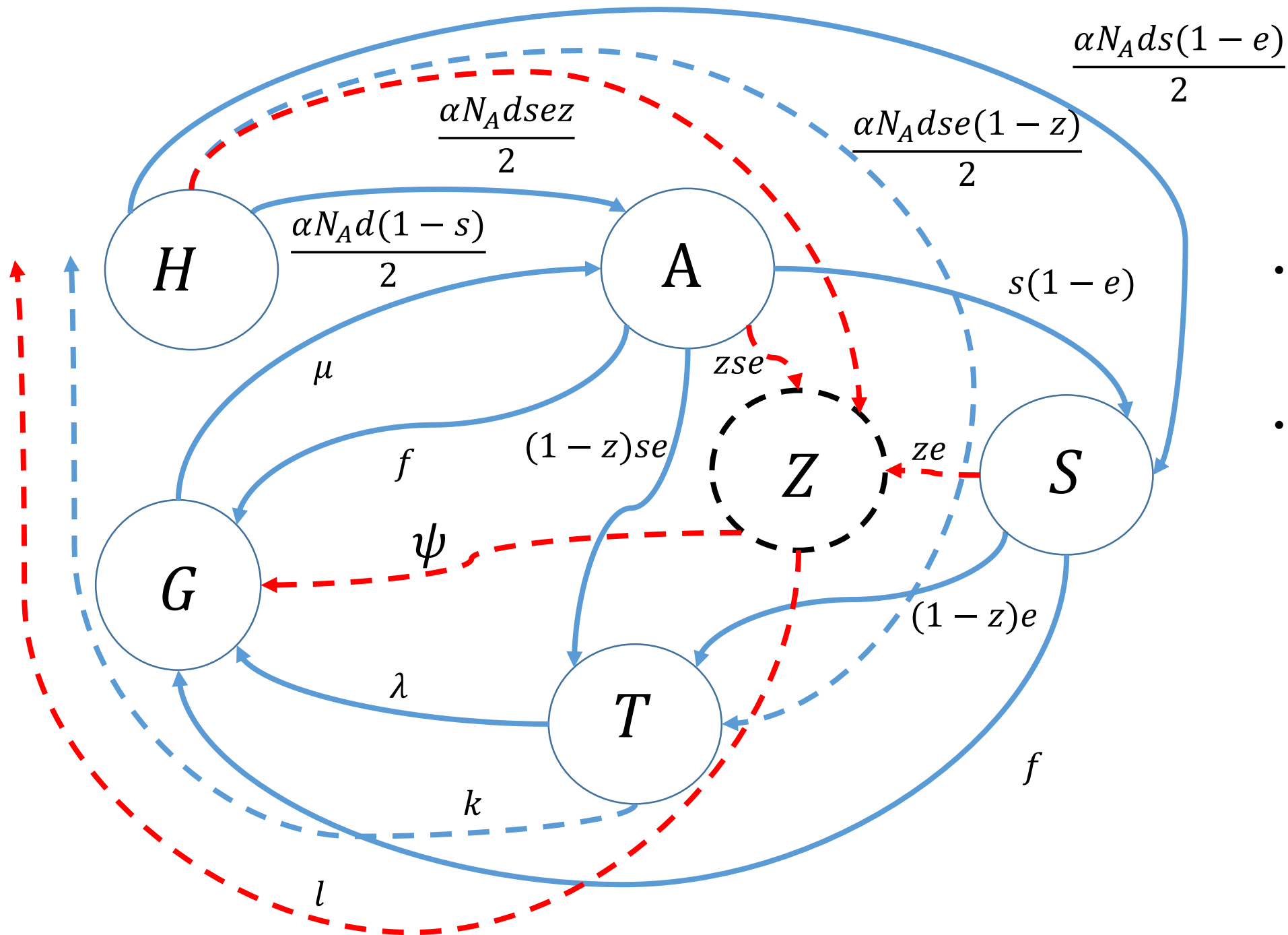


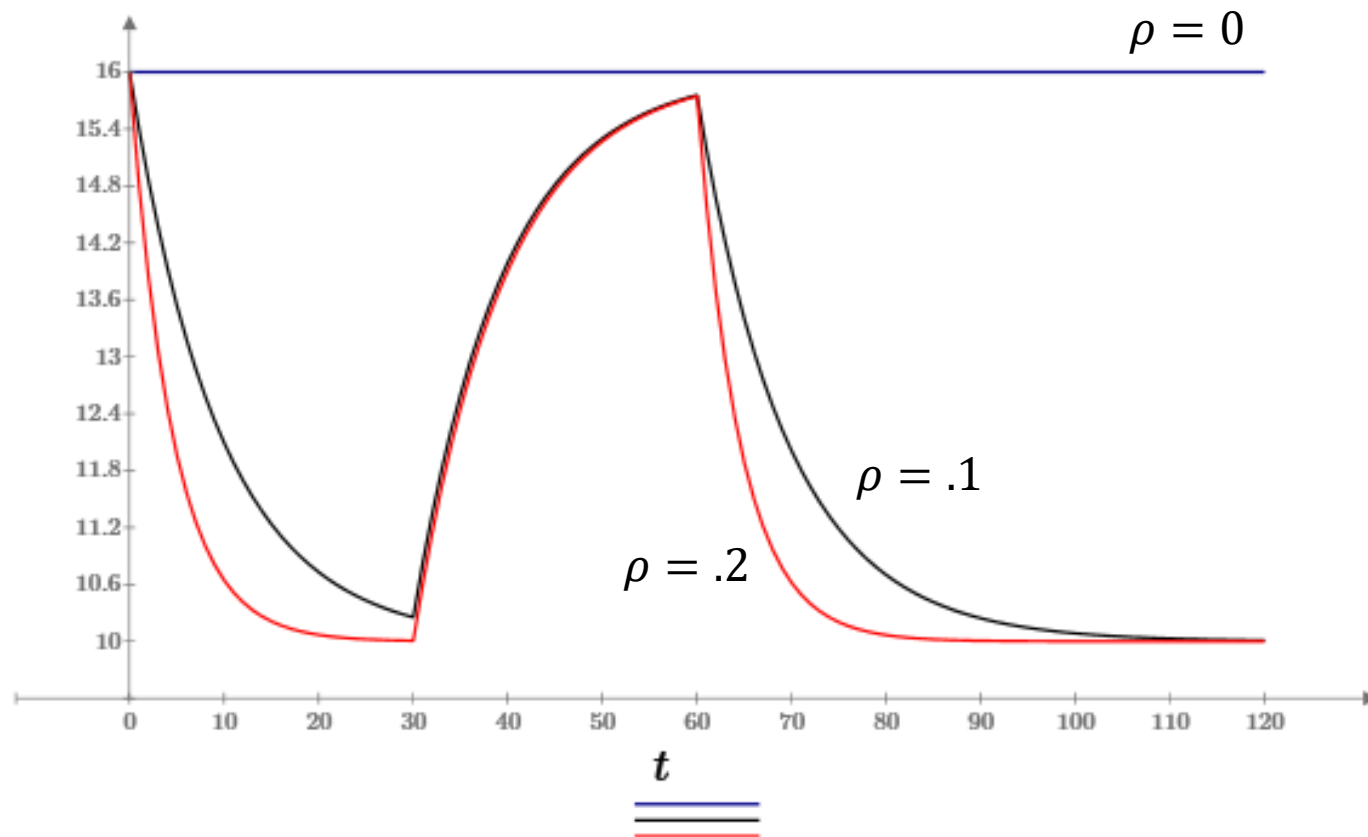
# Corona

Ryoichi Imai  
Kyushu University



- Blue line shows the original model without capacity constraint.
- Red line illustrates the case that medical treatment is bounded by the medical capacity.

# The Repeated Lockdowns



$\alpha_t$  meeting rate changes as

$$\alpha_{t+1} = \alpha_t(1 - \rho) + \rho\alpha_G \quad \text{for } t < 30$$

$$\alpha_{t+1} = \alpha_t(1 - \eta) + \eta\alpha_0 \quad \text{for } 30 \leq t < 60$$

$$\alpha_{t+1} = \alpha_t(1 - \rho) + \rho\alpha_G \quad \text{for } t > 60$$

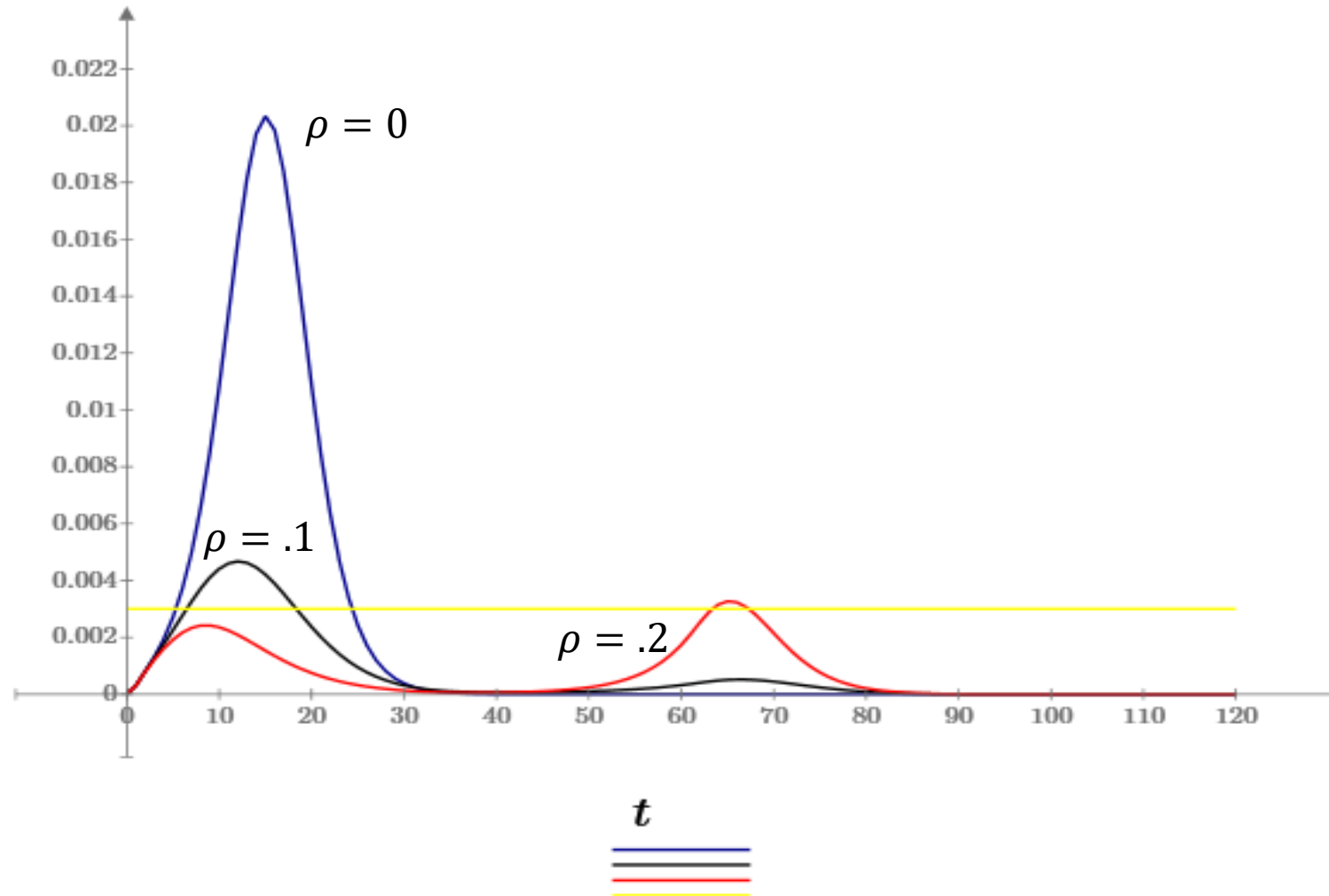
where

$\alpha_G$ : meeting rate goal  
 $\alpha_0 = 16, \alpha_G = 10$

$\rho$ : reduction rate  
 $\eta$ : recovery rate

# Medical Capacity

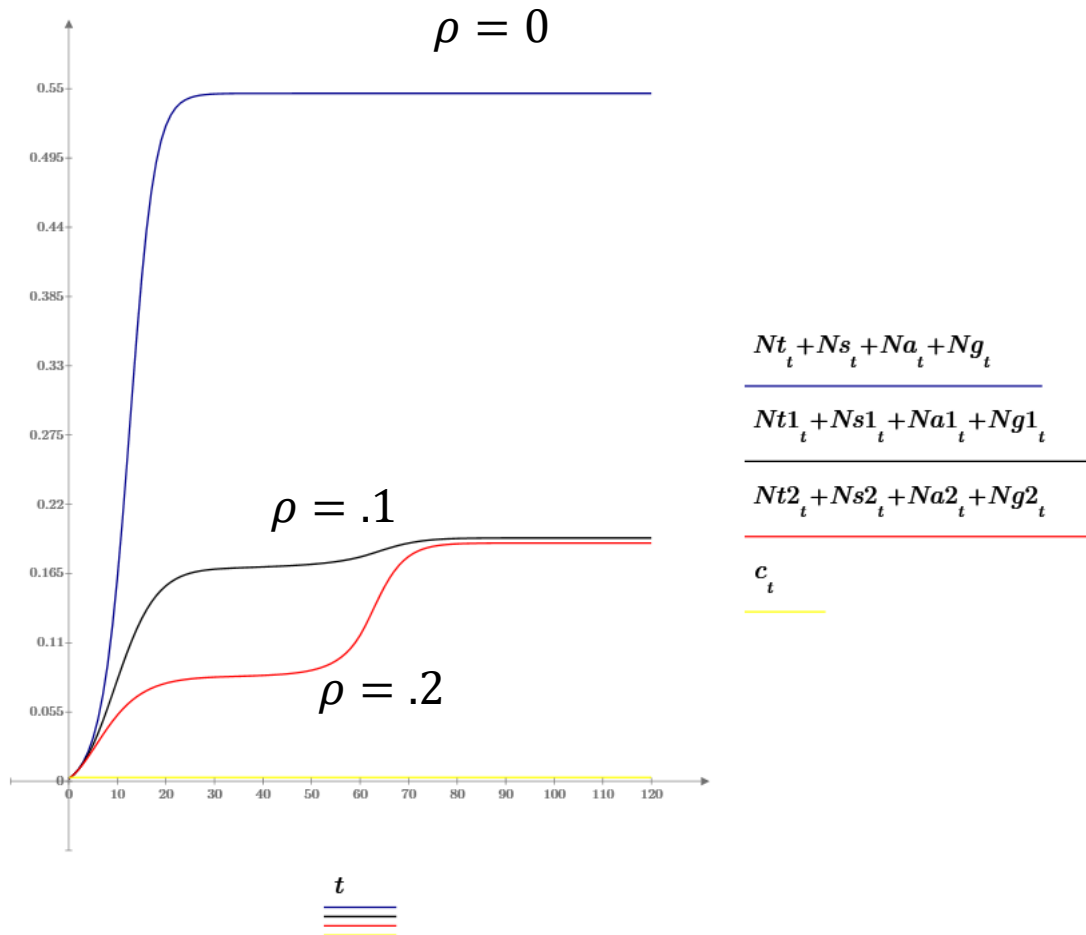
- Without lockdown, the first peak is the highest, while it is followed by no second attack.
- Medical capacity is maintained under a stricter contact control, while the economy is attacked by the second infection.



$$\frac{Nt_t}{Nt1_t}$$

$$\frac{Nt2_t}{c_t}$$

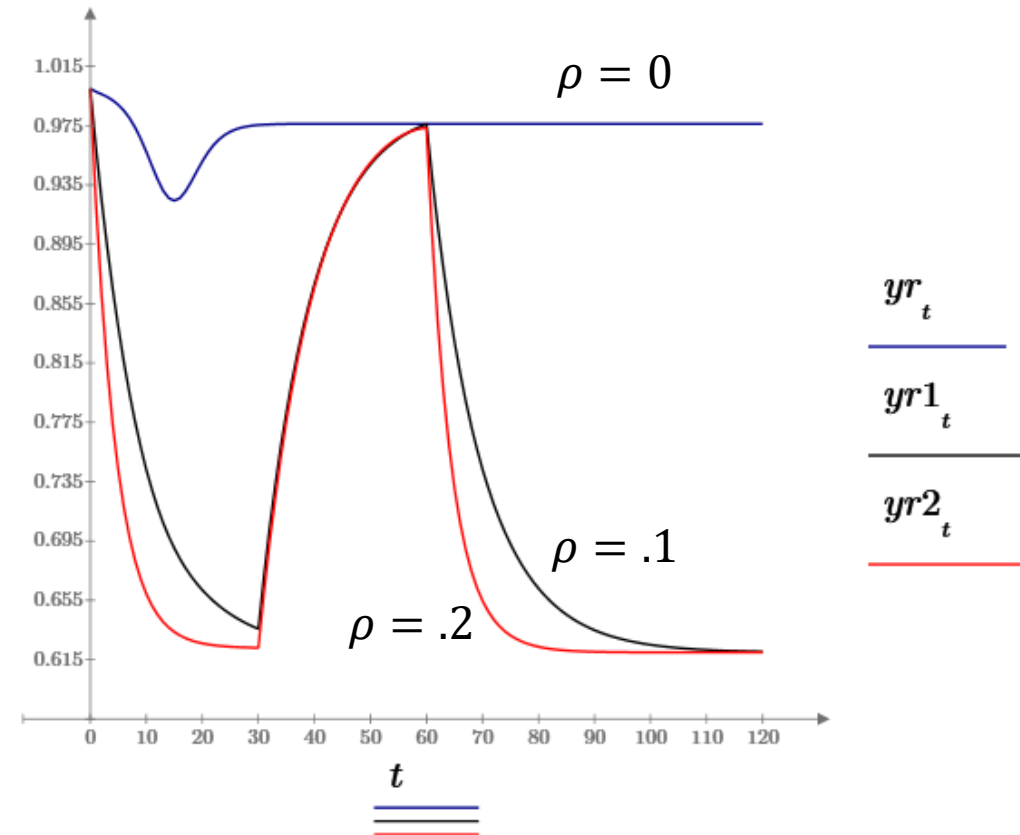
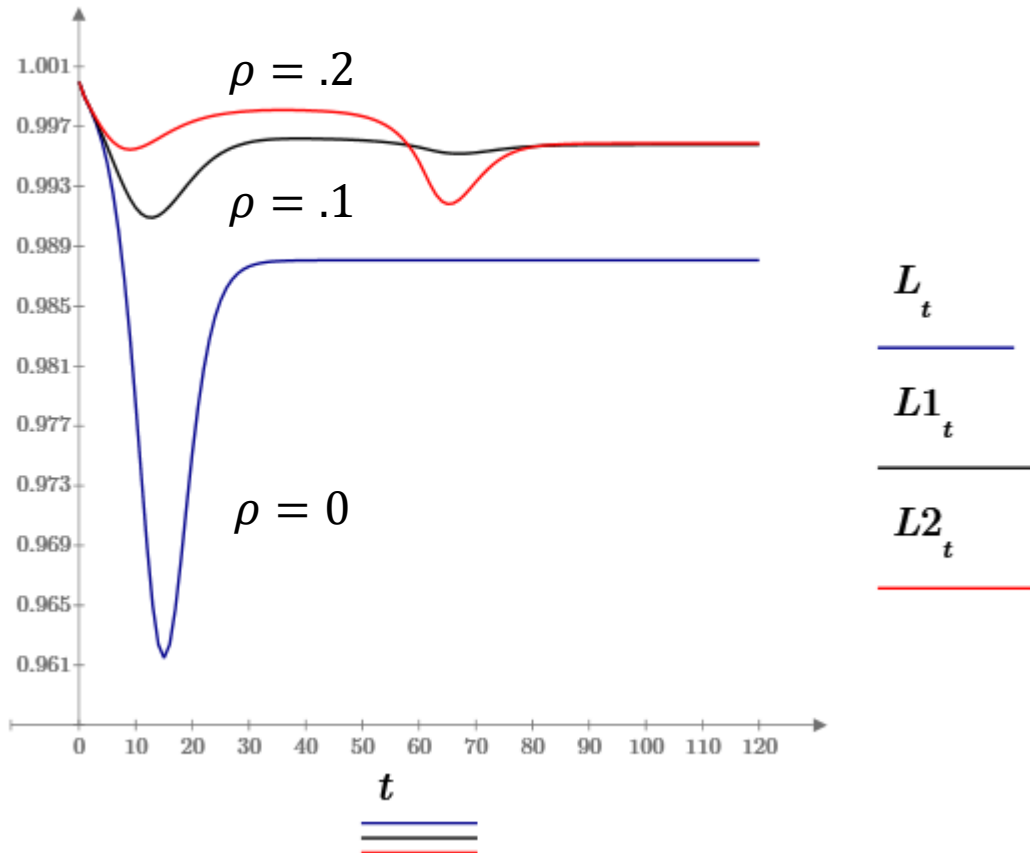
# Immunity



- With no contact control, the economy reaches herd immunity after the first attack.
- With contact control, the economy acquires herd immunity with lower levels of the virus infection.

