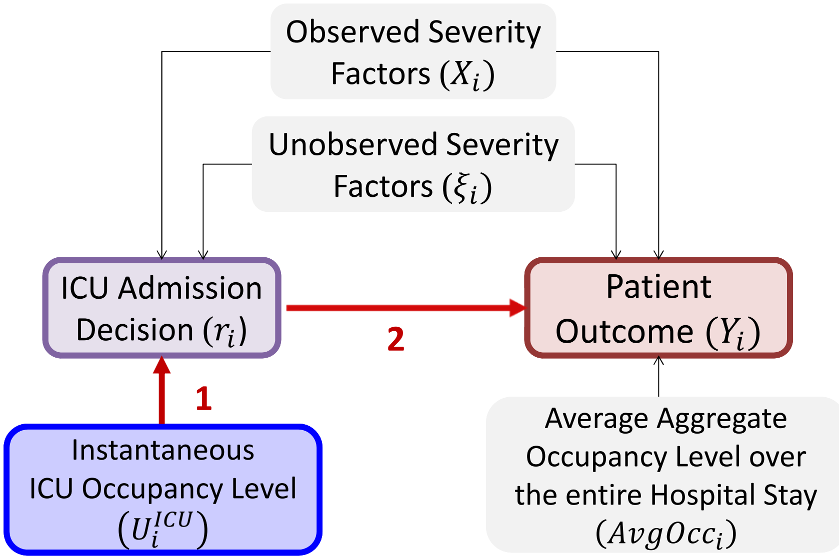


Properties of Optimal Policy

3. Higher rerouting cost → lower threshold
   - $\phi_1(p) \geq \phi_2(p)$ → $\kappa_1^*(x,t) \leq \kappa_2^*(x,t)$



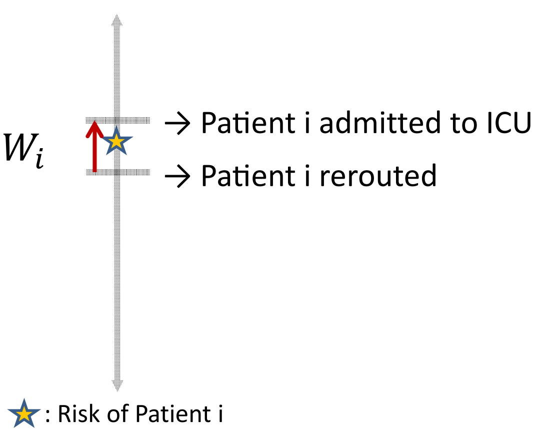
Econometric Challenges: Endogeneity



Effect of Operational Factors on ICU Admission

- Individual threshold, κ_i
  - $W_i = \alpha U_i^{ICU} + Hosp_i$

$$\kappa_i = \kappa + W_i$$



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Effect on ICU Admission

- ICU congestion is associated with lower chance of admission.

	Low ICU Occ	High ICU Occ
$\widehat{Pr}(\text{ICU admission})$	0.110	0.051
Marginal Effect	$\widehat{Pr}(\text{ICU admission}) \downarrow$ 54%	

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Defining Patient Outcomes

1. In-hospital Mortality
2. Total Length of Stay (LOS) in the ICU
   - Among patients who have visited the ICU
3. Hospital LOS
   - After the ED
4. Hospital Readmission
5. Transfer up to higher care level

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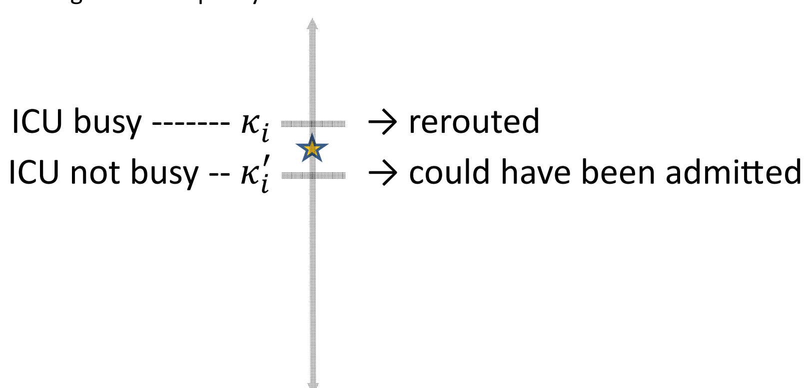
Effect on Patient Outcomes

