

## Negative Binomial PMF:

$\gamma$  is counting  $y$  failures given  $r$  successes. Total # of trials

$$n = y+r$$

$$f(y; p, r) = \binom{y+r-1}{r-1} p^r (1-p)^y$$

where  $p$  is the probability of success in each trial

Lemma:

$$\binom{y+r-1}{r-1} = \binom{y+r-2}{y}$$

Proof:

$$\begin{aligned} \binom{y+r-1}{r-1} &= \frac{(y+r-1)!}{(r-1)!((y+r-1)-r+1)!} = \frac{(y+r-1)!}{(r-2)!y!} \\ &= \frac{(y+r-1)!}{y!(r-1)!} = \frac{(y+r-2)!}{y!(y+r-2-y)!} \\ &= \binom{y+r-2}{y} \end{aligned}$$

□

$\Sigma (\tilde{U} - U)^2$

$\bar{U} - \frac{\partial U}{\partial \mu}$   
Dev. var.

Therefore

$$f(y; p, r) = \binom{y+r-1}{y} p^r (1-p)^y$$

$$\text{Mean: } \frac{r(1-p)}{p} \approx \mu, \quad \text{Variance: } \frac{r(1-p)}{p^2} = \text{Var}(\gamma)$$

- s. II

$$\Rightarrow \mu p = r - rp$$

$$\Rightarrow p(r+\mu) = r$$

$$\Rightarrow p = r/\mu = \text{Var}(\gamma) = \mu/r = \mu/\mu(r+\mu) = \mu/\mu(r+\mu) = \mu + \mu^2/r$$

$$f(y; \mu, r) = \binom{y+r-1}{y} \left(\frac{r}{r+\mu}\right)^r \left(\frac{\mu}{r+\mu}\right)^y$$

$$\Gamma(n) = (n-1)!$$

if  $n \in \mathbb{N}, n \geq 1$   
if  $n$  is a real  
# the  $\Gamma(\cdot)$

$$= \frac{\Gamma(y+r)}{y! \Gamma(r)} \left(\frac{r}{r+\mu}\right)^r \left(\frac{\mu}{r+\mu}\right)^y$$

is well defined

Define  $r := \frac{1}{\alpha}$ ,  $\Rightarrow p = \frac{1}{r} \left( \frac{1}{1+\alpha} + \mu \right) = \frac{1}{1+\alpha} + \mu$

$$f(y; \mu, r) = \frac{\Gamma(y + \frac{1}{\alpha})}{\Gamma(y+1) \Gamma(\frac{1}{\alpha})} \left( \frac{1}{1+\alpha} \right)^{\frac{1}{\alpha}} \left( \frac{\alpha \mu}{1+\alpha} \right)^y$$

$\Rightarrow$  The single data log-likelihood is

$$\begin{aligned} l_i^B &= y_i \log \left( \frac{\alpha \mu}{1+\alpha} \right) - \frac{1}{\alpha} \log(1+\alpha \mu_i) + \log \Gamma(y_i + \frac{1}{\alpha}) \\ &\quad - \log \Gamma(y_i + 1) - \log \Gamma(\frac{1}{\alpha}) \end{aligned} \quad \dots \quad (1)$$

Zero-truncated NB.

The probability of a zero count is

$$f(0; \mu, r) = \frac{\Gamma(\frac{1}{\alpha})}{\Gamma(1) \Gamma(\frac{1}{\alpha})} \left( \frac{1}{1+\alpha} \right)^{\frac{1}{\alpha}} = \left( \frac{1}{1+\alpha} \right)^{\frac{1}{\alpha}}$$

The zero-truncated density is

$$\begin{aligned} f(y|y>0, \mu, r) &= \frac{f(y; \mu, r)}{1 - f(0; \mu, r)} \\ &= \frac{\Gamma(y + \frac{1}{\alpha})}{\Gamma(y+1) \Gamma(\frac{1}{\alpha})} \left( \frac{1}{1+\alpha} \right)^{\frac{1}{\alpha}} \left( \frac{\alpha \mu}{1+\alpha} \right)^y \\ &\quad \frac{1}{1 - \left( \frac{1}{1+\alpha} \right)^{\frac{1}{\alpha}}} \end{aligned}$$