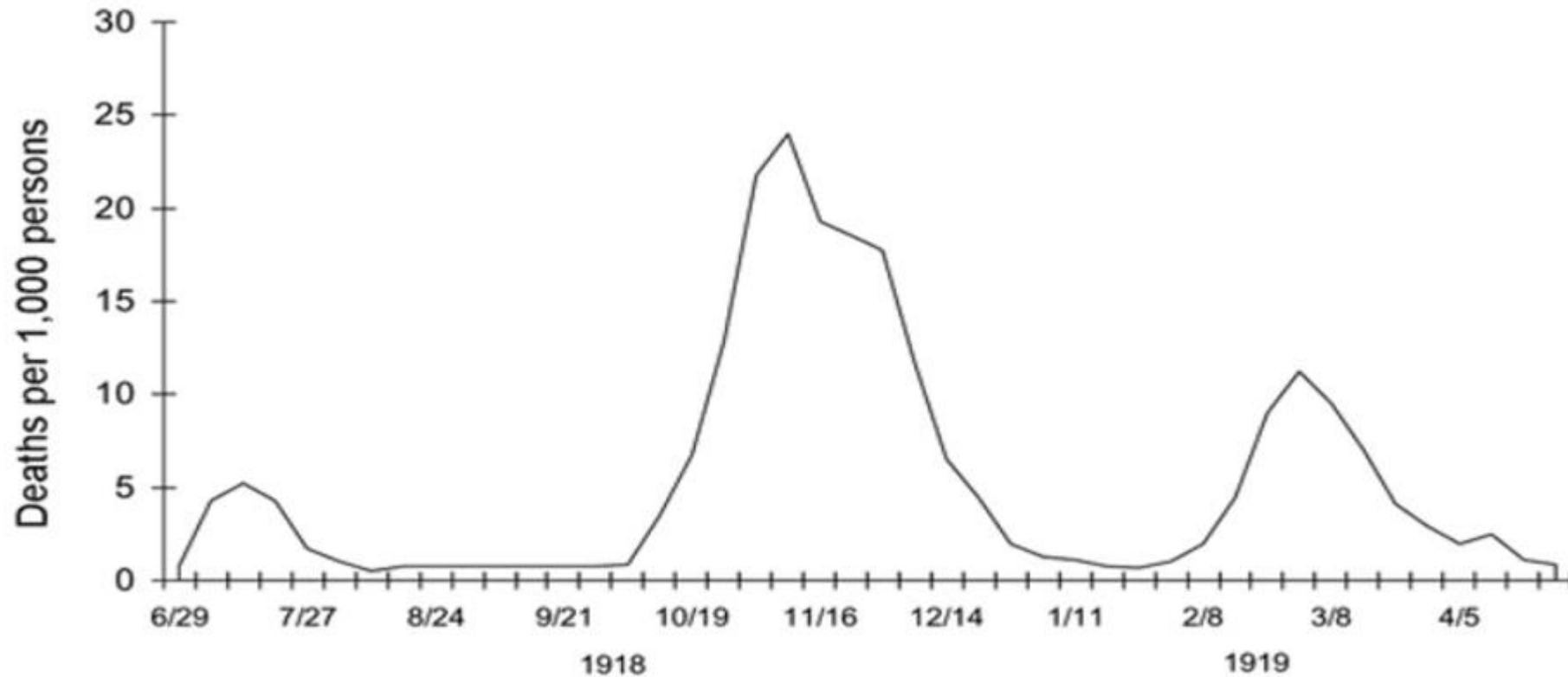
# Labor Force and Output

A stricter control is associated with a smaller loss in labor force and a higher long-run output.



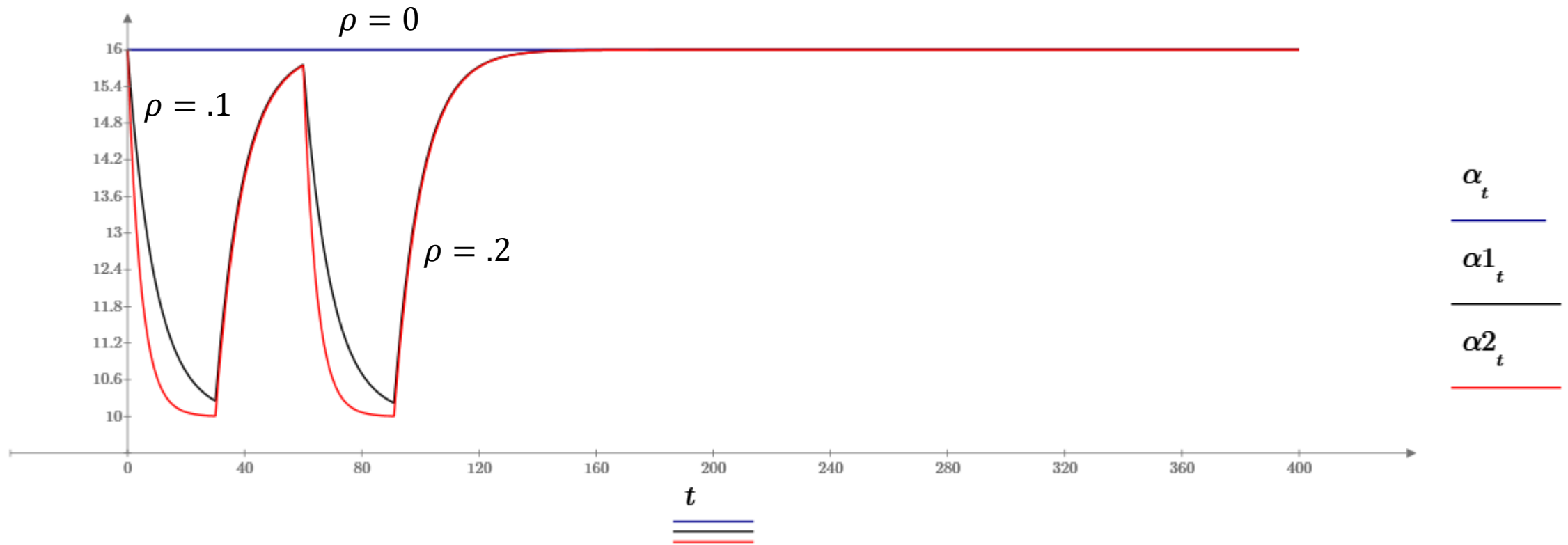
# Spanish Flu 1918-1919

**Figure 1. Three Pandemic Waves of the Spanish Flu in the United Kingdom, 1918-20**



E. Jordan, *Epidemic Influenza a Survey*, Chicago, Ill. American Medical Association, 1927

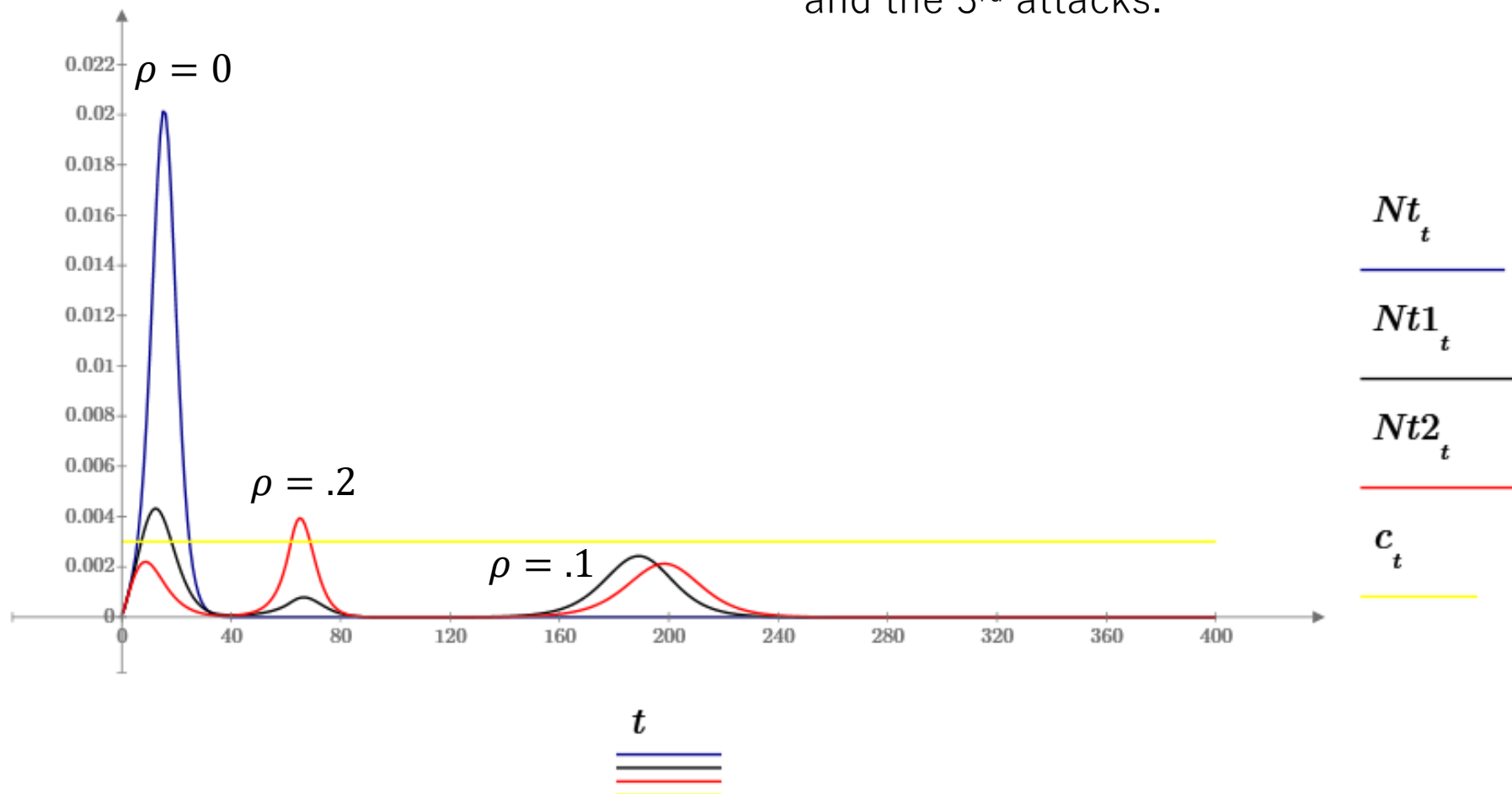
# Two Lockdowns followed by two recovery



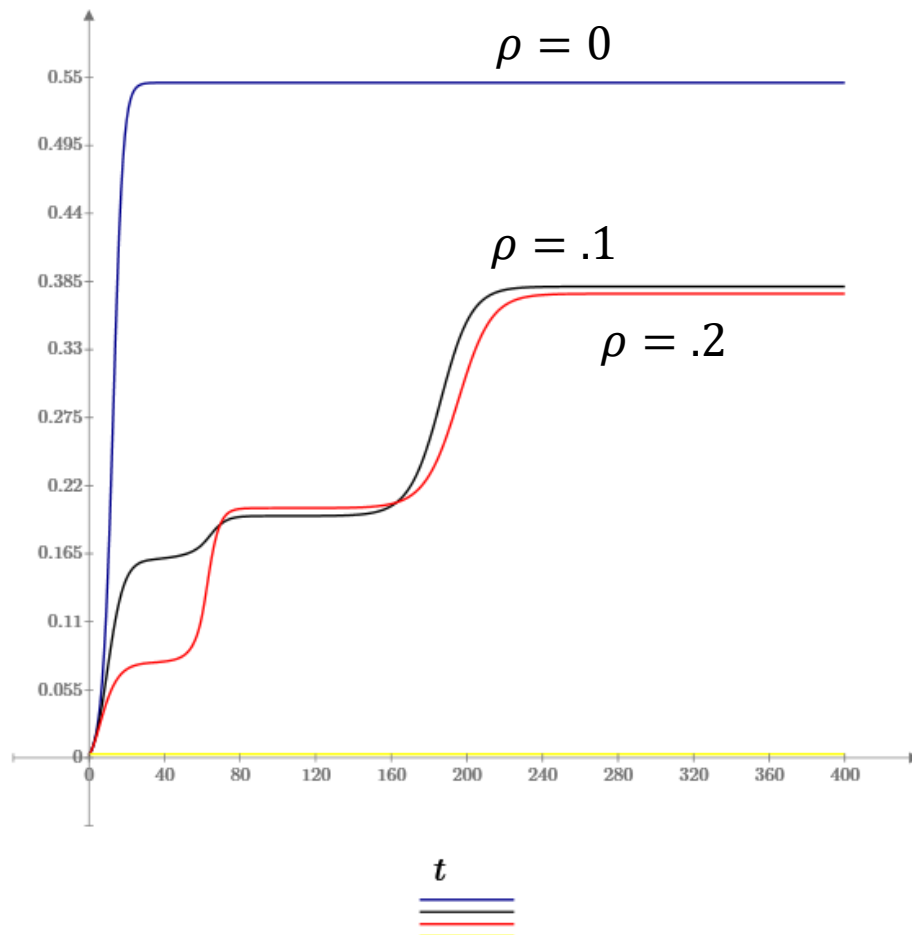


# Medical Capacity

- Without mobility control, 2% of people need to be cared at the hospital, which violates the medical capacity that is .3% of the population, while the pandemic is completed at the first attack.
- If mobility control is enforced, people stay home under the mobility control, and the initial attack is followed by the 2<sup>nd</sup> and the 3<sup>rd</sup> attacks.



# Herd Immunity



- Without Mobility control, herd immunity is achieved at the first attack.
- With mobility control, herd immunity is achieved at a lower level of antibody possession.
- The “hammer-and-dance” strategy makes sense.

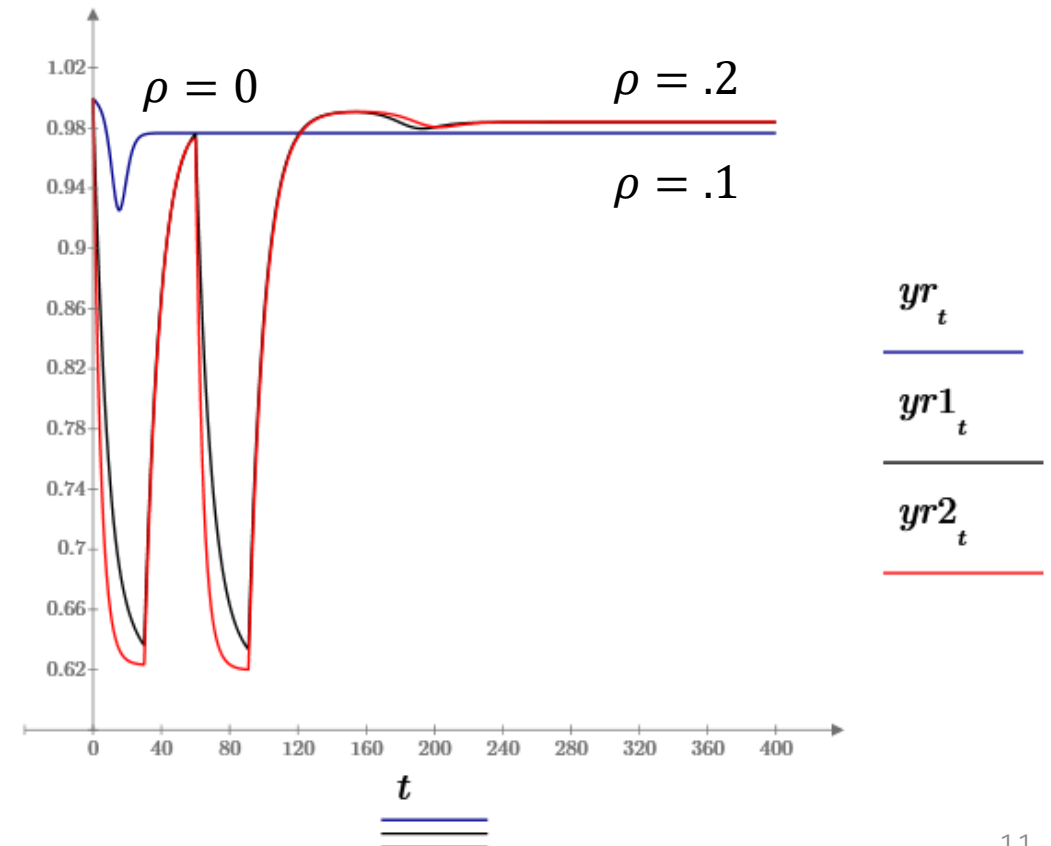
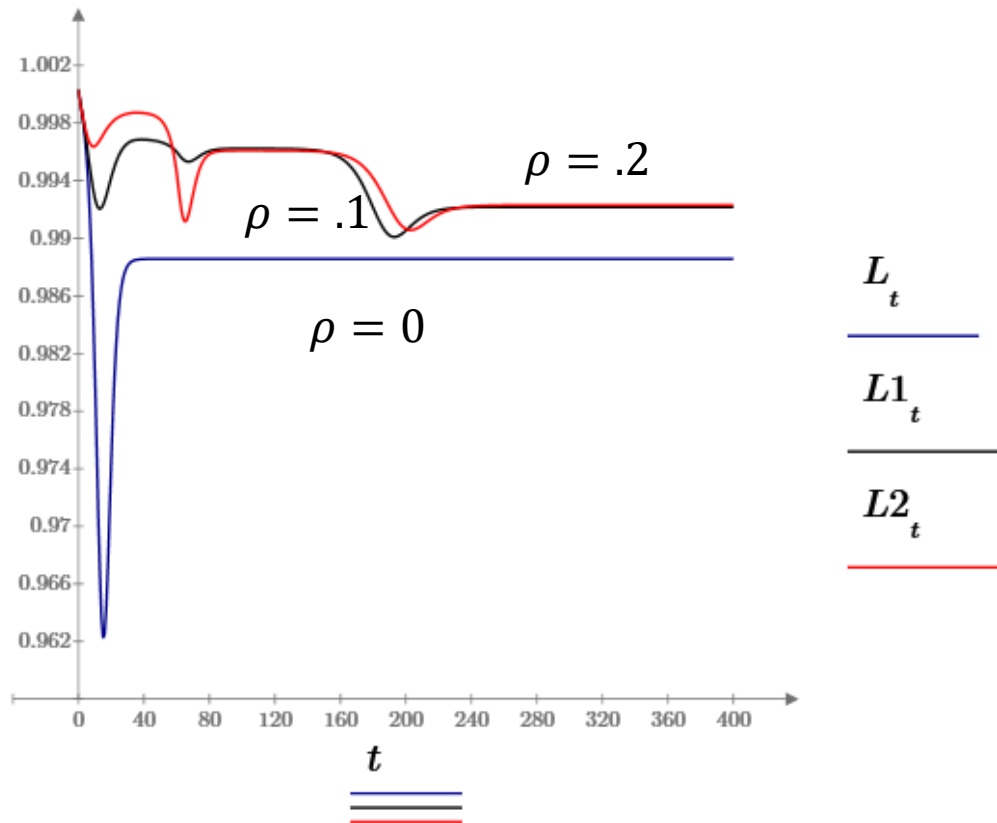
$$\frac{Nt_t + Ns_t + Na_t + Ng_t}{Nt1_t + Ns1_t + Na1_t + Ng1_t}$$

$$\frac{Nt2_t + Ns2_t + Na2_t + Ng2_t}{c_t}$$

$$c_t$$

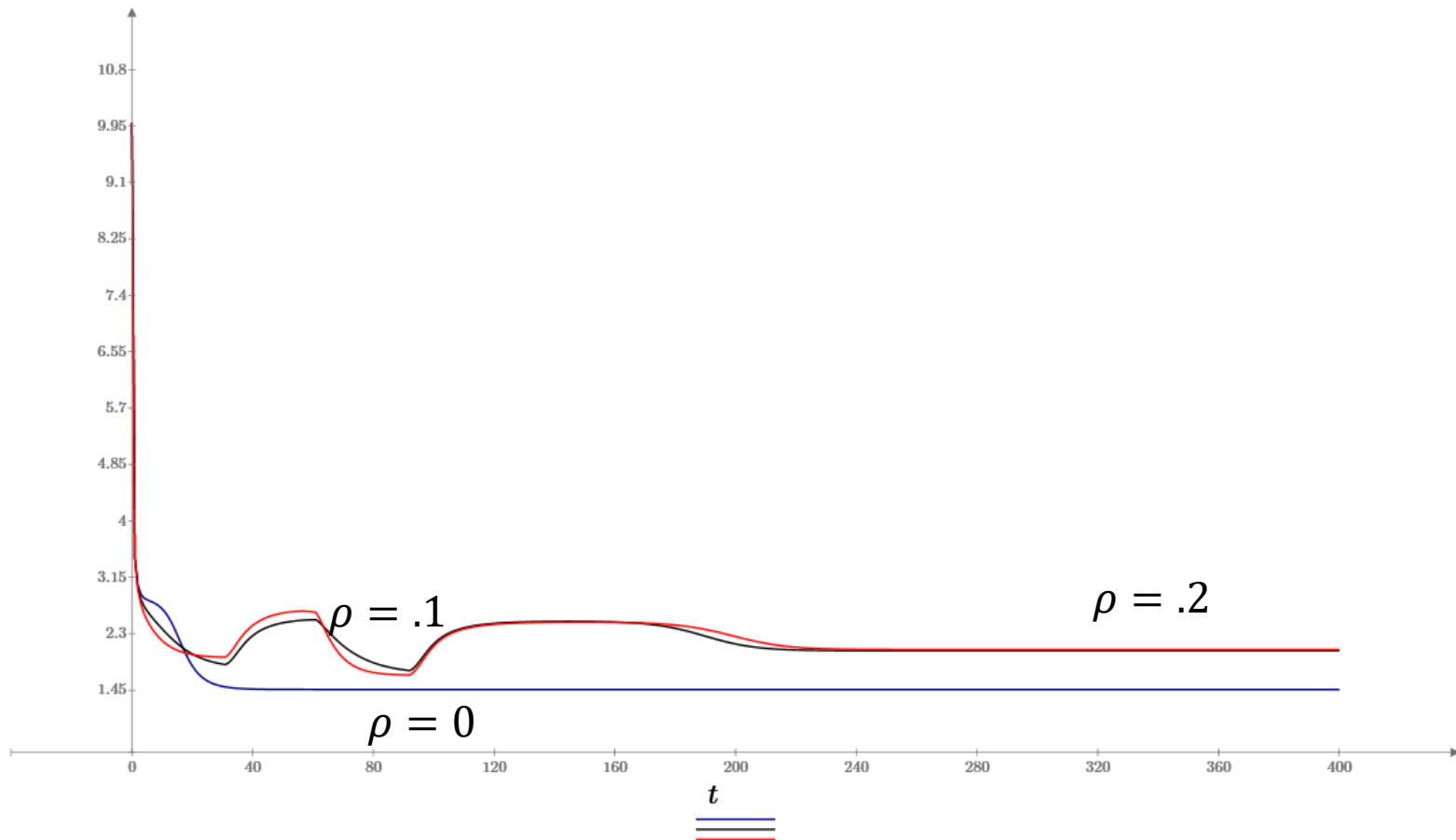
# Labor force and output

- Labor force loss is the highest for the case with no mobility control.
- There are large output losses for the cases with mobility control.