- ICU admission is associated with better patient outcomes.
- Evidence of endogeneity bias

Patient Outcome	Without bias		With bias	
Readmission 2wk	-0.35** (0.12)	↓47%	0.05* (0.02)	↑8%
Hospital Length of Stay	-0.42*** (0.01)	↓35%	0.30*** (0.01)	↑35%
ICU Length of Stay	-0.30*** (0.08)	↓26%	-0.27*** (0.03)	↓24%
Transfer-Up	-0.64*** (0.15)	↓77%	-0.08* (0.03)	↓15%
In-hospital Mortality	0.03 (0.12)	↑5.4%	0.41*** (0.03)	↑98%

Benefit of ICU Admission

- 190 *borderline* patients
  - Patients who were routed when the ICU occupancy was high/very high and whose risk lies between the two thresholds with normal and very high ICU occupancy level



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Benefit of ICU Admission

- 190 *borderline* patients

Patient Outcome	Saving in Patient Outcome	Potential Cost Savings
Readmission 2wk	11.2 readmissions	$121,018
Hospital Length of Stay	456 hospital days	$1,103,064
ICU Length of Stay	3,610 ICU hours	$475,918
TOTAL		$1,700,000

What about discharging a patient?

- Rerouting degrades patient outcomes
- Consider discharging current patient to make room

Q1: How does ICU occupancy affect patient discharges?

Q2: How does speedup affect patient readmissions?

Hypotheses

BUSY = $1_{\{Q1 > rN\}}$

1. ICU LOS ↓when BUSY
2. P(Readmission) ↑ when BUSY
3. P(Death) not affected by BUSY
   - Doctors will not utilize OPERATIONAL tool (speedup) at expense of CLINICAL outcome (Death)

- Controls: severity, admission type, age, hospital, primary condition, etc.
- Queueing effects: r for BUSY depends on ICU size

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Regression Results

ICU Size (# beds)	Speedup Threshold: r	Coefficient	(1) ICULOS	(2) P(Readmission)
Small (9-12)	.6	γ	-19.2970*	
		α		.3788*
Medium (13-15)	.7	γ	-14.5578*	
		α		.4412**
Large (20+)	.8	γ	-5.8649*	
		α		.2746**

$^{*}p < .10$, $^{**}p < .05$

Speedup threshold increases with ICU size

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Small ICU: Estimated Model Coefficients

Coefficient	Estimated Value	95% CI
$1/\mu_L$ (hours)	84.76	[68.49, 101.03]
$1/\mu_H$ (hours)	65.46	[53.27, 77.66]
p_L	0.0615	[0.0422, 0.0887]
p_H	0.0873	[0.0676, 0.1120]
δ (hours)	88.88	[54.13, 107.63]

- When ICU is BUSY
  - ICU LOS reduced by 23%
  - P(Readmission) increased by 42%

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Research Questions

- What is the impact of speedup?
  - What is the steady-state of the ICU and other units?
  - What proportion of patients are speedup?
- How to make operational decisions to meet performance guarantees?
  - How many ICU beds?
  - When to start speedup?

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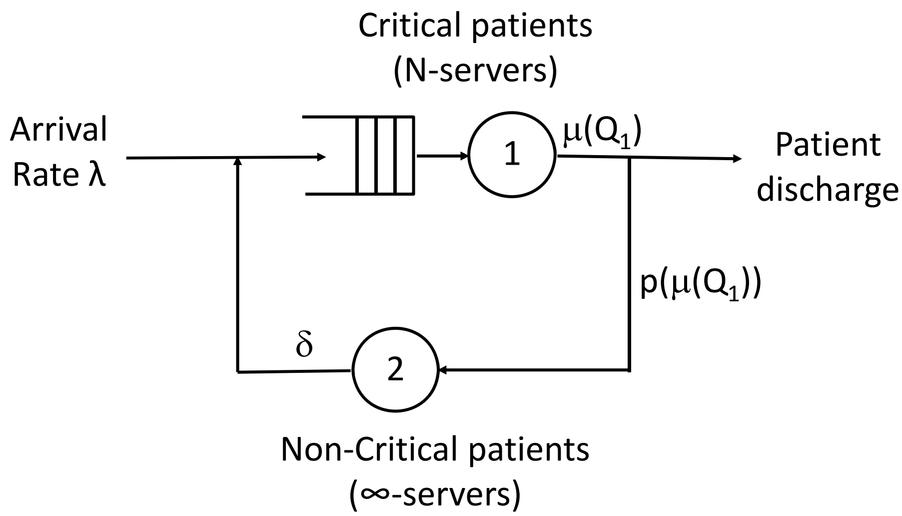
Stylized ICU Queueing Model