This gives us the single data log-likelihood;

$$l_i^{ZT} = l_i^B - \log \left\{ 1 - \left( \frac{1}{1+\alpha} \right)^{\frac{1}{\alpha}} \right\} \quad \dots \quad (2)$$

Where (2) is the ZTB single data log-likelihood as given in (1)

## Zero Inflated Negative Binomial (Hurdle model in Tutz (2012))

We use a similar parameterization as in Hlood et al. (2017) SA I. written by a

$$g(y; \mu, r) = \begin{cases} 1-q & y=0 \\ q f(y|y>0, \mu, r) & \text{otherwise} \end{cases}$$

where  $q$  is the probability of a positive counts

Similar to Hlood et al. (2017), we adopt the unconstrained parameterization

$$\sigma = \log \mu, \eta = \log \hat{p} - \log(1-q)$$

This gives us the single-data log-likelihood (we drop the data index  $i$ )

$$l^{z^1} = \begin{cases} \log(1-q) & y=0 \\ \log q + \log f(y|y>0, \mu, r) & \text{otherwise} \end{cases}$$

$$= \begin{cases} -e^\eta & y=0 \\ \log(1-e^{-e^\eta}) + l^{z^1} & \text{otherwise} \end{cases}$$

$$\Rightarrow \begin{cases} -e^\eta & y=0 \\ \log(1-e^{-e^\eta}) + l^{HB} - \log \left\{ 1 - (1+e^{-\eta})^{-\frac{1}{r}} \right\} & \text{otherwise} \end{cases}$$

$$= \begin{cases} -e^\eta & y=0 \\ \log(1-e^{-e^\eta}) + l^{z^1} & \text{otherwise} \end{cases}$$

where  $L^{AB} = L^{AB} - \log \{1 - ((1 + \alpha e^x)^{-\frac{1}{\alpha}})\}$  is the Z<sup>AB</sup> log-likelihood.  
and  $L^{AB} = y \log \left( \frac{\alpha e^x}{1 + \alpha e^x} \right) - \frac{1}{\alpha} \log (1 + \alpha e^x) + \log \Gamma(y + \frac{1}{\alpha})$   
 $- \log \Gamma(y+1) - \log \Gamma(\frac{1}{\alpha})$

$$\Rightarrow L^{Z^A} = y \log \left( \frac{\alpha e^x}{1 + \alpha e^x} \right) + \log \Gamma(y + \frac{1}{\alpha}) - \log \Gamma(y+1) - \log \Gamma(\frac{1}{\alpha})$$
 $+ \log \left\{ \frac{1}{(1 + \alpha e^x)^{\frac{1}{\alpha}}} \right\} + \log \left\{ \frac{1}{1 - \frac{1}{(1 + \alpha e^x)^{\frac{1}{\alpha}}}} \right\}$

looking at the last two terms basically is

$$\log \left\{ \frac{1}{(1 + \alpha e^x)^{\frac{1}{\alpha}}} - 1 \right\} = - \log \{ (1 + \alpha e^x)^{\frac{1}{\alpha}} - 1 \}$$
 $\Rightarrow L^{Z^A} = y \log \left\{ \frac{\alpha e^x}{1 + \alpha e^x} \right\} + \log \Gamma(y + \frac{1}{\alpha}) - \log \Gamma(y+1)$ 
 $- \log \Gamma(\frac{1}{\alpha}) - \log \{ (1 + \alpha e^x)^{\frac{1}{\alpha}} - 1 \}$ 
 $= y \log \alpha + yx - y \log (1 + \alpha e^x) - \log \{ (1 + \alpha e^x)^{\frac{1}{\alpha}} - 1 \}$ 
 $+ \log \Gamma(y + \frac{1}{\alpha}) - \log \Gamma(y+1) - \log \Gamma(\frac{1}{\alpha})$