# Ratio of infectious agents all to recognized

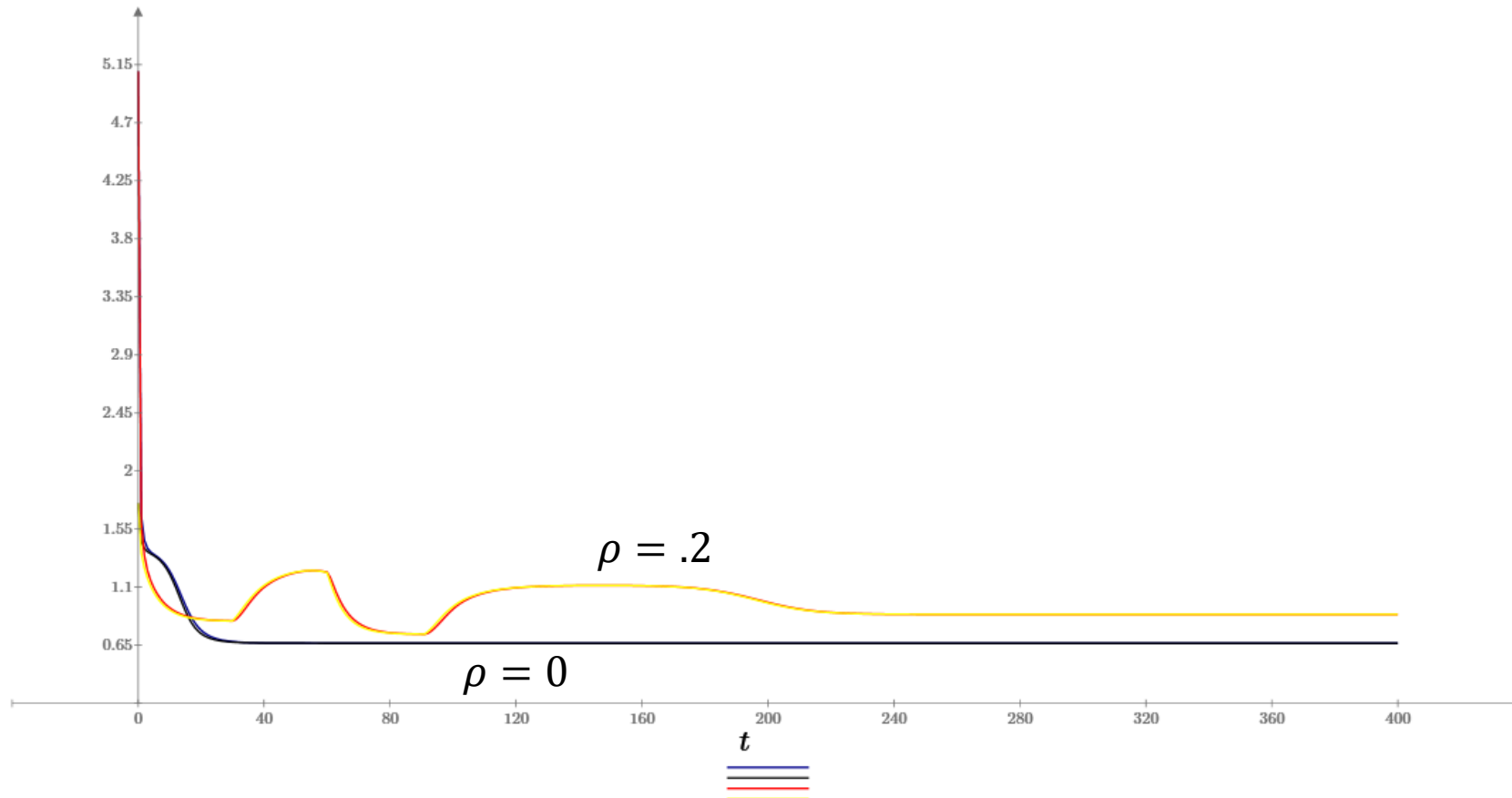
- $N_a$  denotes people infected, not diagnosed, and remains in the labor force.
- $N_t$  denotes patients hospitalized, while  $N_s$  stay at home
- The ratio of all the infected people to the people infected and diagnosed is as large as 10, while it immediately falls down to around two.



$$\frac{\frac{Na_t + Nt_t + Ns_t}{Nt_t + Ns_t}}{\frac{Na1_t + Nt1_t + Ns1_t}{Nt1_t + Ns1_t}} = \frac{Na2_t + Nt2_t + Ns2_t}{Nt2_t + Ns2_t}$$

# Ratio of Growth Rate of Diagnosed to all Infected

- The growth rate of the diagnosed infected people is 5 times as high as the growth rate of all the infected people.
- But it soon falls below one.
- In other words, the diagnosed infected people grow more slowly than all the infected people.



$$\frac{Nt_{t+1} + Ns_{t+1}}{Nt_t + Ns_t}$$


---


$$\frac{Na_{t+1} + Nt_{t+1} + Ns_{t+1}}{Na_t + Nt_t + Ns_t}$$


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$$\frac{Nt^2_{t+1} + Ns^2_{t+1}}{Nt^2_t + Ns^2_t}$$

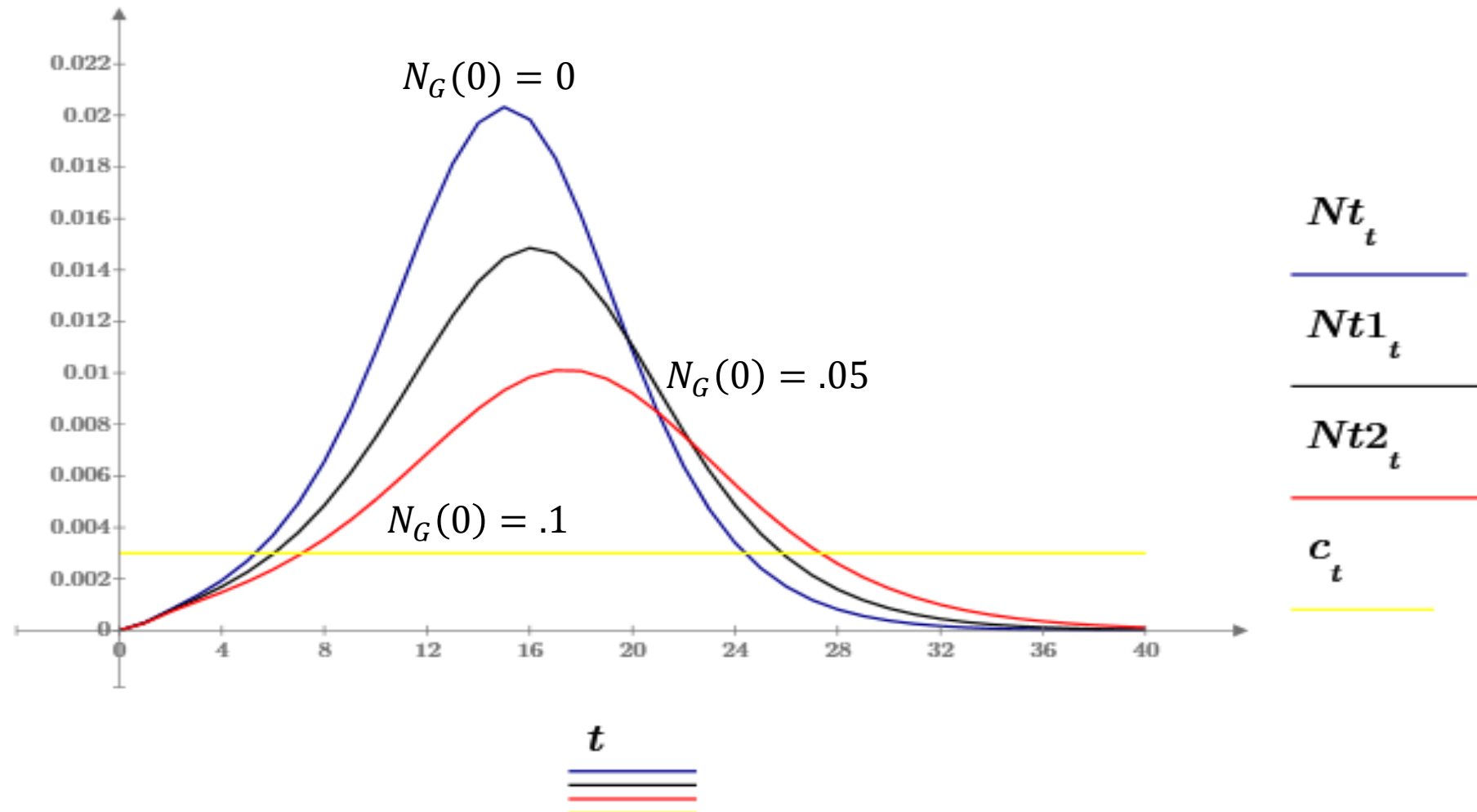

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$$\frac{Na^2_{t+1} + Nt^2_{t+1} + Ns^2_{t+1}}{Na^2_t + Nt^2_t + Ns^2_t}$$

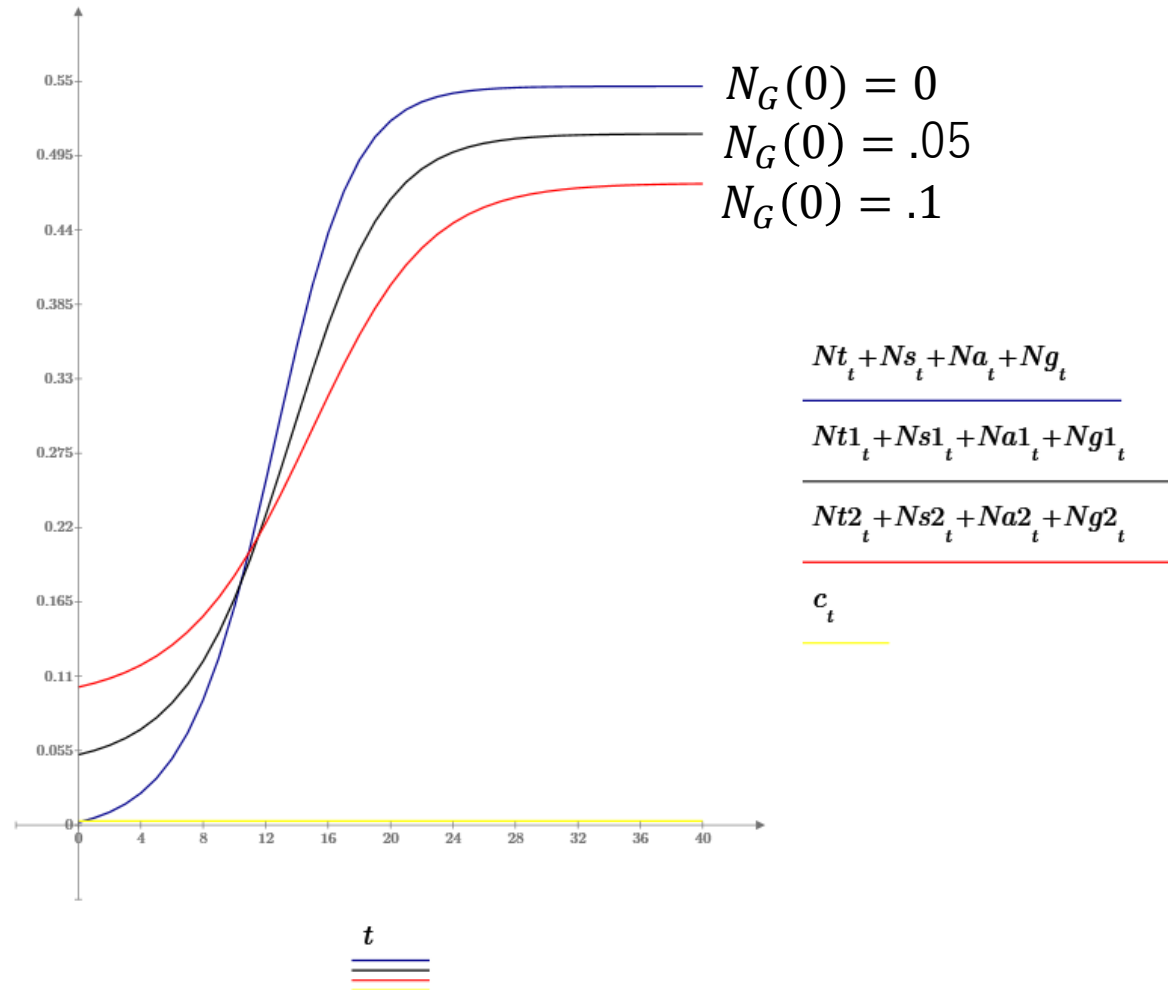

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# Initial Immunity

- $N_G(0)$  denotes the initial (natural) immunity.
- A higher initial immunity lowers the peak created by the initial attack.

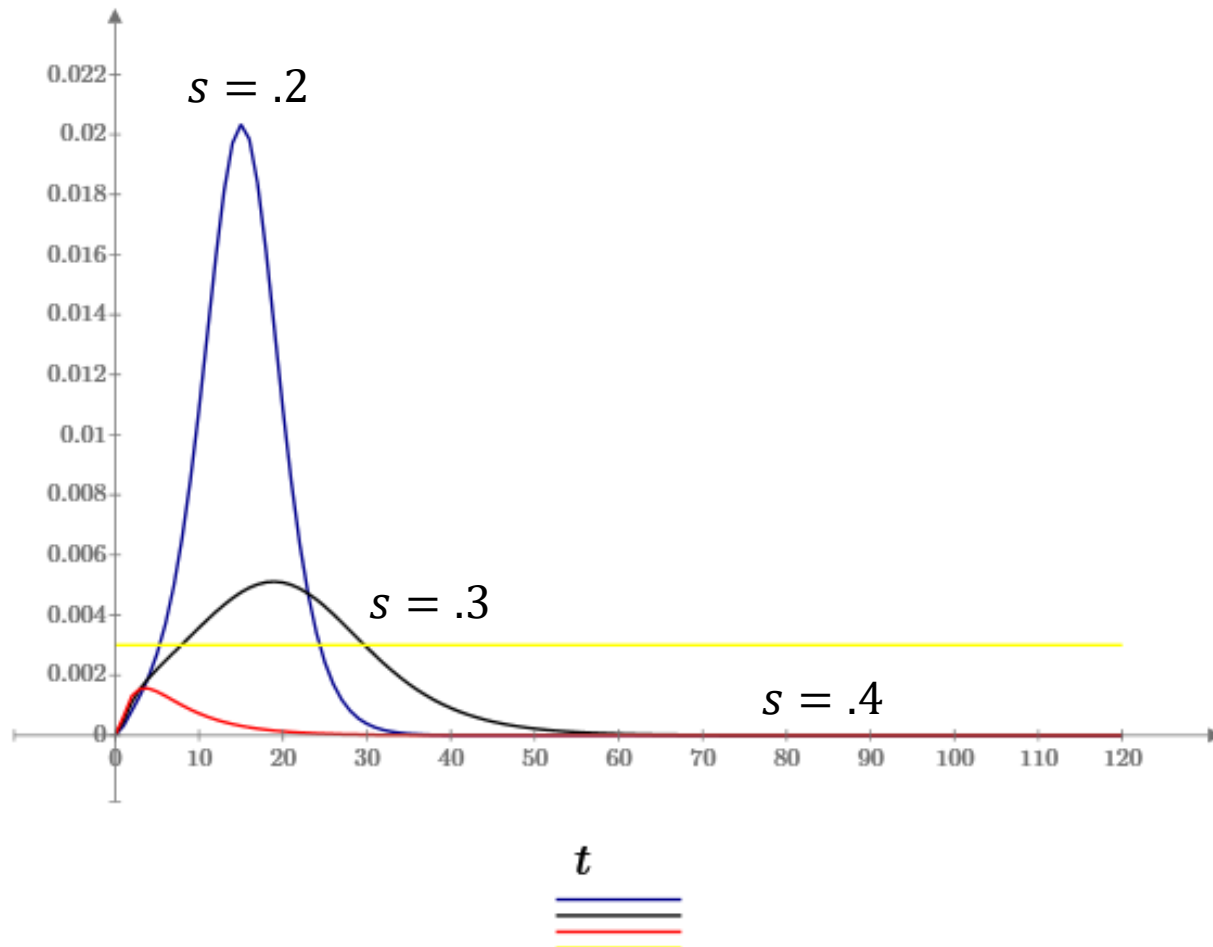


# Herd Immunity and Initial Immunity



- Higher Initial (natural) Immunity leads to herd immunity with a lower level of antibody possession.
- The BCG or the past experiences of people to be exposed to any other virus make them more resilient.