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System Dynamics

- Arrival rate: λ
- Speedup threshold: N*
- Critical Patients:

	Overloaded ($Q_1 \geq N^*$)	Underloaded ($Q_1 < N^*$)
ICU LOS	$1/\mu_H$	$1/\mu_L$
Readmission Probability	p_H	p_L

*Assume $\mu_H > \mu_L$, $p_H > p_L$

- Non-Critical Patients
  - Only keep track of readmitted patients
  - LOS: $1/\delta$ (time to readmission)

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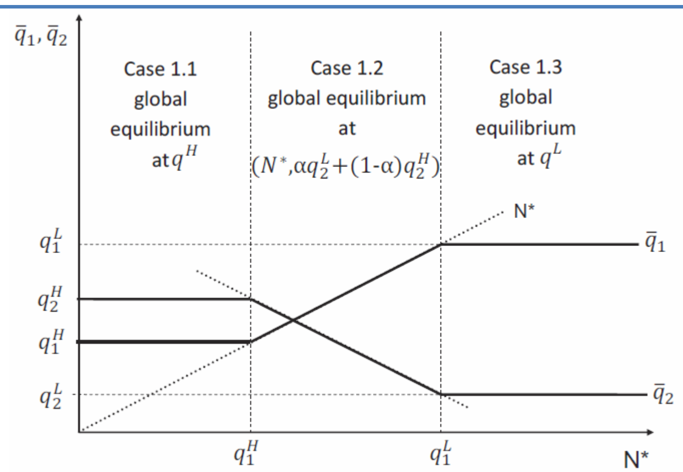
Instability

- ICU Offered-load:

Never Speedup	Always Speedup
$q_1^L = \frac{\lambda}{(1-p_L)\mu_L}$	$q_1^H = \frac{\lambda}{(1-p_H)\mu_H}$

- Instability Conditions:
  1. $q_1^H \le q_1^L$: The system is unstable if $N < q_1^H$
  2. $q_1^H > q_1^L$: The system is unstable if $N < q_1^L$ or if $N < q_1^H$ & $N^* < q_1^L$
- Insights:
  - Speedup allows for stability for fewer beds
  - The “right” threshold may be required for stability

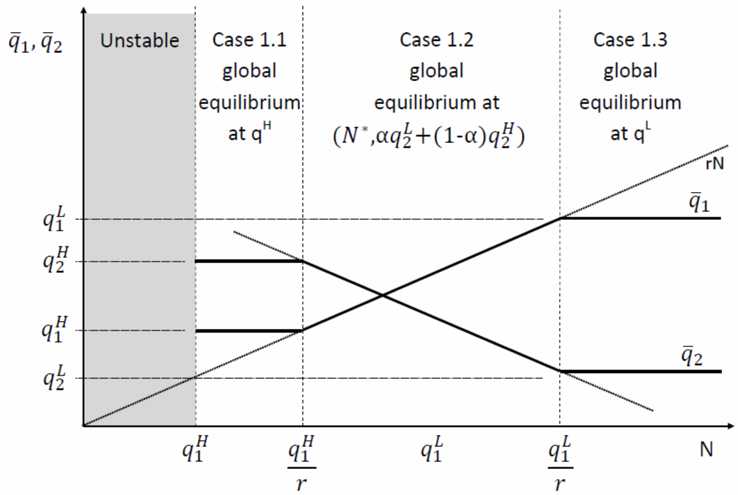
Case 1: Equilibrium



Speedup can improve access:

↓threshold → ↑P(Speedup), ↓ ICU occupancy, ↓ P(Wait)

Case 1: "Supply-sensitive" Demand



Fix r = N*/N: Number of Critical patients increases with capacity

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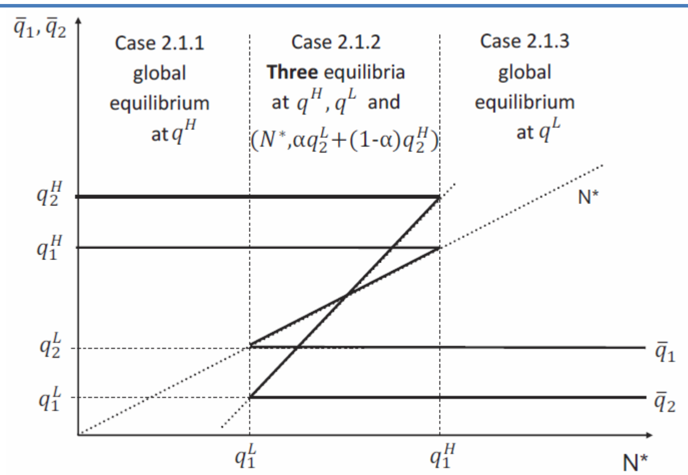
Case 2 $q_1^H > q_1^L$: Equilibrium



Speedup reduces access and increases readmissions

↓threshold → ↑occupancy of ICU & other units, ↑ P(Wait)

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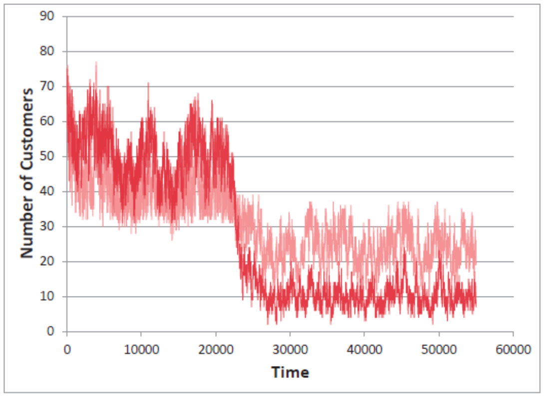
Case 2: Sample Path



- Two locally stable equilibria! (e.g. [Gibbons,Hunt,Kelly 90])
  Stochastic fluctuations cause transitions between them.
- May be long time before return to `better' equilibrium
- Interventions (diversion, surgical cancellations) may be necessary

Connecting to Empirical Operating Regime

- Case 1:

ICU size (# beds)	q_1^L/q_1^H
Small (9-12)	1.26
Medium (13-15)	1.21
Large(20+)	1.06

  - Good. Because looks like speedup is used
- Large ICUs seem to benefit less from speedup
  - May have heterogeneous effects a la [Kc and Terwiesch]

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Changing the speedup policy

ICU size (# beds)	Current r			Increased r			No speedup
	N*	P(Speedup)	P(R)	N*	P(Speedup)	P(R)	P(R)
Small (10)	6	.70	.081	8	.47	.075	.065
Medium (15)	12	.59	.092	13	.51	.089	.071
Large(30)	24	.54	.061	27	.34	.058	.053

Small changes may have substantial impact

Operational Decisions

- Desire P(Wait) < 10%, P(Readmission) < 8%

ICU size (# beds)	N	N*
Small	11	8
	12	12
Medium	18	17
Large	31	26
	32	32

- Tradeoff: ↑ beds → ↓speedup and readmissions

Conclusions

- Empirical Modeling of Congestion Effects
  - Rerouting and Speedup
  - Degradation of patient outcomes
- Queueing Model to understand effect of speedup
  - Speedup is beneficial if $q_1^H \leq q_1^L$
    - Use speedup threshold, N*, to control ICU load
    - An explanation for supply-sensitive demand
  - Speedup may hurt if $q_1^H > q_1^L$
    - Large interventions may be necessary

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Future Research

- More detailed empirical analysis for heterogeneous patient types
- Extended Queueing Model
- Diffusion approximations
- Look at routing/speedup/delay jointly

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