Here as well, some care is required to evaluate  $L^{Z^A}$  without unnecessary overflow, since it is easy for  $1 - e^{-\frac{1}{\alpha}}$  and  $(1 + \alpha e^x)^{\frac{1}{\alpha}} - 1$  to evaluate to zero in finite precision arithmetic. Hence the limiting results  $\log(1 - e^{-\frac{1}{\alpha}}) \rightarrow \log(e^n - e^{\frac{1}{\alpha}n} + \frac{e^{\frac{1}{\alpha}n}}{6}) \rightarrow y$  as  $n \rightarrow \infty$ .  
Similar as  $x \rightarrow -\infty$ ,  $\log \{ (1 + \alpha e^x)^{\frac{1}{\alpha}} - 1 \} \rightarrow x$  and as  $x \rightarrow \infty$   
 $\log \{ (1 + \alpha e^x)^{\frac{1}{\alpha}} - 1 \} \rightarrow \log(e^x - 1) \xrightarrow[\text{provided } x > -\infty]{} e^x$

Proof:

$$\textcircled{1} \quad \log(1 - e^{-\frac{1}{\alpha}}) \rightarrow \log(e^n - e^{\frac{1}{\alpha}n} + \frac{e^{\frac{1}{\alpha}n}}{6}) \rightarrow y \quad n \rightarrow \infty$$

as  $n \rightarrow \infty$ ,  $e^{-\frac{1}{\alpha}n} \rightarrow 0$ ,  
we know that  $e^n \rightarrow 1 + n + \frac{n^2}{2} + \frac{n^3}{6}$  as  $n \rightarrow \infty$

 $\Rightarrow e^{-\frac{1}{\alpha}n} \rightarrow 1 - e^{-\frac{1}{\alpha}n} + e^{\frac{1}{\alpha}n} - \frac{e^{\frac{1}{\alpha}n}}{6}$

Implemented  
taking  $\alpha$  as  
fixed.

$$= 0 \text{ as } \eta \rightarrow -\infty, \log(1 - e^{-e^\eta})$$

$$\rightarrow \log\left(1 - 1 + e^\eta - \frac{e^{2\eta}}{2} + \frac{e^{3\eta}}{6}\right)$$

$$\text{as } \eta \rightarrow -\infty, e^{2\eta} \text{ and } e^{3\eta} \rightarrow 0 \text{ faster than } e^\eta$$

$$= \log(e^\eta - \frac{e^{2\eta}}{2} + \frac{e^{3\eta}}{6})$$

$$= 0 \quad \log(e^\eta - \frac{e^{2\eta}}{2} + \frac{e^{3\eta}}{6})$$

$$\rightarrow \log e^\eta \rightarrow \eta$$

②  $\log\{(1 + \alpha e^r)^{\frac{1}{\alpha}} - 1\} \rightarrow r \text{ as } \alpha \rightarrow -\infty$

as  $r \rightarrow -\infty$ ,  $e^r \rightarrow 0 \Rightarrow \alpha e^r \rightarrow 0$  (fixed  $\alpha$ )  
 We know that  $(1+x)^{\frac{1}{x}} \rightarrow 1 + \frac{1}{x}x$  as  $x \rightarrow 0$

$$\Rightarrow (1 + \alpha e^r)^{\frac{1}{\alpha}} \rightarrow 1 + \frac{1}{\alpha}(\alpha e^r) = 1 + e^r$$

$$= \log\{(1 + \alpha e^r)^{\frac{1}{\alpha}} - 1\} - \log\{(1 + e^r) - 1\}$$

$$= \log(e^r) = r$$

as  $r \rightarrow -\infty$

③  $\log\{(1 + \alpha e^r)^{\frac{1}{\alpha}} - 1\} \rightarrow e^r \text{ as } \alpha \rightarrow 0$  for fixed  $r$

remember that  $(1 + \alpha e^r)^{\frac{1}{\alpha}} = \left(1 + \frac{e^r}{r}\right)^r$ ,  
 so as  $\alpha \rightarrow 0$ ,  $r \rightarrow \infty$

$$\text{and } \lim_{r \rightarrow \infty} \left(1 + \frac{e^r}{r}\right)^r = e^{e^r} \text{ for } r \in \mathbb{R}$$

$$\Rightarrow (1 + \alpha e^r)^{\frac{1}{\alpha}} \rightarrow e^{e^r} \text{ as } \alpha \rightarrow 0$$

$$= \log\{(1 + \alpha e^r)^{\frac{1}{\alpha}} - 1\} \rightarrow \log\{e^{e^r} - 1\} \text{ as } \alpha \rightarrow 0$$

also, for very large  $r$ ,  $e^{e^r} - 1$  is dominated by  $e^{e^r}$

$$\Rightarrow \log\{e^{e^r} - 1\} \rightarrow \log e^{e^r} = e^r \quad \square$$

On the expectation of  $y$  in the ZINB.