# Testing



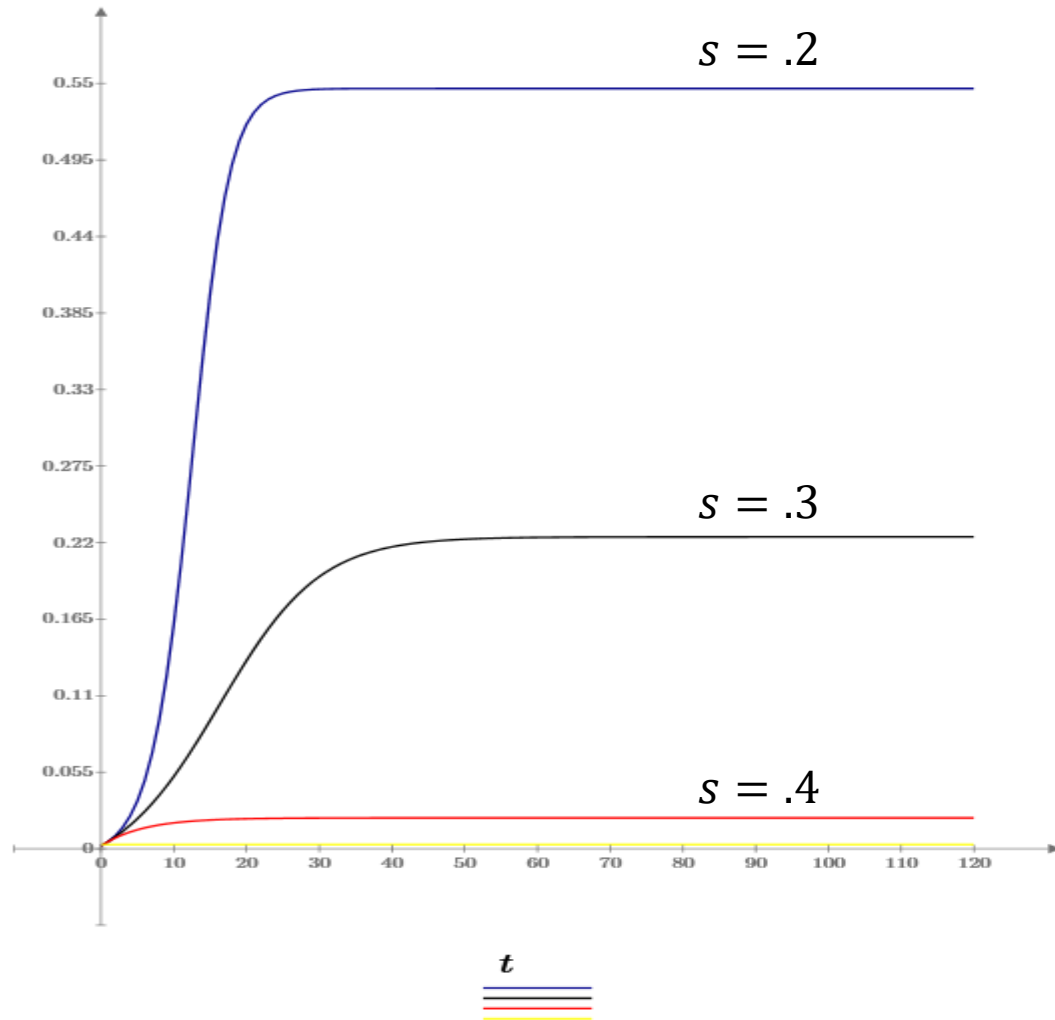
- $s$  denotes the probability that an infected person is diagnosed positive.
- A higher testing (finding) rate reduces the peak caused by the first virus attack, not followed by the second attack.
- A strict testing policy needs to be arranged with a similarly strict policy to contain people diagnosed positive in containment facilities, like South Korea.

$$\frac{Nt_t}{Nt1_t}$$

$$\frac{Nt2_t}{c_t}$$



# Immunity remains low under strict testing



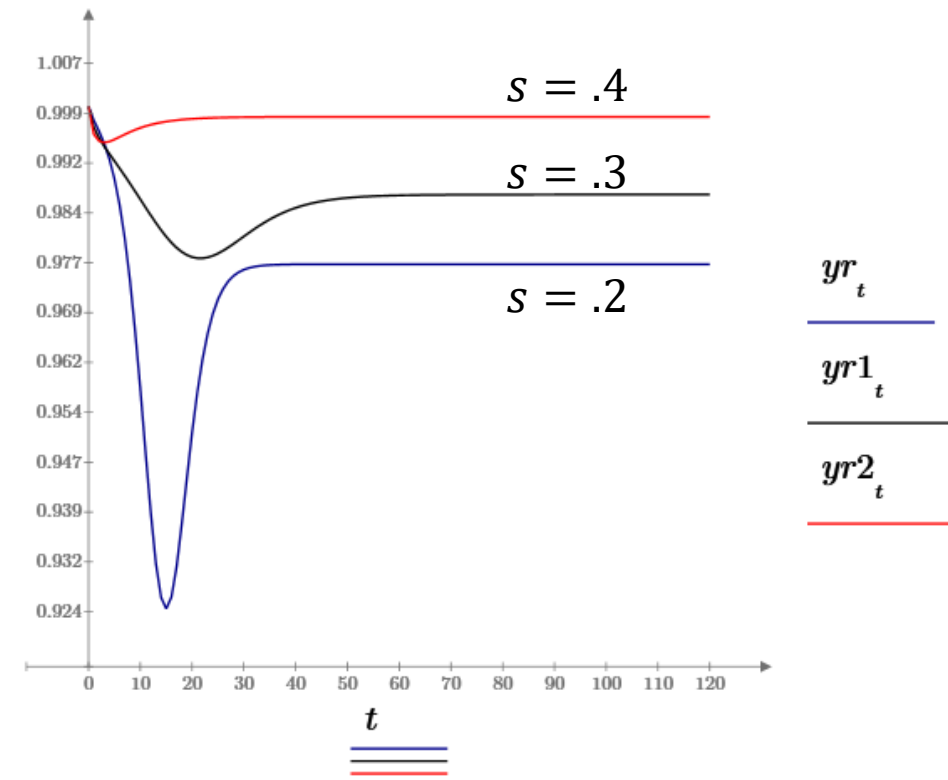
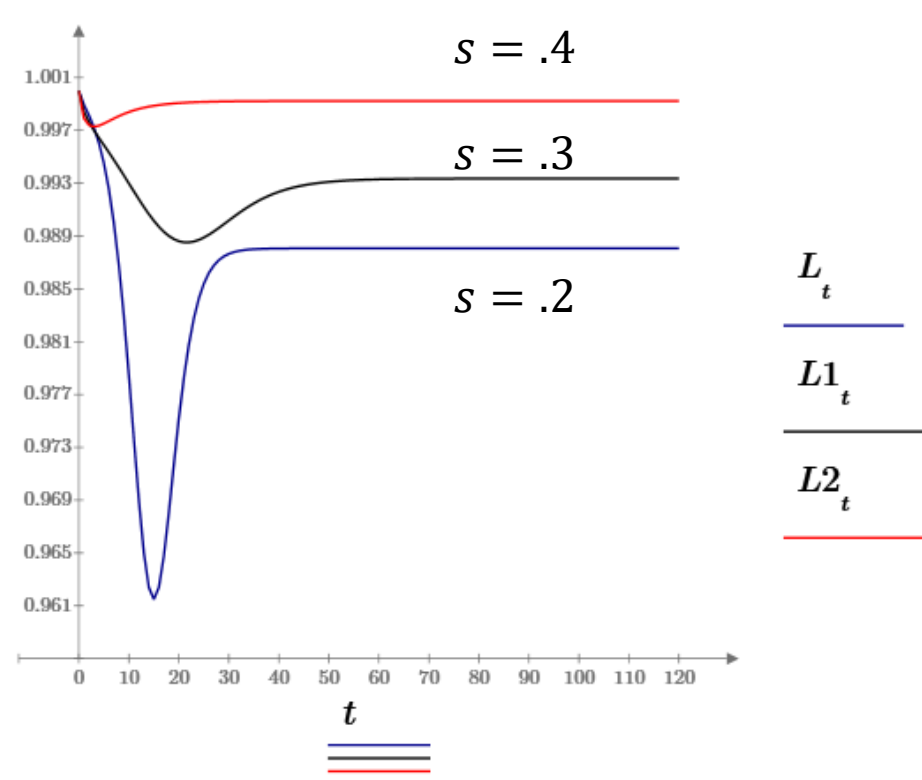
- A stricter testing policy achieves herd immunity at a lower level of infection.
- The society is vulnerable to the second virus attack which is brought by outside.
- South Korea is famous for its strict testing policy, while it is vulnerable to the second attack, since its level of herd immunity is low.

$$\frac{Nt_t + Ns_t + Na_t + Ng_t}{Nt1_t + Ns1_t + Na1_t + Ng1_t}$$

$$\frac{Nt2_t + Ns2_t + Na2_t + Ng2_t}{c_t}$$

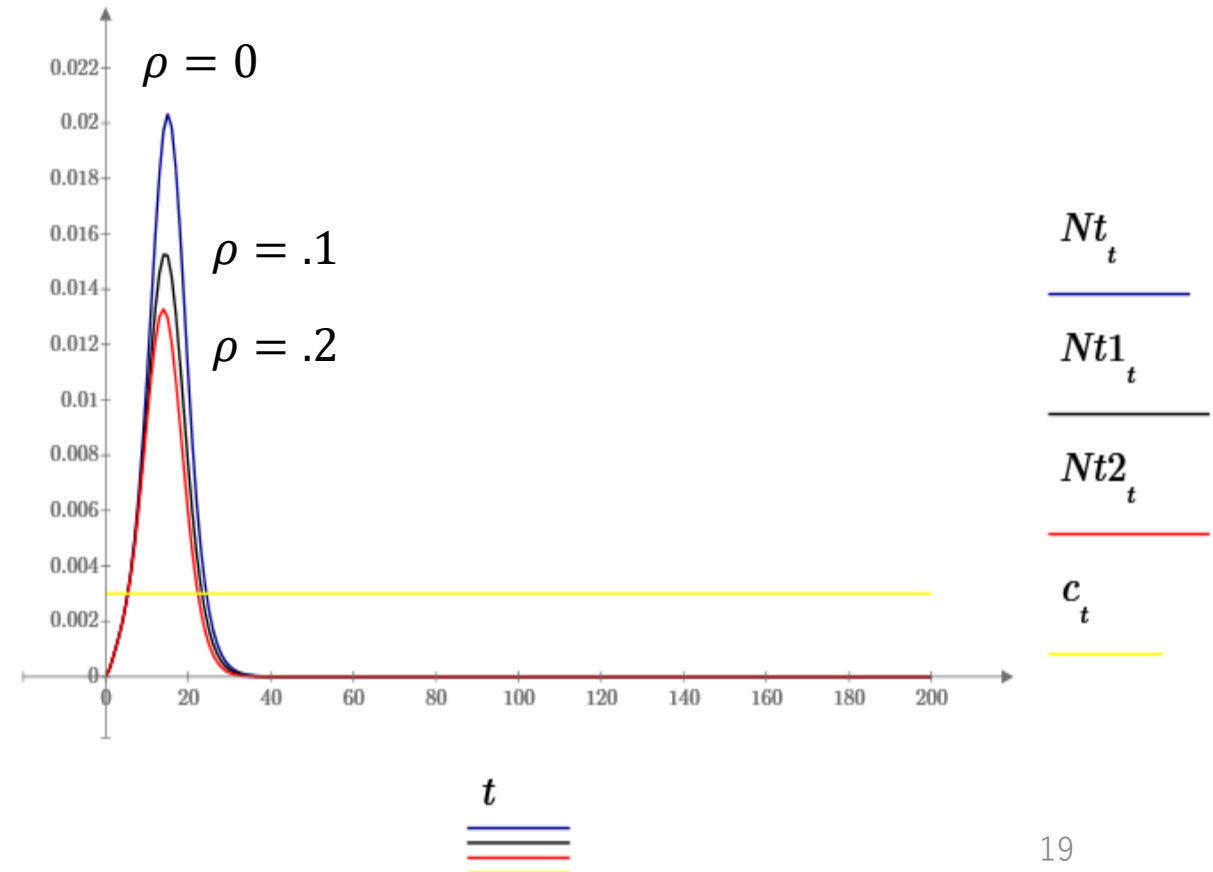
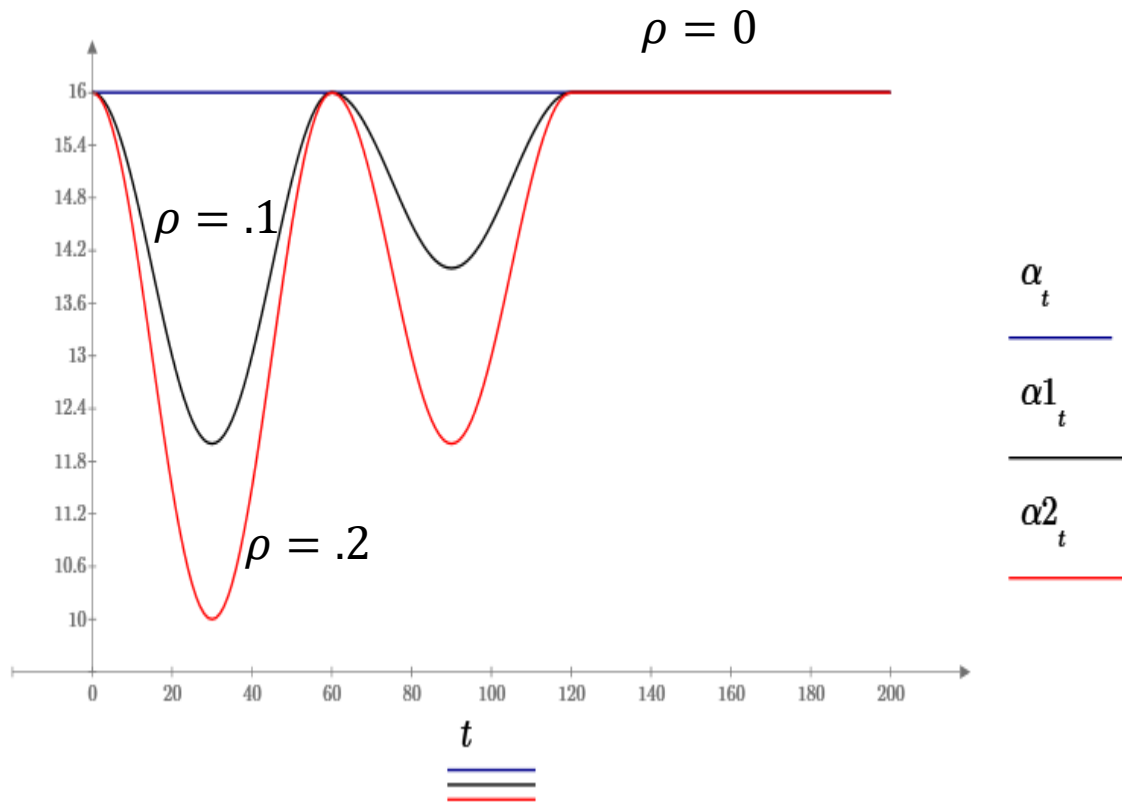
# Labor Force and Output

A stricter testing policy brings smaller losses in labor force and output.

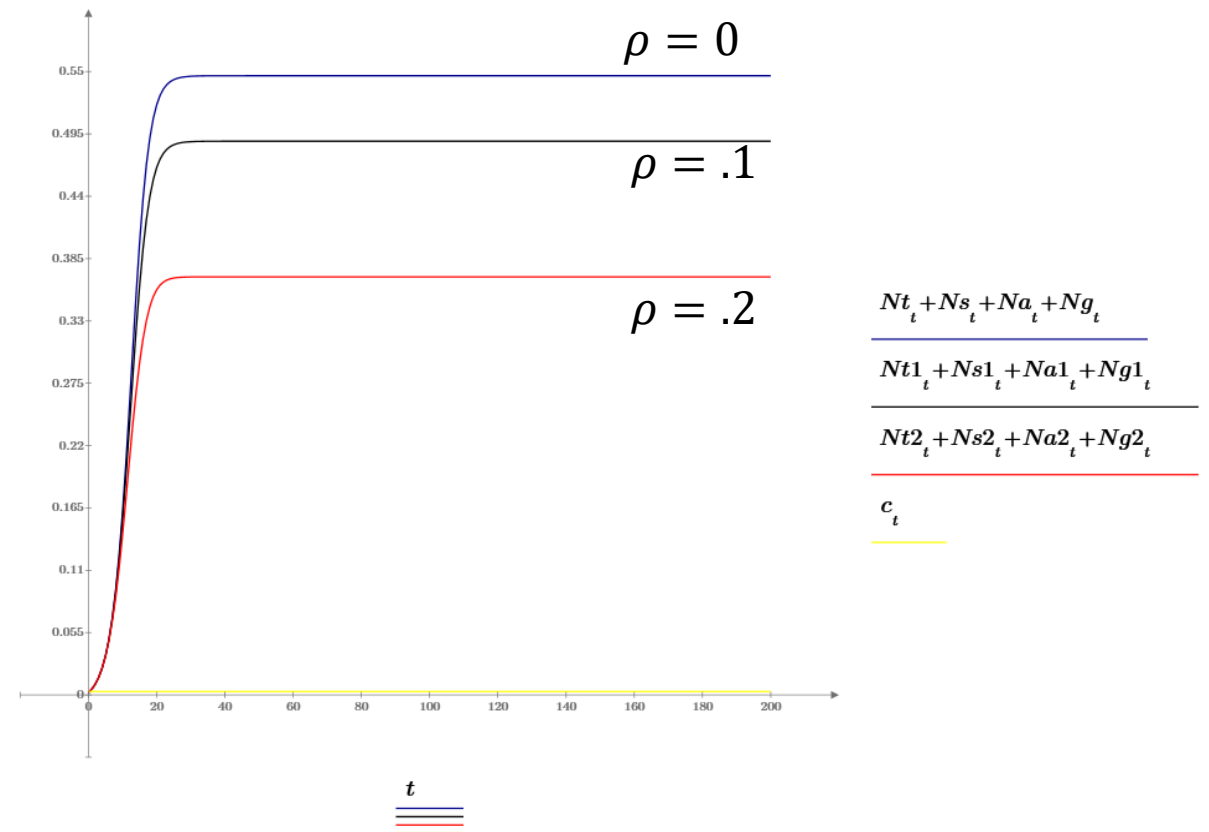
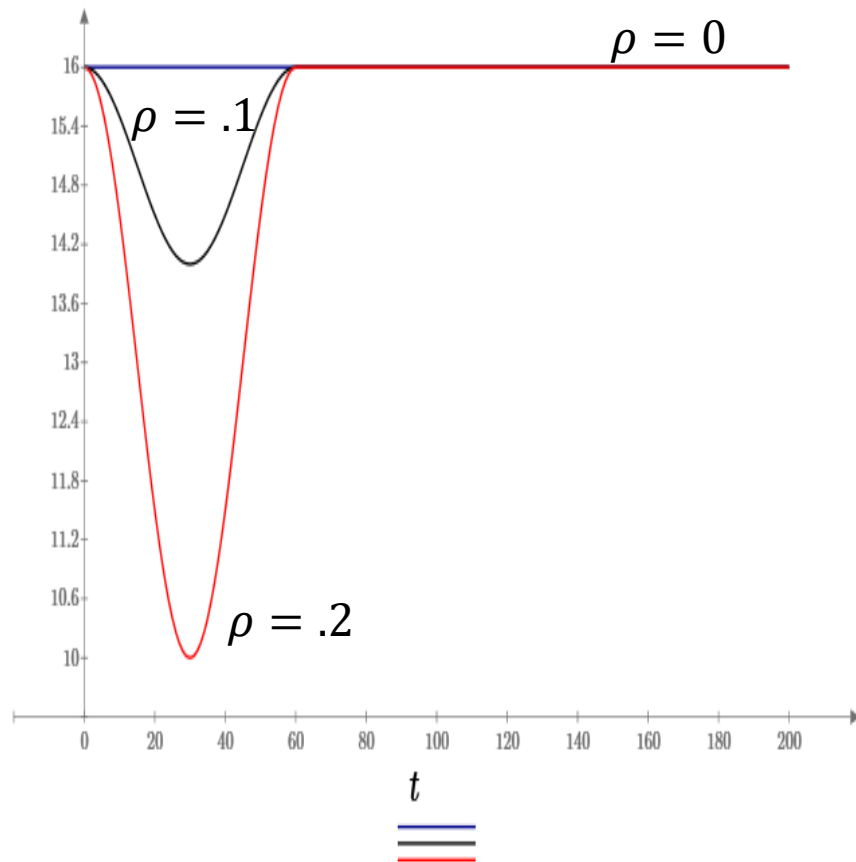


# The Cosine Curve

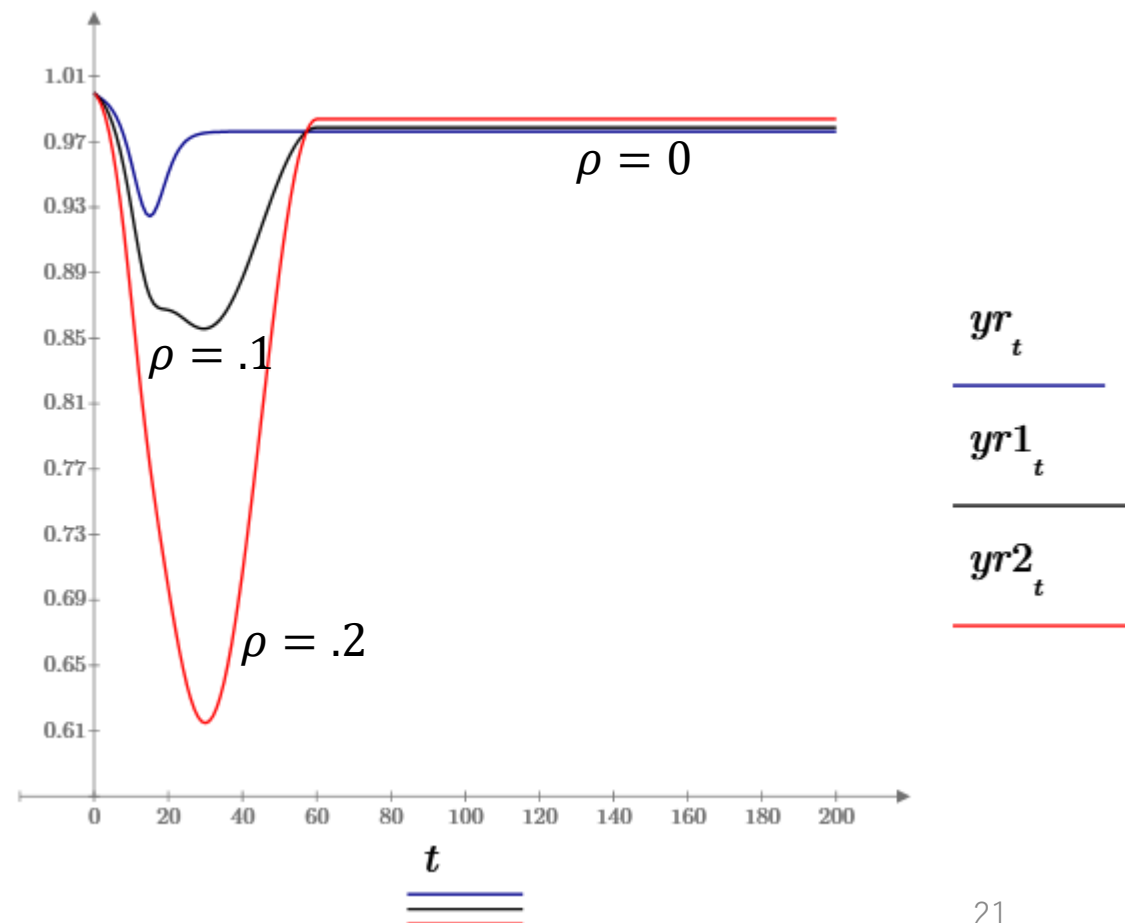
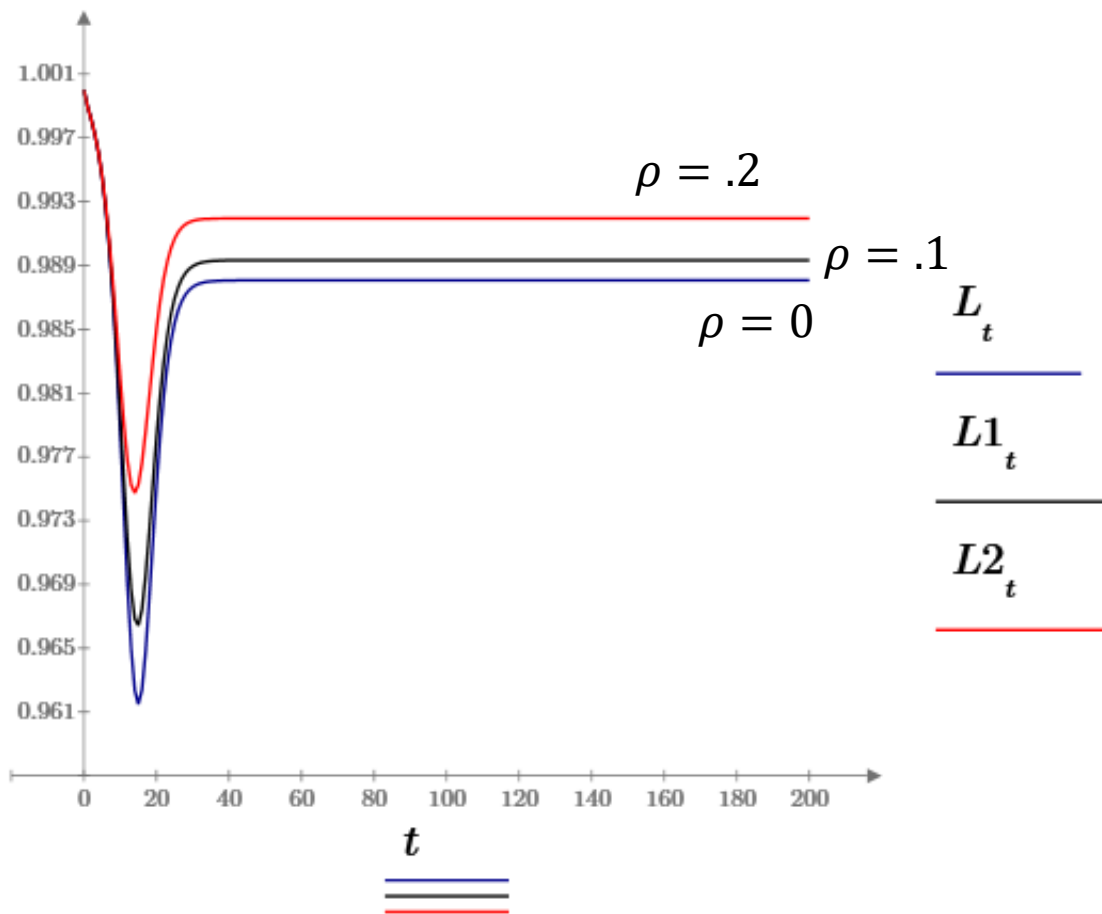
- If the meeting rate changes like the cosine curve, the pandemic is completed at the initial attack, and there is no second or third attack.
- Under mobility control, the meeting rate falls at a slower speed at the beginning, then approaches its target at a faster speed.



# No need to have a second Lockdown

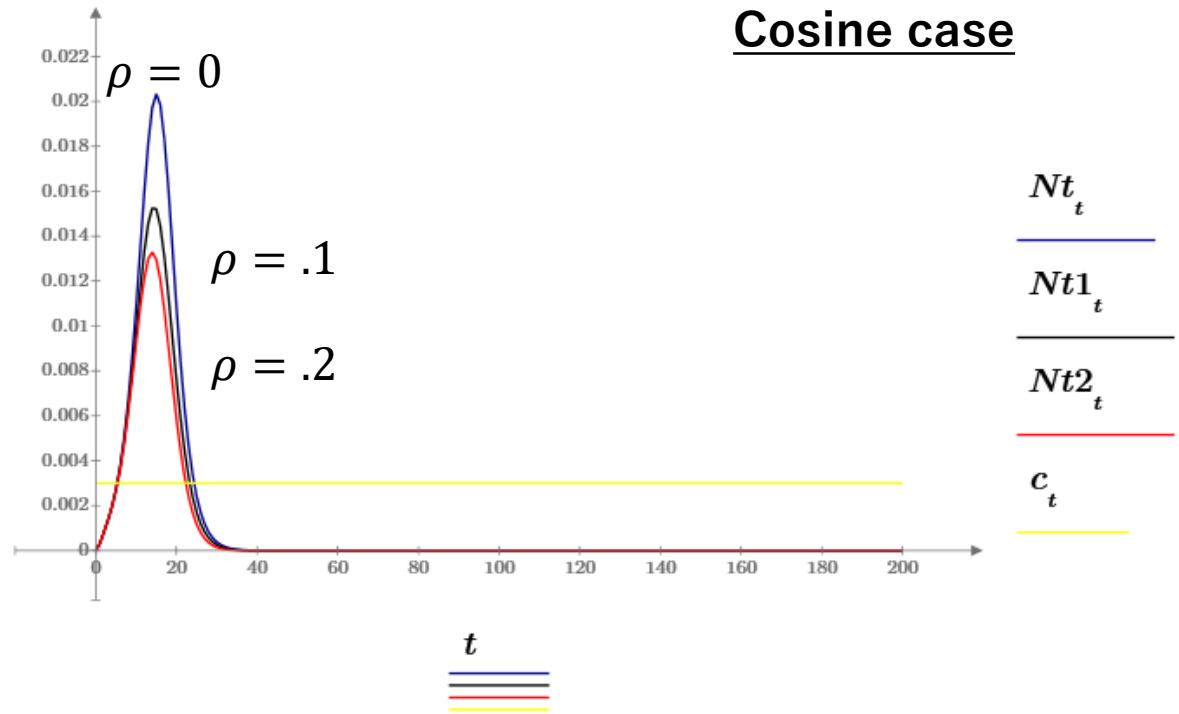


# Labor force and output

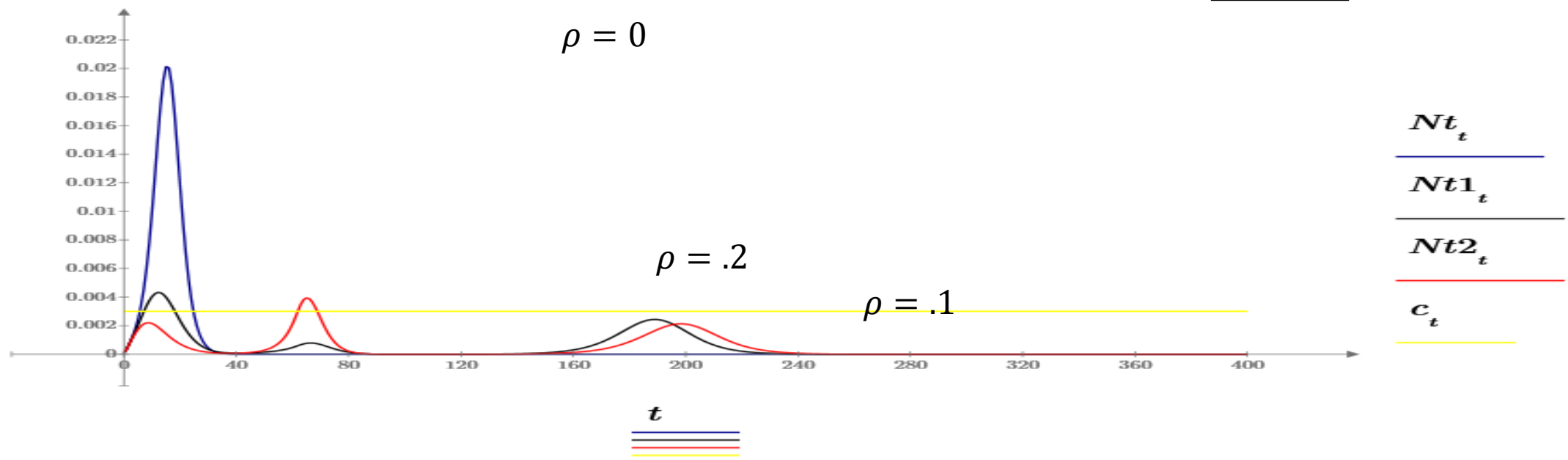


# Comparison: Medical Capacity

## Cosine case

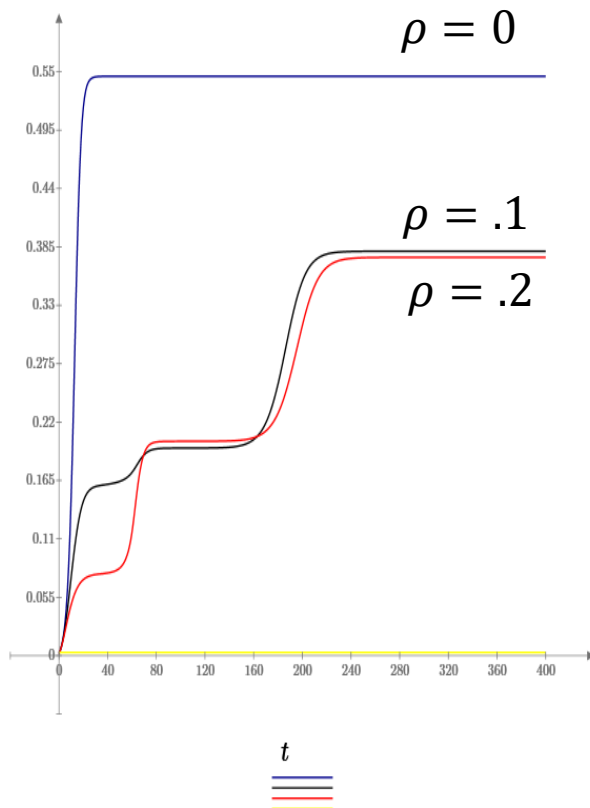


## AR case



# Comparison: Herd Immunity

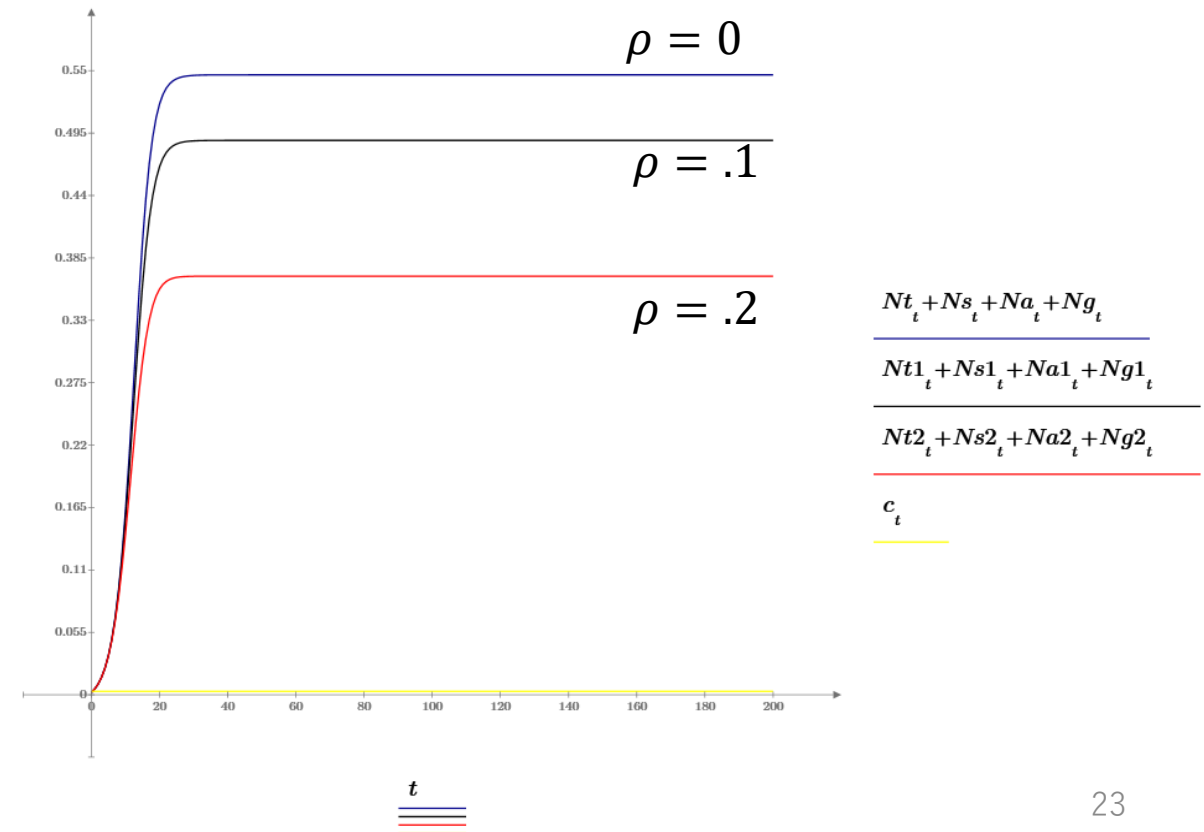
## AR case



$$\frac{Nt_t + Ns_t + Na_t + Ng_t}{Nt1_t + Ns1_t + Na1_t + Ng1_t}$$

$$\frac{Nt2_t + Ns2_t + Na2_t + Ng2_t}{c_t}$$

## Cosine case

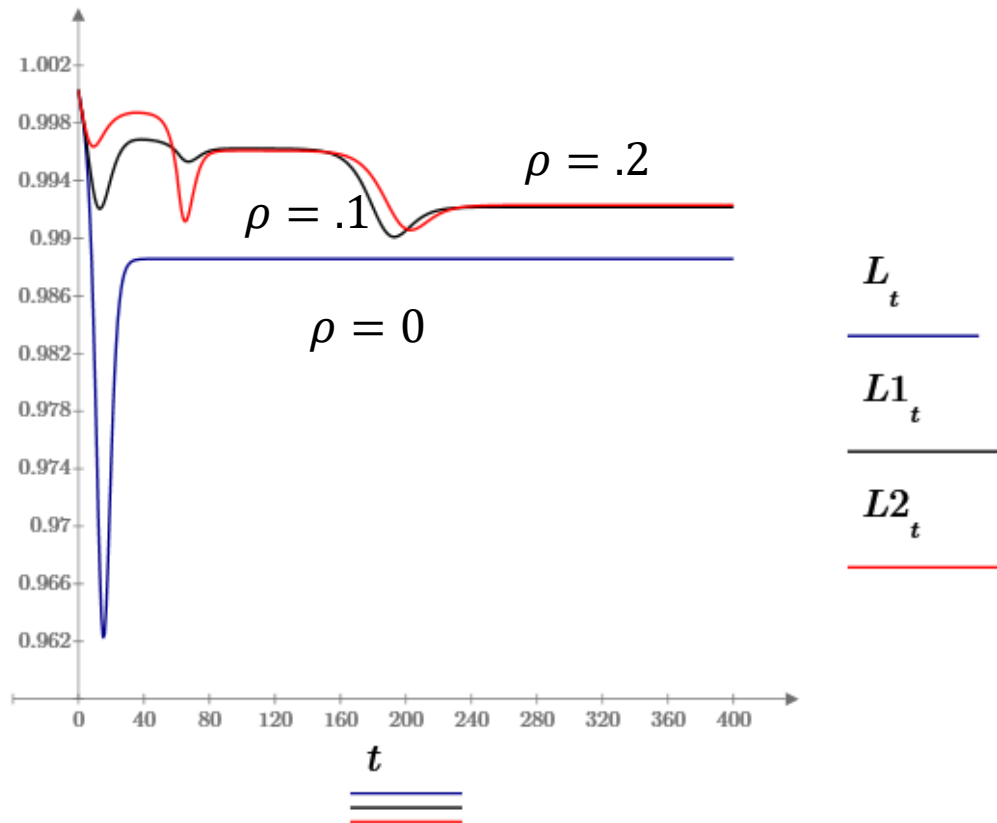


$$\frac{Nt_t + Ns_t + Na_t + Ng_t}{Nt1_t + Ns1_t + Na1_t + Ng1_t}$$

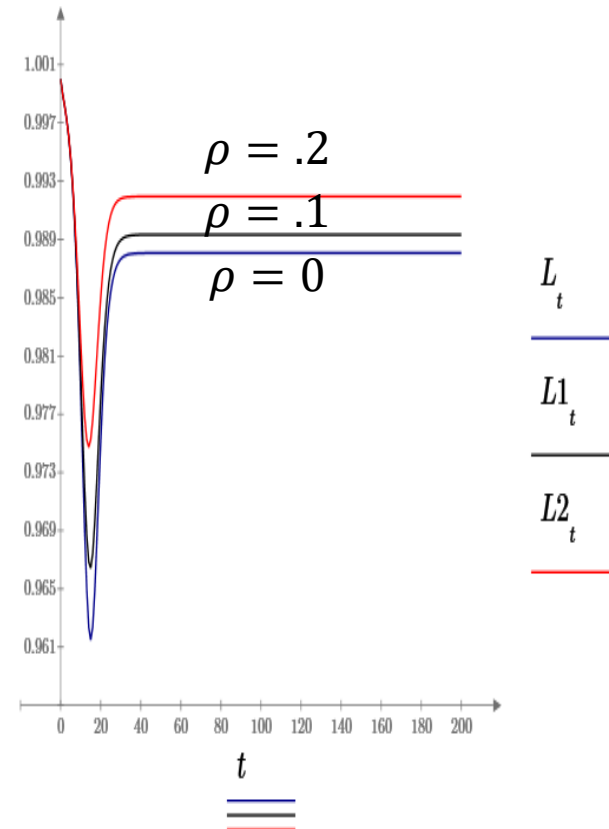
$$\frac{Nt2_t + Ns2_t + Na2_t + Ng2_t}{c_t}$$