Recall the model's density

$$g(y; \mu, r) = \begin{cases} 1 - q & y=0 \\ q f(y>0; \mu, r) & y>0 \end{cases}$$

$$\text{where } f(y|y>0; \mu, r) = \frac{f(y; \mu, r)}{1 - f(0; \mu, r)}$$

Therefore, the model adopts the form of hurdle models discussed in Tufy, section 7.8.

$$\text{Let } v := \frac{P(y>0)}{1 - f(0; \mu, r)} \stackrel{\text{ZINB}}{=} q^r, \text{ since in ZINB } P(y>0) = q^r, \mu = e^r \text{ and } f(0; \mu, r) = \frac{1}{(1 + e^r)^r}$$

Therefore, the mean is given by

$$\begin{aligned} E[y] &= \sum_{s=1}^{\infty} s f(s; \mu, r) v = \sum_{i=1}^{\infty} s f(s; \mu, r) \cdot \frac{P(y>0)}{1 - f(0; \mu, r)} \\ &= P(y>0) \sum_{s=1}^{\infty} s f(s; \mu, r) \end{aligned}$$

$$= P(y>0) E[y|y>0, \mu, r]$$

( $y_2$  the underlying  
NB r.v.)

$$\text{or } = \frac{P(y>0)}{1 - f(0; \mu, r)} E[y_2] \leftarrow \text{doesn't depend on } \mu.$$

For the ZINB model, which as  $f(s; \mu, r)$  is the PMF of a NB distribution with mean  $\mu$ ;

$$= P E[y] = v\mu = q^r \mu = q^r e^r \quad (\mu = e^r).$$

$$\text{where } r = \frac{1}{1 - ((1 + e^r)^{-1})^{\frac{1}{\lambda}}} = \frac{1}{1 - ((1 + e^r)^{-1})^{\frac{1}{\lambda}}}$$

$$\text{also } \lim_{r \rightarrow \infty} e^{tr} = \lim_{r \rightarrow \infty} e^r / r$$

$$\begin{aligned}
 (\text{Using Hopital}) &= \lim_{r \rightarrow \infty} \frac{e^r}{\frac{1}{\alpha} \alpha e^r (1 + \alpha e^r)^{-1/\alpha - 1}} \quad (\text{for fixed } \alpha) \\
 &= \lim_{r \rightarrow \infty} \frac{1}{(1 + \alpha e^r)^{-1/\alpha - 1}} = 1
 \end{aligned}$$

$$\Rightarrow E[Y] \rightarrow q \text{ as } r \rightarrow \infty$$

as  $r \rightarrow \infty$ ,  $t \rightarrow 1$  for fixed  $\alpha$

$$\Rightarrow E[Y] \rightarrow q e^{\mu} = q \mu.$$

On the variance of  $y$  in the ZINB.

$$\begin{aligned}
 \text{Var}(y) &= \sum_{s=1}^{\infty} s^2 f(s; \mu, r) v - \left( \sum_{r=1}^{\infty} s f(s; \mu, r) v \right)^2 \\
 &= P(y>0) \sum_{s=1}^{\infty} \frac{s^2 f(s; \mu, r)}{1-f(0; \mu, r)} - \left( P(y>0) E[y|y>0, \mu, r] \right)^2 \\
 &= P(y>0) \left[ \text{var}(y|y>0, \mu, r) + E[y|y>0, \mu, r]^2 \right] \\
 &\quad - P(y>0)^2 E[y|y>0, \mu, r]^2 \\
 &= P(y>0) \text{var}(y|y>0, \mu, r) + P(y>0) (1 - P(y>0)) E[y|y>0, \mu, r]^2
 \end{aligned}$$

which in the ZINB case gives, for  $f(y; \mu, r)$  the underlying NB,  
 $y_r$ , with  $\text{var}(y_r; \mu, r) = \mu + \frac{\mu^2}{r} = \mu + \mu^2$ , we have,  
 $E[y_r^2; \mu, r] = \mu + \mu^2 + \frac{r\mu^2}{r} = \mu + 2\mu^2$