# Comparison: Labor Force

AR case

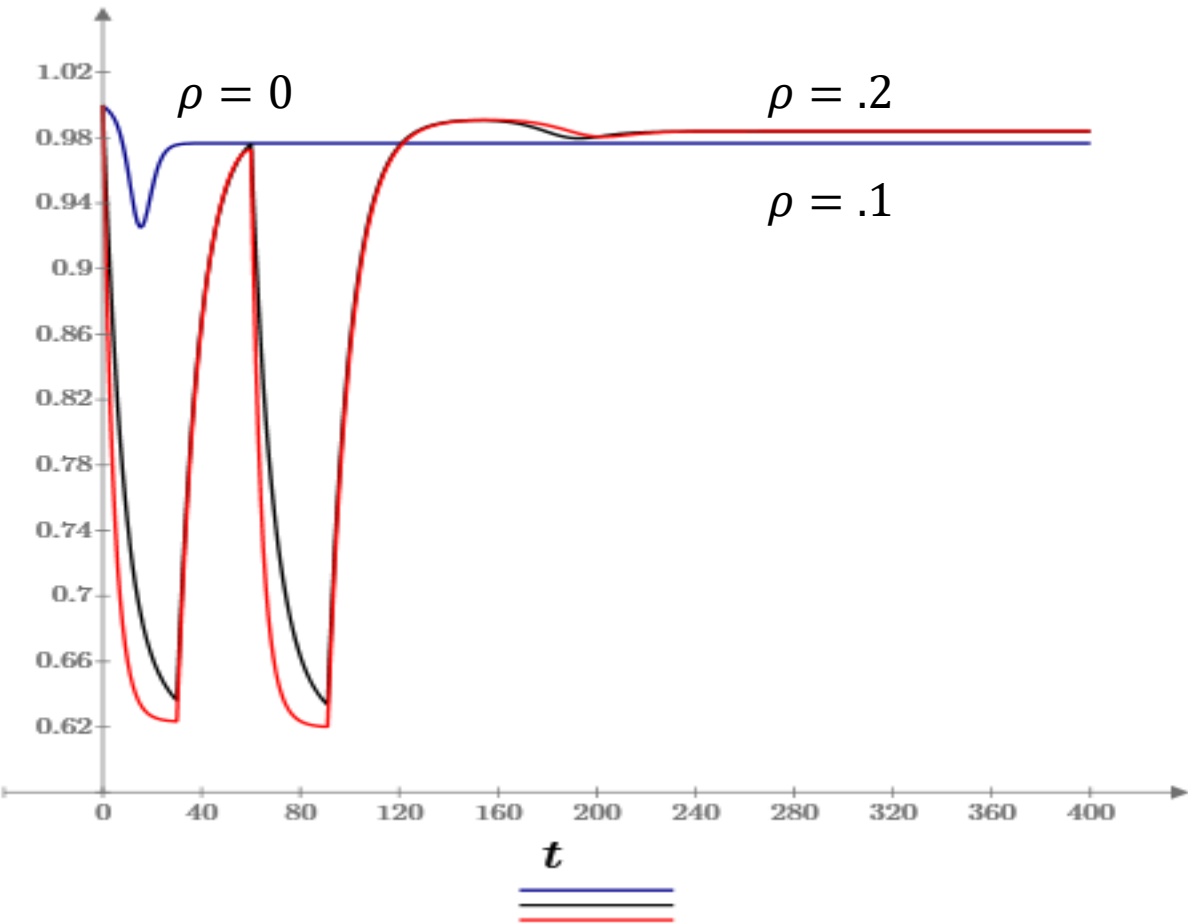


Cosine case





# Comparison: Output

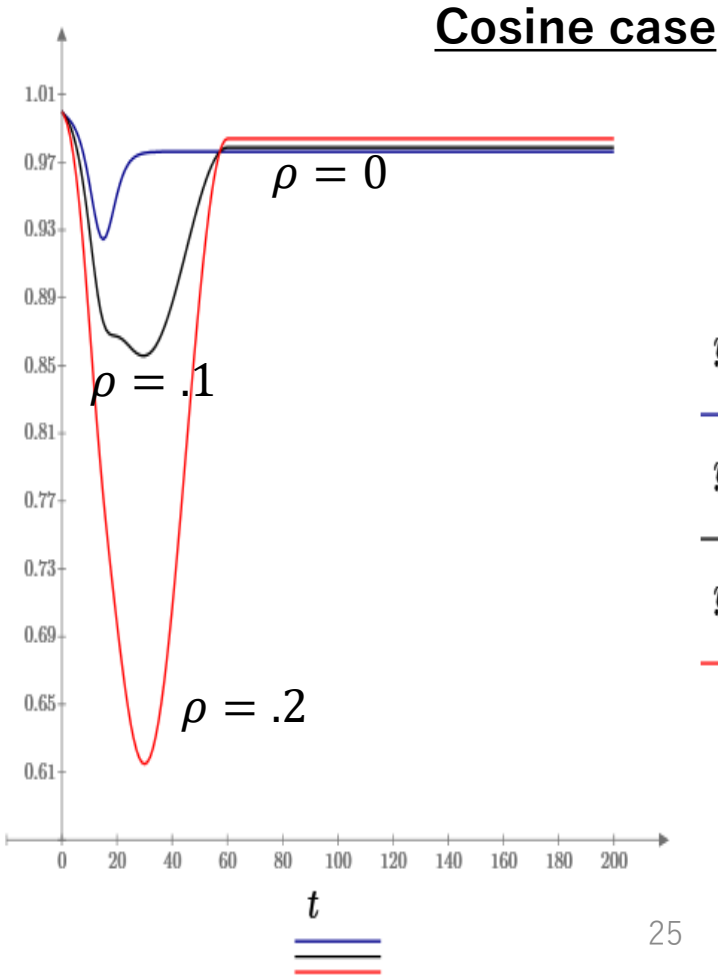


AR case

$y_r_t$

$y r1_t$

$y r2_t$



Cosine case

$y r_t$

$y r1_t$

$y r2_t$

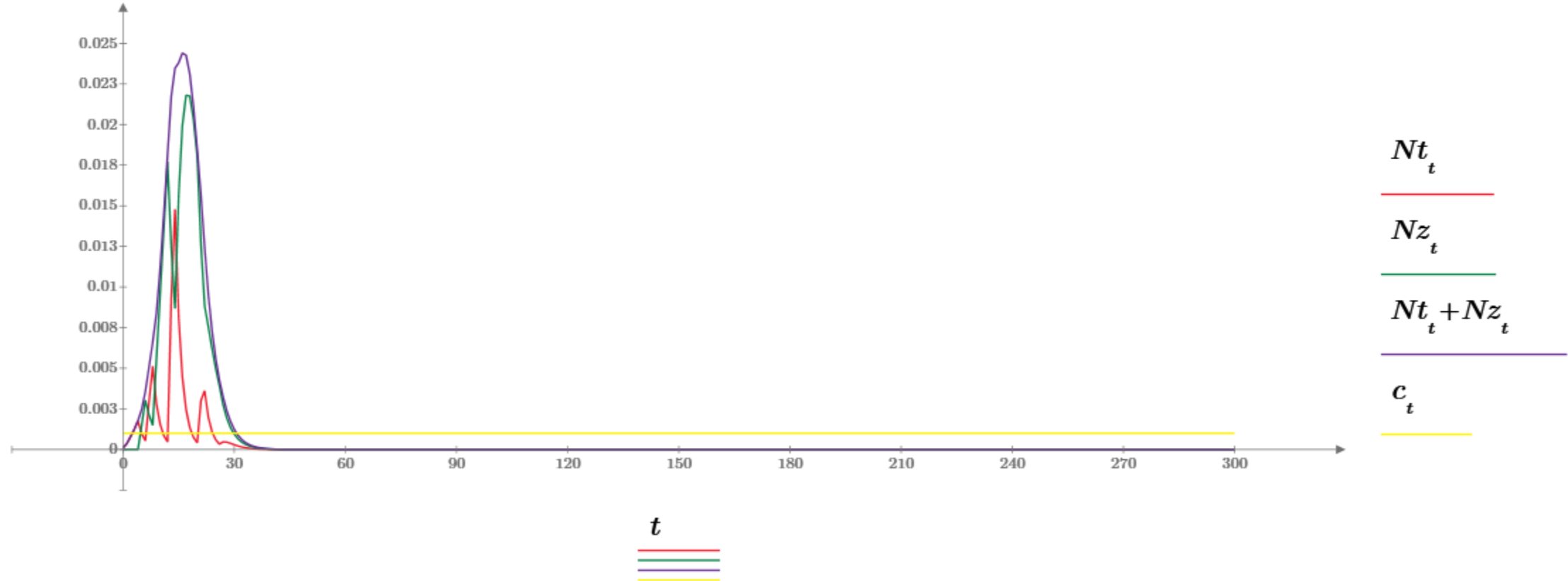
# Medical Capacity

- Consider the situation that hospitals do not accept patients if their capacity is short of the population of patients.
- Those who are not accepted by hospitals take care of themselves at their home.
- The quality of self-care is lower than the quality of staying at hospitals.
- Self-cared patients die at higher rate and recover to be healthy at a lower rate.
- Let  $c$  be the medical capacity. I simulate the model for  $c=.001$  and  $c=.005$
- $N_t$ : in hospital, and  $N_z$ : out of hospital

## No contact control, $c=.001$

Most people cannot be hospitalized

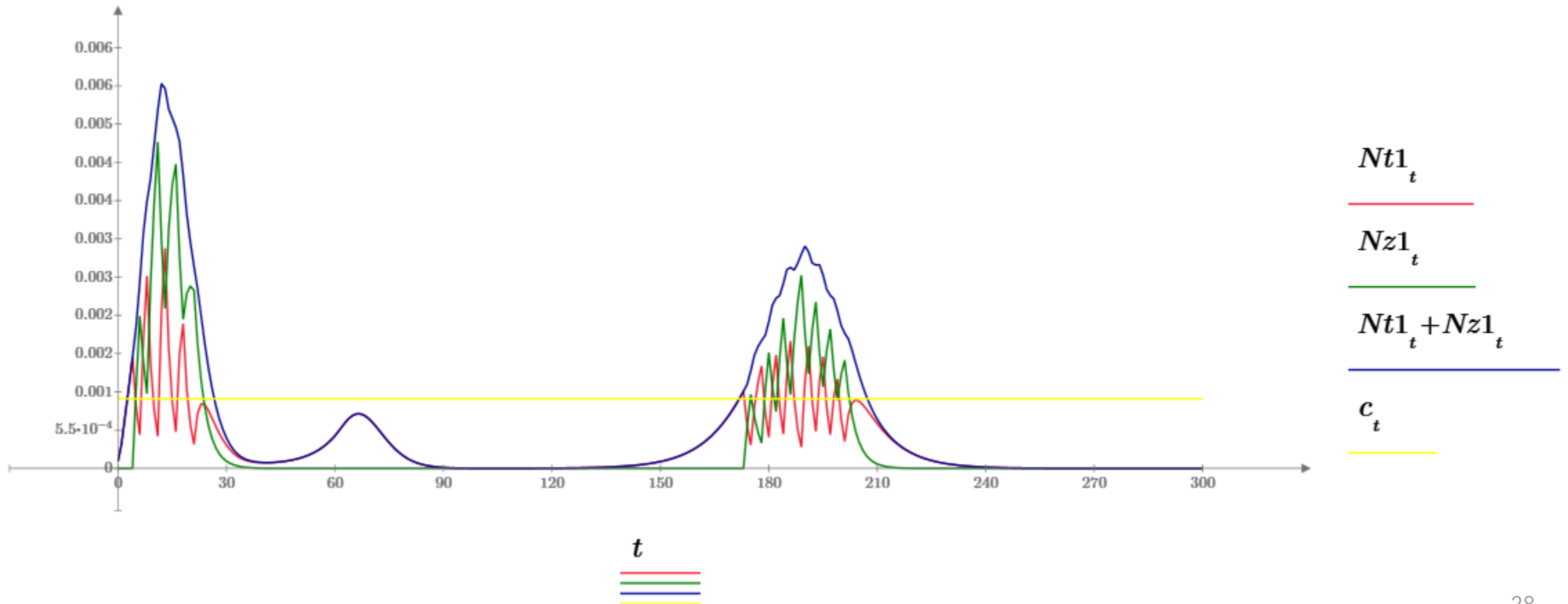
At peak, 2.3% of people need being hospitalized, while capacity is .1%



## Looser contact control, $c=.001$

Most people cannot be hospitalized

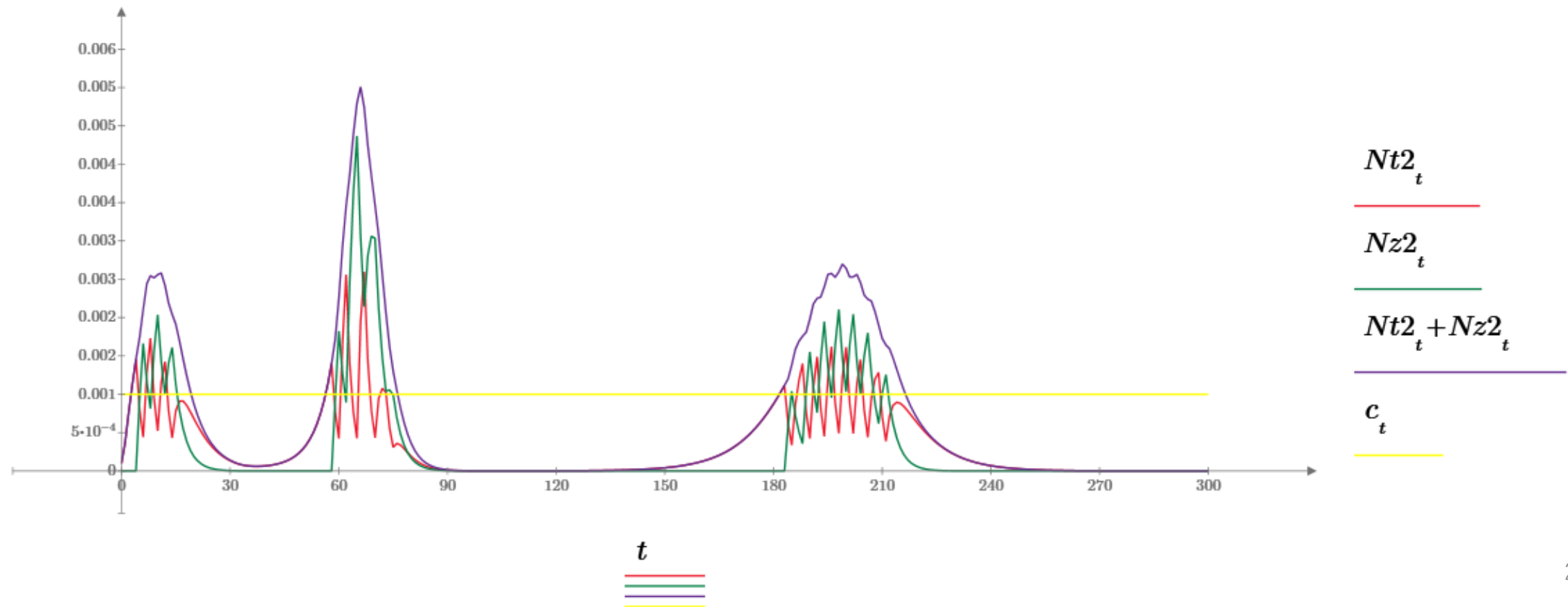
At peak, 0.6% of people need being hospitalized, while capacity is .1%



# Tighter contact control, $c=.001$

Most people cannot be hospitalized

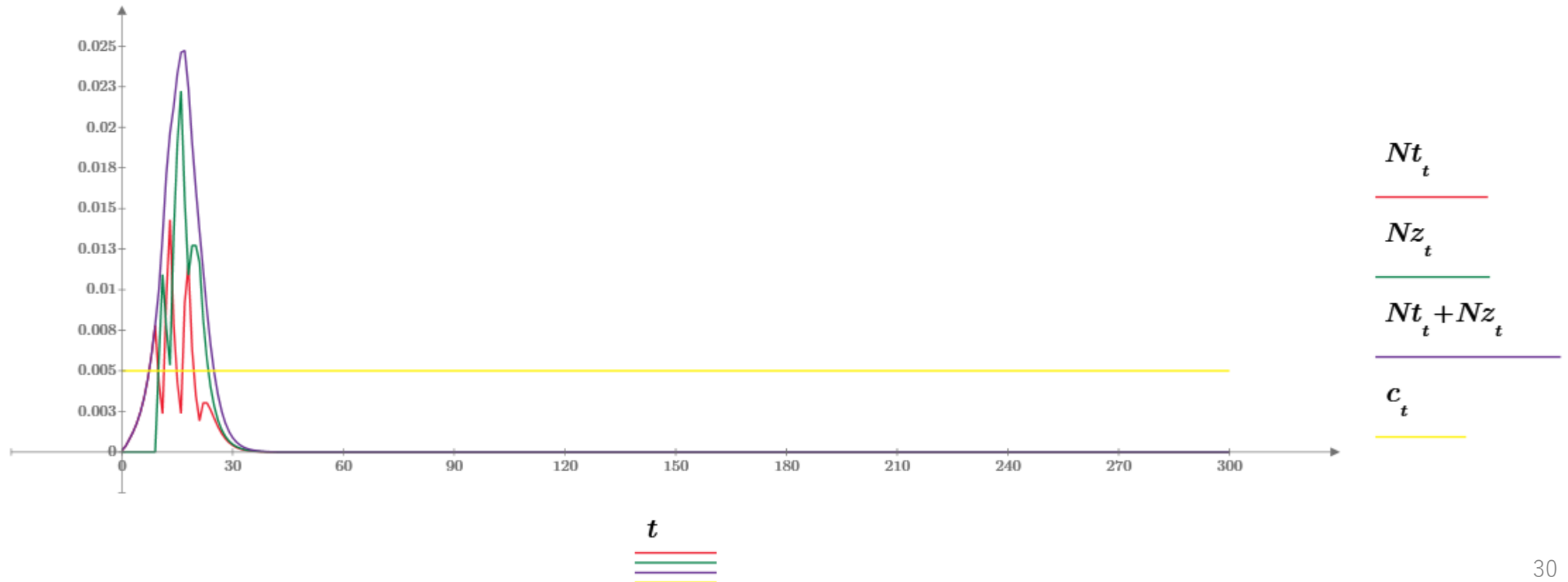
At peak, 0.5% of people need being hospitalized, while capacity is .1%



## No contact control, $c=.005$

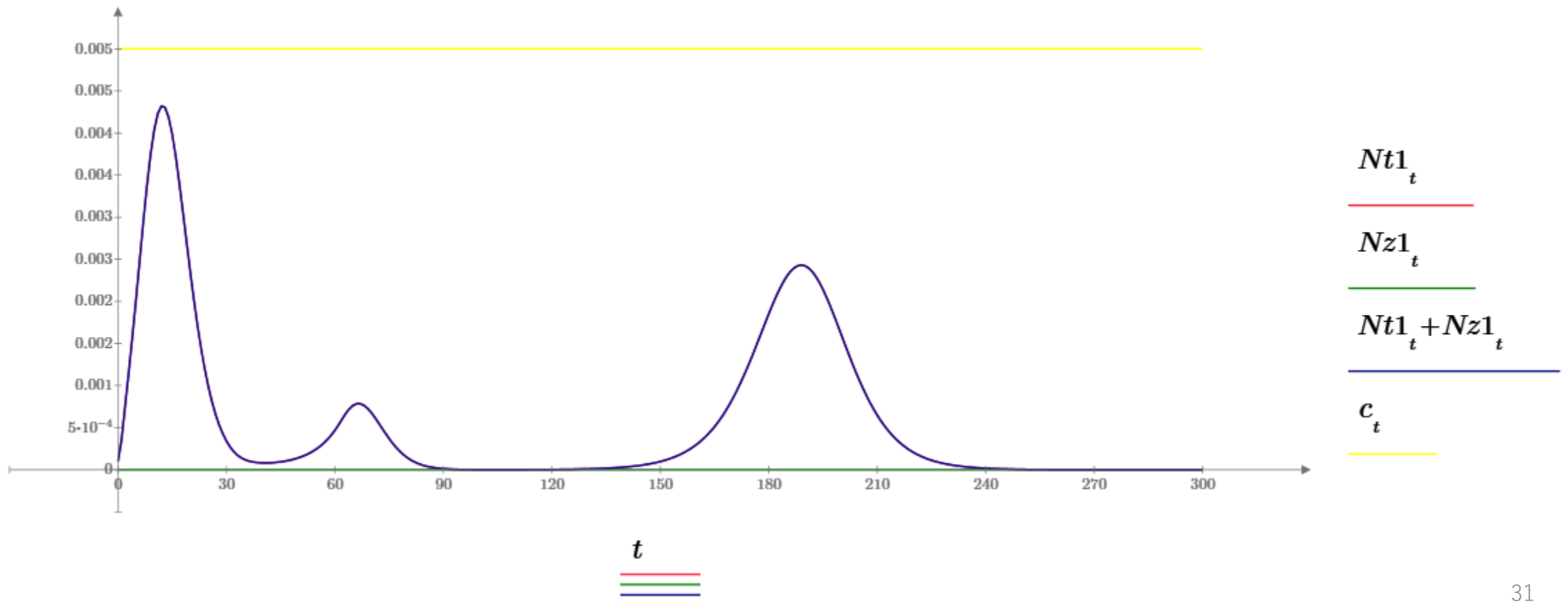
Most people cannot be hospitalized

At peak, 2.5% of people need being hospitalized, while capacity is .5%



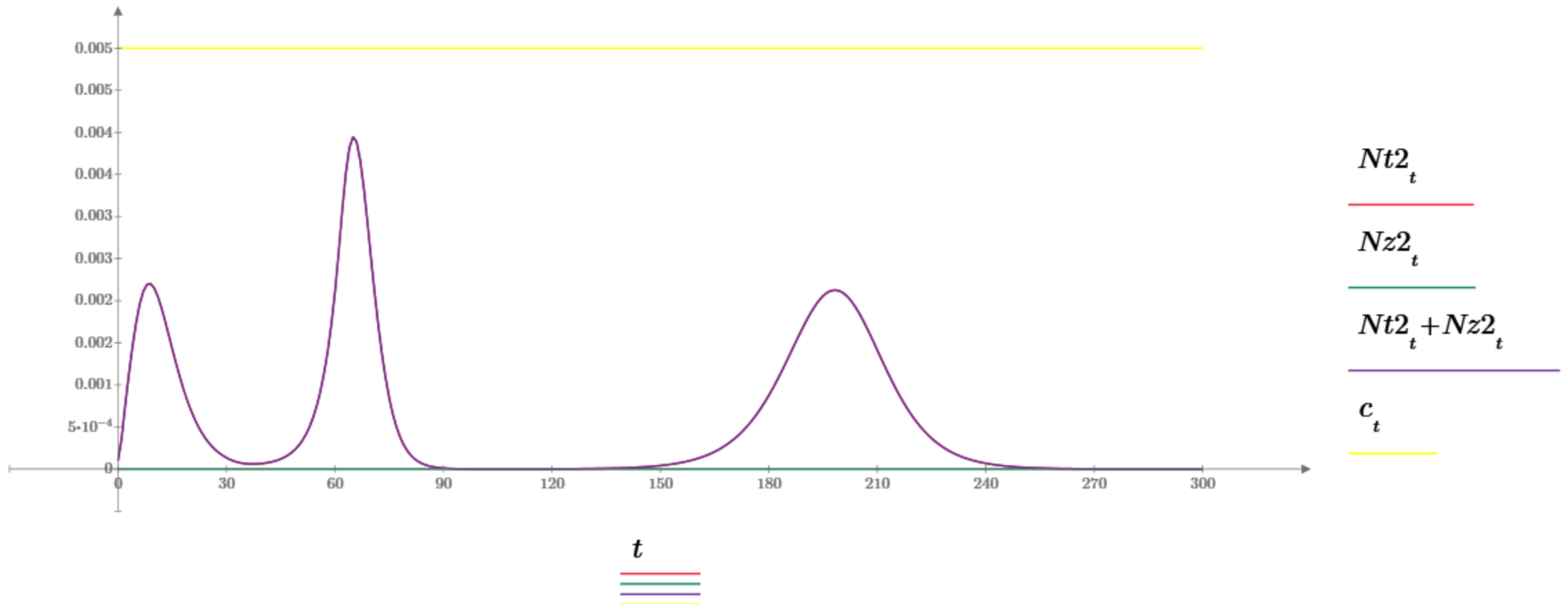
# Looser contact control, $c=.005$

At peak, 0.45% of people need being hospitalized, and all of them are hospitalized.



# Looser contact control, $c=.005$

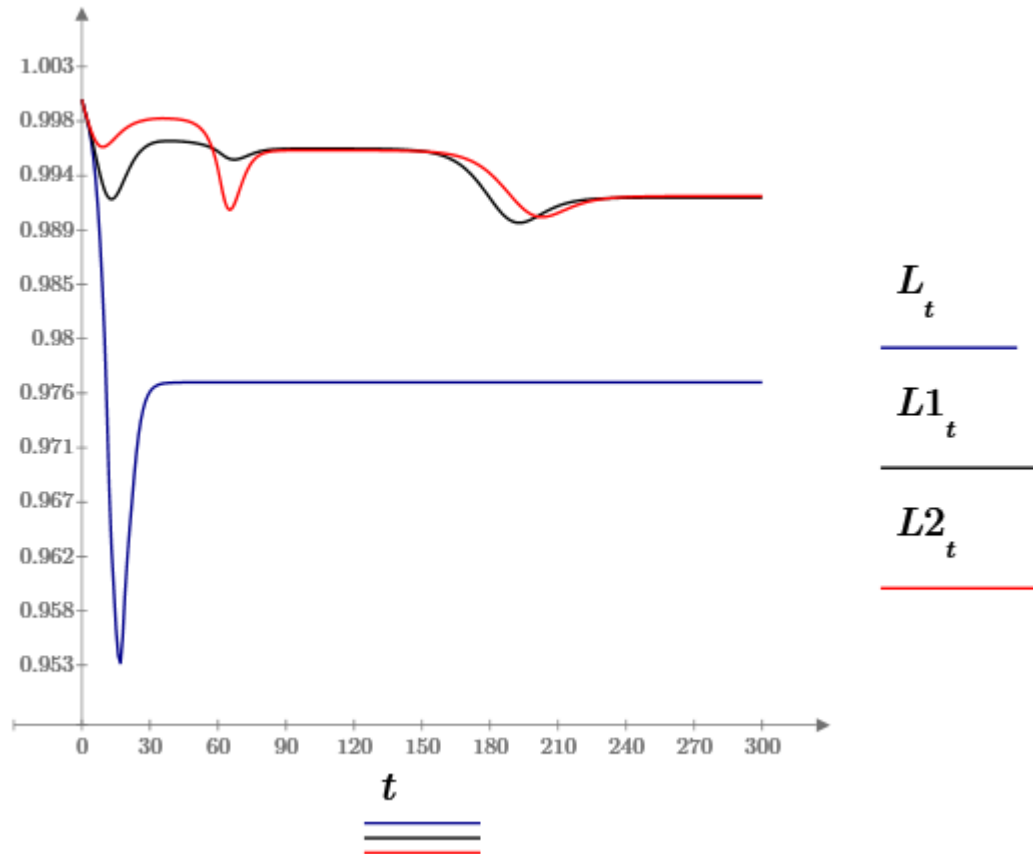
At peak, 0.4% of people need being hospitalized, and all of them are hospitalized.



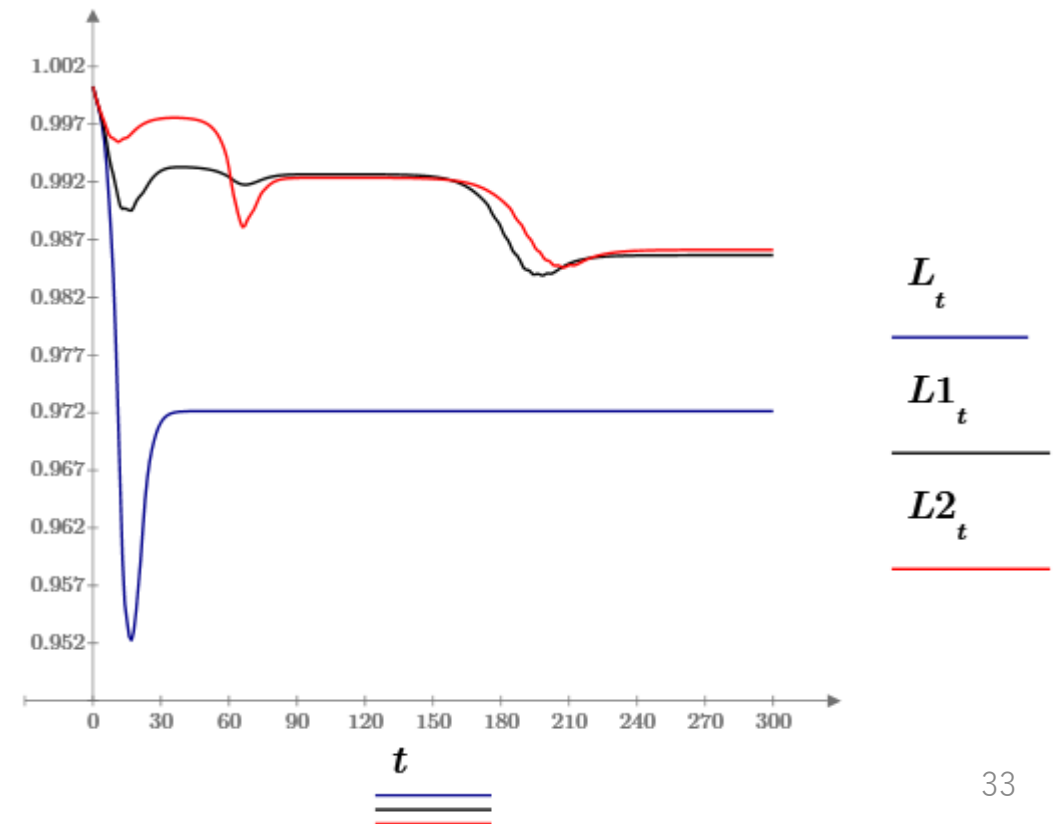


# Lower medical capacity is followed by larger loss in labor force and output

$c=.0005$



$c=.0001$



# Welfare

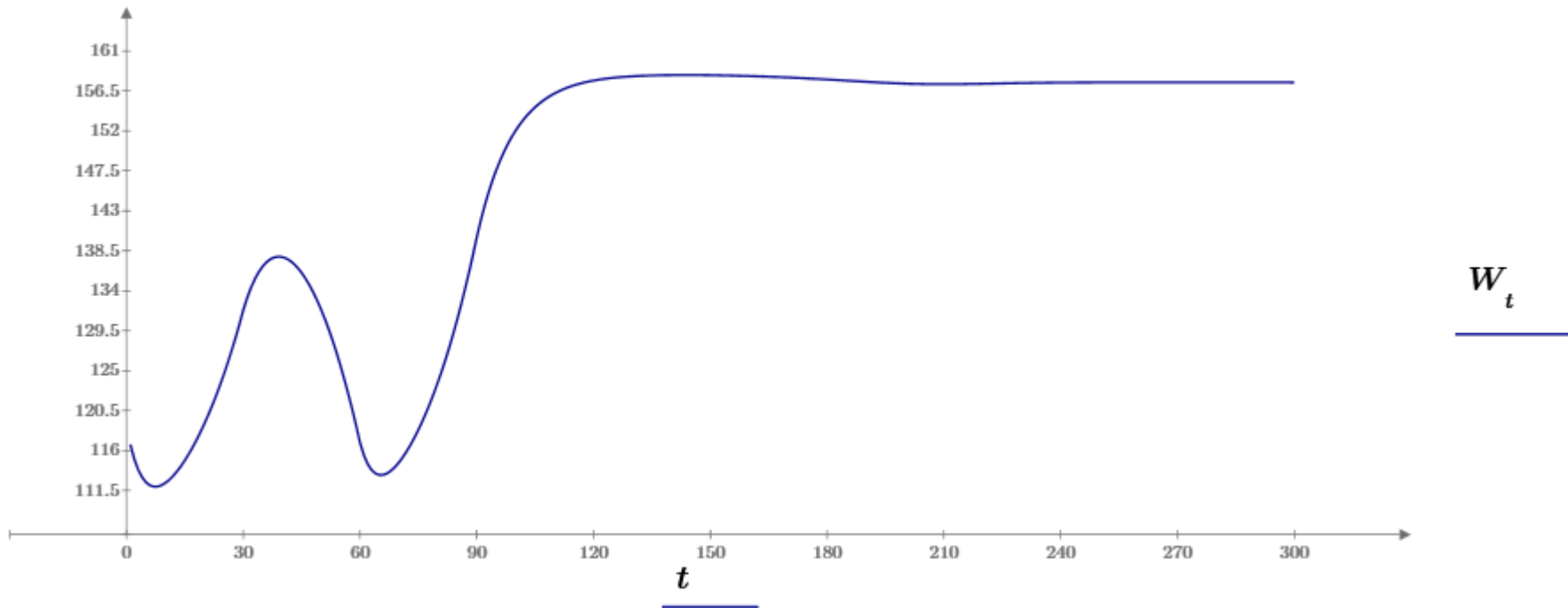
- People act forward-looking. Then the value functions are solved by backward induction.
- In this model, however, people act mechanically
- At time T, the economy reaches a steady state after the virus pandemic is over.
- Then solving value functions is equivalent to solving a terminal value problem, while the distribution of people is solved as a usual initial-value problem.
- We assume the meeting rate follows a repeated hammer-and-dance process as in the right-above.
- The terminal values at time T are given as in the right-below.
- $Vz_T$  denotes the value of being ill without being hospitalized.
- The file: corona047-value-dynamics-correct.

$$\alpha_{t+1} := \left\| \begin{array}{l} \text{if } t < 30 \\ \quad \left\| \alpha_t \cdot (1 - \rho) + \rho \cdot \alpha_g \right\| \\ \text{if } t > 29 \\ \quad \left\| (1 - \eta) \cdot \alpha_t + \eta \cdot \alpha_1 \right\| \\ \text{if } 59 < t < 90 \\ \quad \left\| \alpha_t \cdot (1 - \rho) + \rho \cdot \alpha_g \right\| \\ \text{if } t > 90 \\ \quad \left\| (1 - \eta) \cdot \alpha_t + \eta \cdot \alpha_1 \right\| \end{array} \right\|$$

$$\begin{bmatrix} Vh_T \\ Va_T \\ Vs_T \\ Vt_T \\ Vz_T \\ Vg_T \end{bmatrix} = \begin{bmatrix} 158.72 \\ 154.155 \\ 141.548 \\ 126.311 \\ 90.02 \\ 158.72 \end{bmatrix}$$

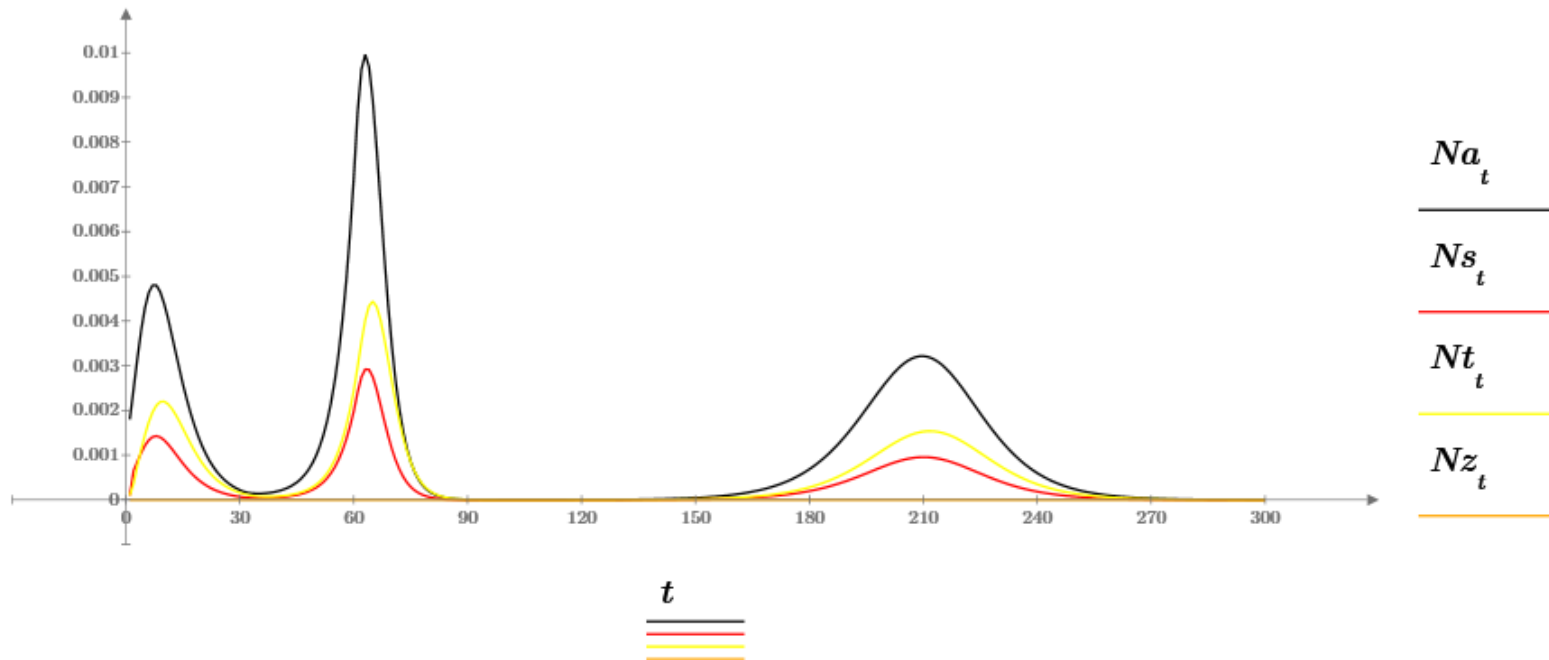
# The Aggregate Welfare

$$W_t := N h_t \cdot V h_t + N a_t \cdot V a_t + N s_t \cdot V s_t + N t_t \cdot V t_t + N z_t \cdot V z_t + N g_t \cdot V g_t$$



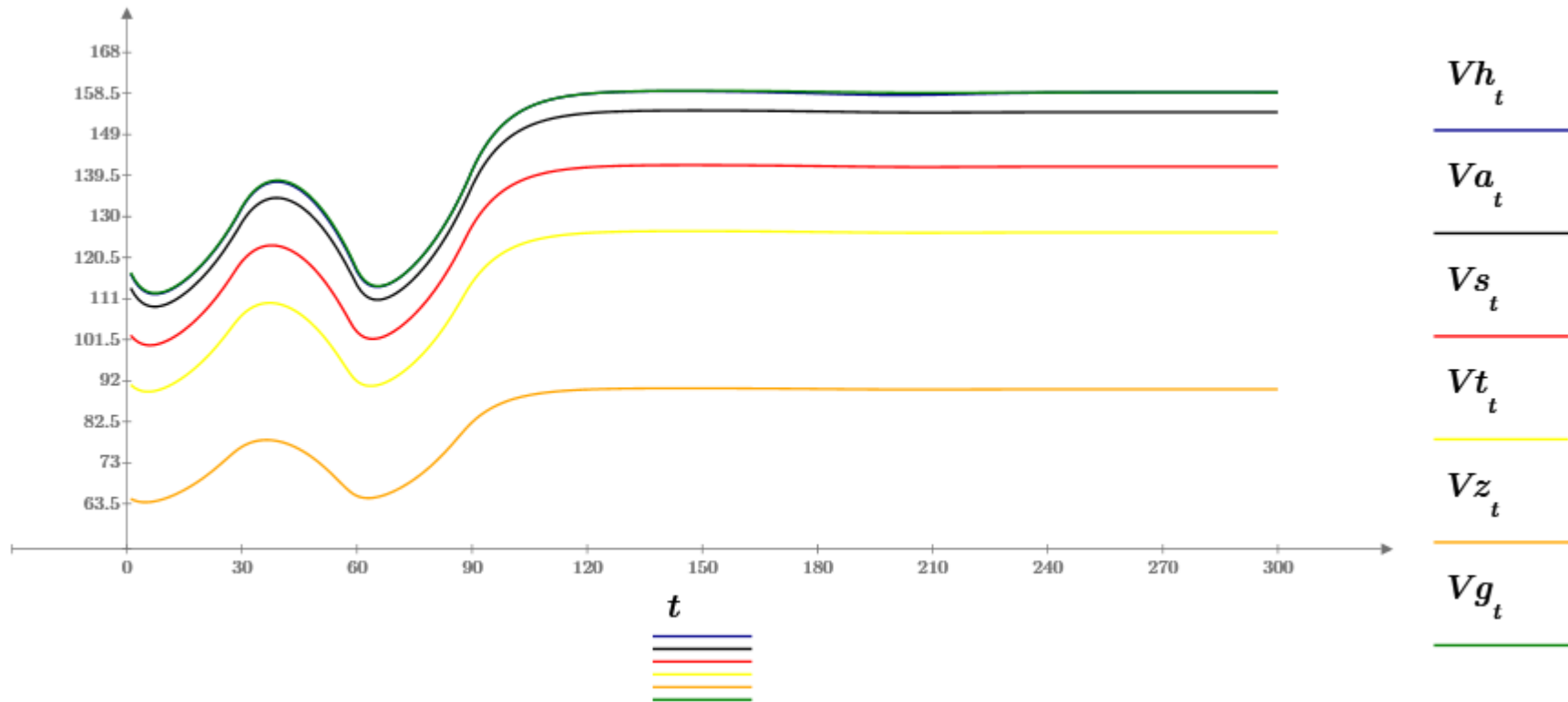
- The aggregate welfare is the population-weighted sum of individual life-time utility of being at each state.
- At time 0, the aggregate welfare drops down from  $W=156$  to  $W=112$  since the life is threatened by the virus pandemic, then it gradually recovers to its original level.

# A Spanish Flu pattern

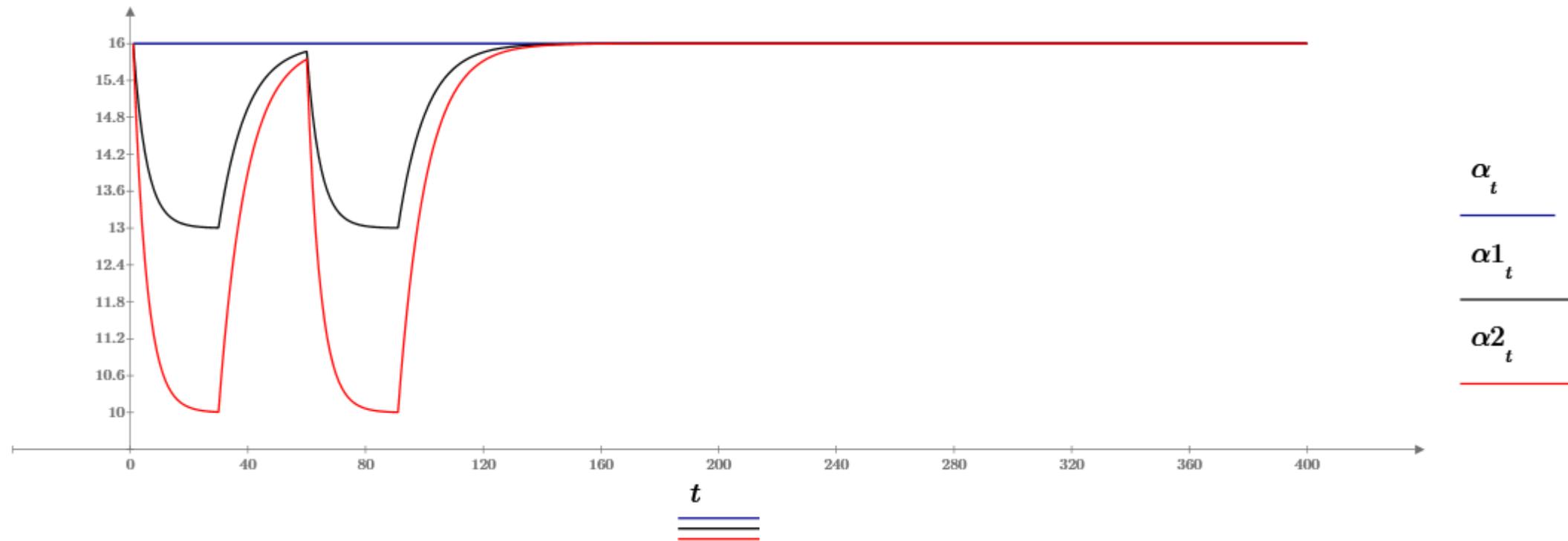


- $Na_t$ : infectious and not recognized in the labor market.
- $Ns_t$ : infected and separated from the labor market.
- $Nt_t$ : infected and hospitalized.
- $Nz_t$ : infected and not hospitalized because of medical capacity shortage.

The values changes accordingly.



# Shallow or Deep?



- The meeting rate starts at  $a=16$ .
- The meeting rate is maintained at  $a=16$ , or goes down to  $a1=13$  (loose regulation), or  $a2=10$  (tight regulation).
- There is a medical capacity  $c=.001$

# The terminal values

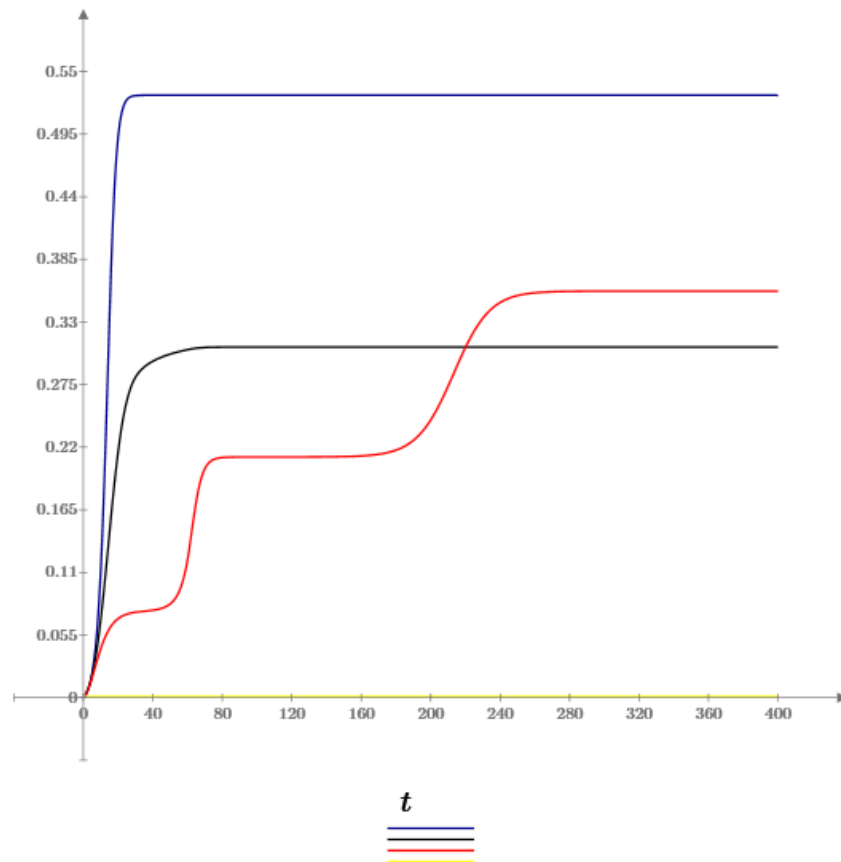
$$\begin{bmatrix} Vh_T \\ Va_T \\ Vs_T \\ Vt_T \\ Vz_T \\ Vg_T \end{bmatrix} = \begin{bmatrix} 155.36 \\ 150.892 \\ 138.551 \\ 123.637 \\ 88.115 \\ 155.36 \end{bmatrix}$$

$$\begin{bmatrix} Vh1_T \\ Va1_T \\ Vs1_T \\ Vt1_T \\ Vz1_T \\ Vg1_T \end{bmatrix} = \begin{bmatrix} 157.6 \\ 153.067 \\ 140.549 \\ 125.42 \\ 89.385 \\ 157.6 \end{bmatrix}$$

$$\begin{bmatrix} Vh2_T \\ Va2_T \\ Vs2_T \\ Vt2_T \\ Vz2_T \\ Vg2_T \end{bmatrix} = \begin{bmatrix} 157.76 \\ 153.223 \\ 140.691 \\ 125.547 \\ 89.476 \\ 157.76 \end{bmatrix}$$

- The terminal values are not different so much, mainly reflecting the loss of labor force.
- The files is corona047-LRLR-dynamics-target.

# Herd Immunity



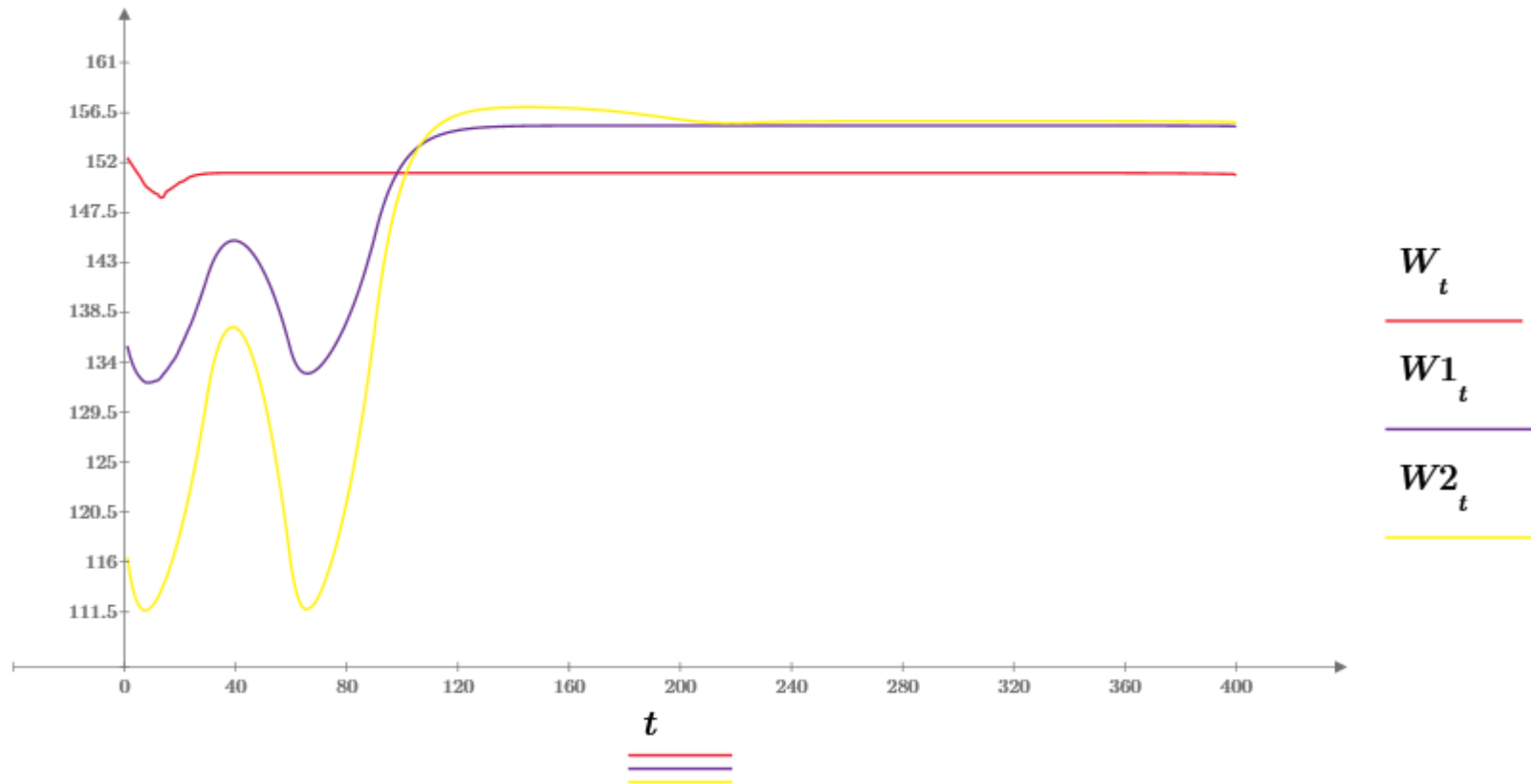
$$\frac{Nz_t + Nt_t + Ns_t + Na_t + Ng_t}{Nz1_t + Nt1_t + Ns1_t + Na1_t + Ng1_t}$$

$$\frac{Nz2_t + Nt2_t + Ns2_t + Na2_t + Ng2_t}{c_t}$$

- Herd Immunity is achieved at lower level of infection if people are protected by a tighter regulation.
- This is a major benefit of regulation on mobility.



# Welfare gain of mobility control

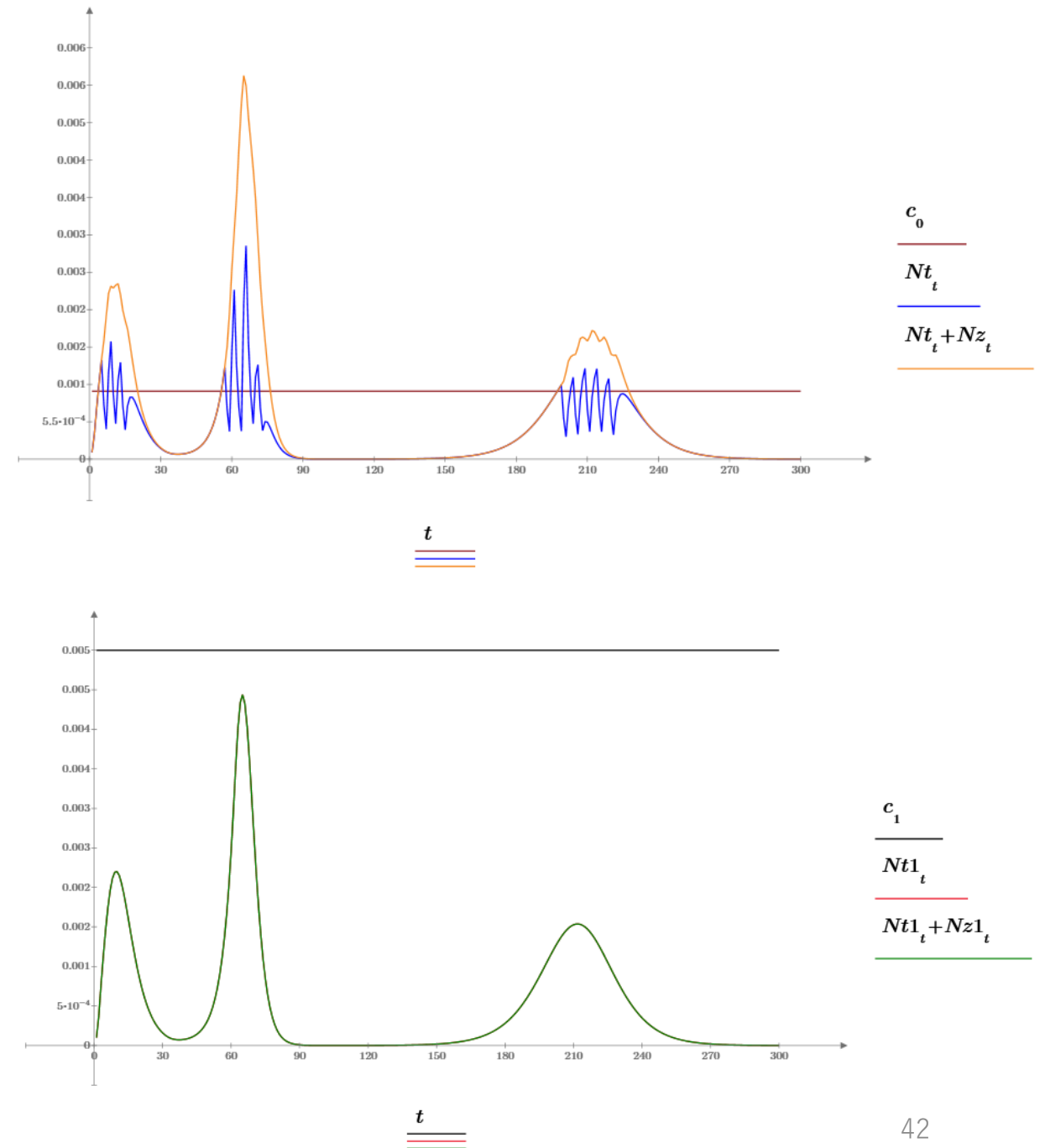


- A tighter contact control is followed by a larger output loss, while the loss is compensated by a larger output after the pandemic is over.
- The welfare gap is not so large between  $a1=13$  and  $a2=16$ , suggesting that a tighter regulation is not rewarded by enough gains.

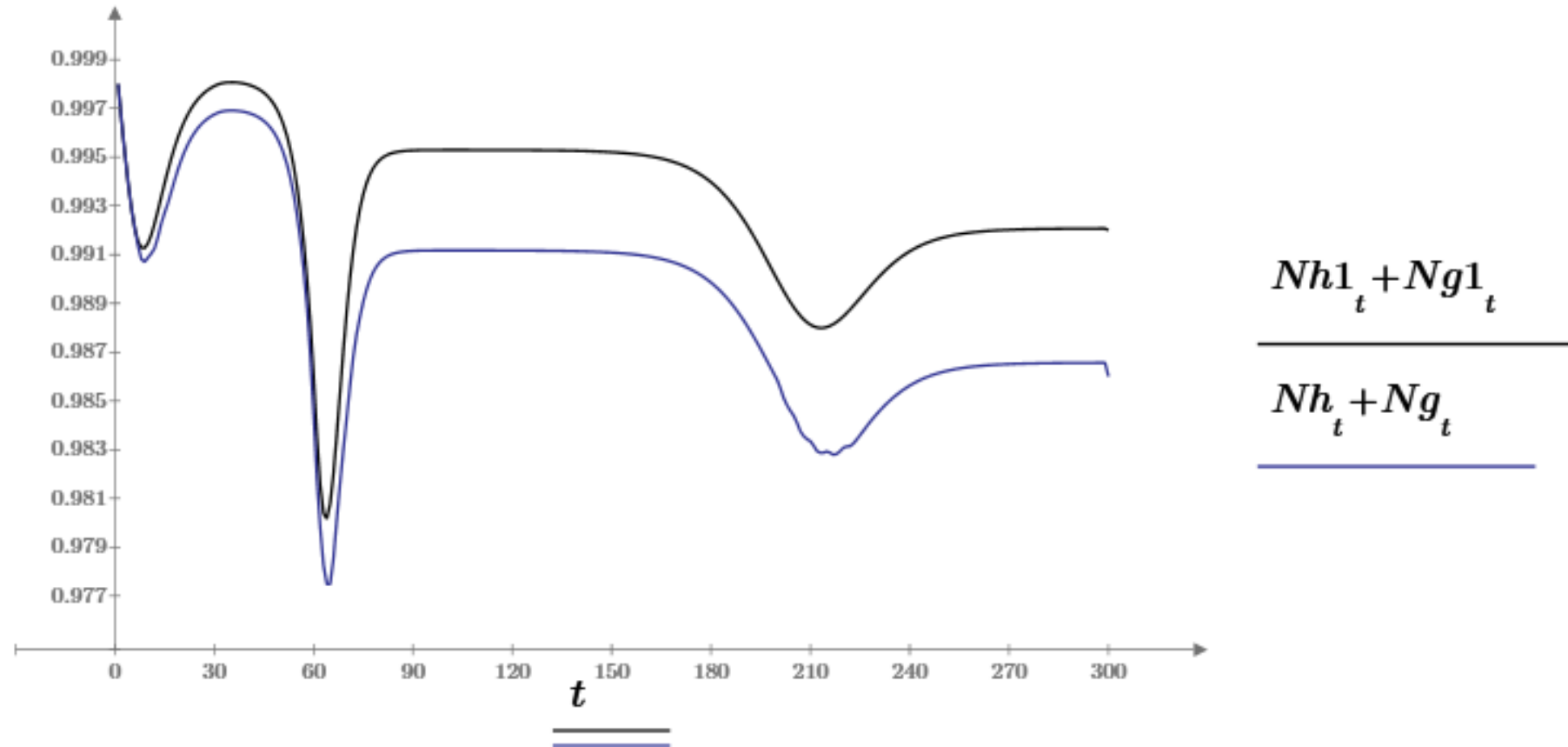
# Medical Capacity

$$\alpha_{t+1} := \begin{cases} \text{if } t < 30 \\ \quad \alpha_t \cdot (1 - \rho) + \rho \cdot \alpha_g \\ \text{if } t > 29 \\ \quad (1 - \eta) \cdot \alpha_t + \eta \cdot \alpha_1 \\ \text{if } 59 < t < 90 \\ \quad \alpha_t \cdot (1 - \rho) + \rho \cdot \alpha_g \\ \text{if } t > 90 \\ \quad (1 - \eta) \cdot \alpha_t + \eta \cdot \alpha_1 \end{cases}$$

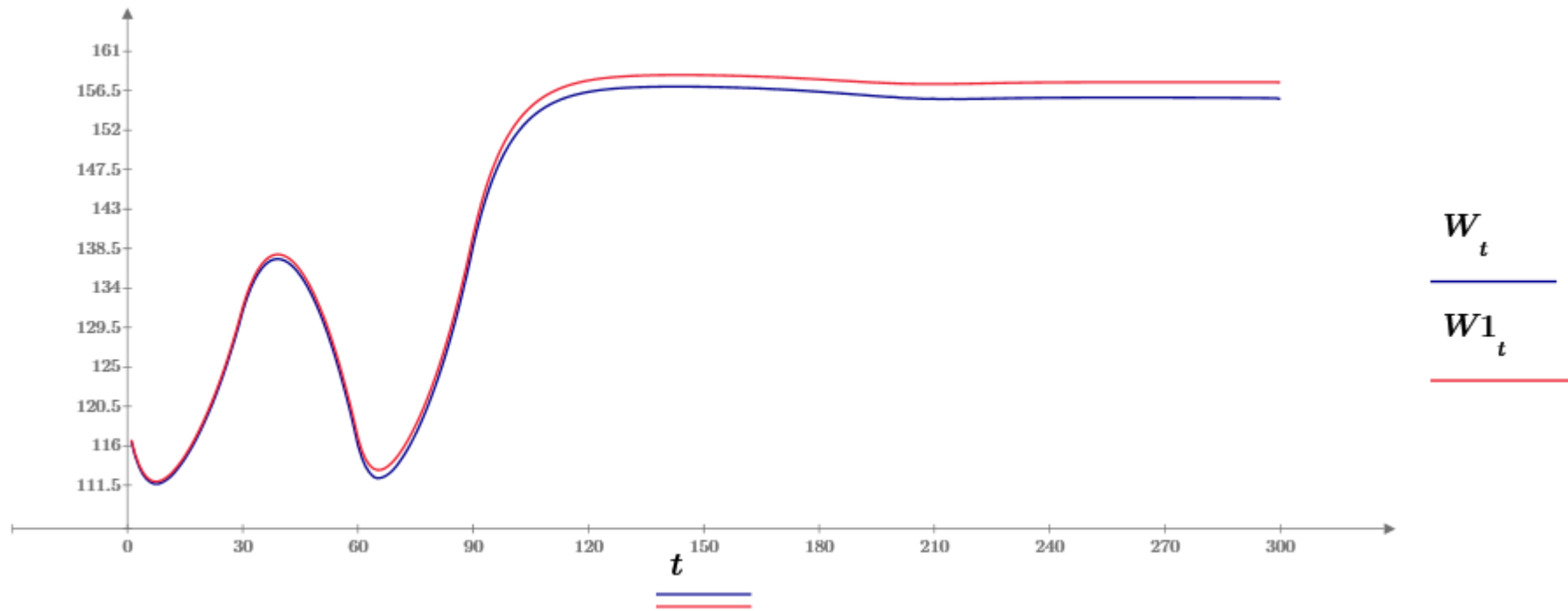
- Consider a mobility control policy with  $a_1=16$  and  $a_g=10$ .
- Medical capacity constraint  $c_0=.001$  or  $c_1=.005$ .
- Pandemic occurs three times.
- Under  $c_0=.001$ , some infected people are not hospitalized.



# Larger medical capacity reduces labor force loss



Medical capacity makes no big difference in welfare.



# Welfare

- After all, causing a medical collapse without mobility control will result in more long-term workforce loss, but in smaller short-term economic loss.
- In order to evaluate economic welfare, the question is how to take the lost utility of dead people into account.
- The total utility goes down as the population declines
- Can we evaluate economic welfare appropriately, by simply adding the lifetime utility of people alive?