$$\begin{aligned}
 \text{Since } r = \frac{1}{\alpha} \Rightarrow E[y_r^2; \mu, r] &= \mu + \mu^2 + \alpha\mu^2 \text{ and } \text{var}(y_r; \mu, r) = \mu + \alpha\mu^2 \\
 &= E[y_r^2; \mu, r] \\
 \Rightarrow \text{Var}(y) &= \underbrace{\frac{P(y>0)}{1-f(0; \mu, r)}}_{=v} \left\{ \overbrace{\text{var}(y_r; \mu, r)} + E[y_r; \mu, r]^2 \right\} \\
 &\quad - \left( \frac{P(y>0)}{1-f(0; \mu, r)} \right)^2 \mu^2 \\
 &= v(\mu + \mu^2 + \alpha\mu^2) - v^2\mu^2 \\
 &= v\mu(1 + \mu + \alpha\mu - v\mu)
 \end{aligned}$$

$$\Rightarrow \frac{\text{Var}(y)}{E[y]} = \frac{1 + \mu + \alpha\mu - v\mu}{\mu} = 1 + \mu(1 + \alpha - v), \text{ assume non-trivial } \mu$$

Overdispersion if  $1 + \alpha - v > 0 \Rightarrow -v > -1 - \alpha$

$\Rightarrow v < 1 + \alpha$ ; but we know  
 that  $v > 0$  from its definition (provided  $P(y>0) \neq 0$ )

$\Rightarrow$  overdispersion if  $0 < v < 1 + \alpha$

For underdispersion, we have that

$$1 + \mu(1 + \alpha - v) < 1 \quad \text{and} \quad \frac{1}{\mu} \operatorname{var}(y) > 0, \text{ if } \mu(1 + \alpha - v) > 0$$

$$\Rightarrow 1 + \alpha - v < 0 \quad \text{and} \quad 1 + \alpha - v > -\frac{1}{\mu}$$

$$\Rightarrow -v < -1 - \alpha \quad \text{and} \quad -v > -\frac{1}{\mu} - 1 - \alpha$$

$$\Rightarrow v > 1 + \alpha \quad \text{and} \quad v < \frac{1}{\mu} + 1 + \alpha$$

$\Rightarrow$  underdispersion, provided,

$$1 + \alpha < v < \frac{1}{\mu} + 1 + \alpha$$

Thus the model is indeed flexible and allows for both under- and over-dispersion.

Finally if  $q = \frac{1}{\mu} = \frac{(1 + \alpha \mu)^{\frac{1}{\alpha}} - 1}{(1 + \alpha \mu)^{\frac{1}{\alpha}}}$  then we recover the NB model.

Proof:

$$g(y; \mu, r) = \begin{cases} 1 - q & y = 0 \\ \frac{q}{(1 - f(0; \mu, r))} \cdot f(y; \mu, r) & y > 0 \end{cases}$$

$$\text{but } 1 - f(0; \mu, r) = \frac{(1 + \alpha \mu)^{\frac{1}{\alpha}} - 1}{(1 + \alpha \mu)^{\frac{1}{\alpha}}} = q \text{ and } 1 - q = \frac{1}{(1 + \alpha \mu)^{\frac{1}{\alpha}}} = f(0; \mu, r)$$

$$\Rightarrow g(y; \mu, r) = \begin{cases} f(0; \mu, r) & y = 0 \\ f(y; \mu, r) & y > 0 \end{cases} = f(y; \mu, r) \quad \text{The NB density}$$

□.

## Implementation (Following Hood et al. (2017))

According to the framework proposed in Hood et al. (2017), we need the deviance and its derivatives to implement an extend GAM model (see section 3.3.1 of that paper);

Differentiating w.r.t.  $y_i$ ,  $\frac{\partial D_i}{\partial y_i}$ ,  $\frac{\partial^2 D_i}{\partial y_i^2}$ ,  $\frac{\partial^3 D_i}{\partial y_i^3}$ ,  $\frac{\partial^4 D_i}{\partial y_i^4}$  (For  $\hat{p}$ )

instead of  $m_i$ ,  $\frac{\partial^4 h_i}{\partial y_i^4}$ ,  $\frac{\partial^5 D_i}{\partial y_i \partial \theta_j}$ ,  $\frac{\partial^5 D_i}{\partial y_i \partial \theta_j \partial \theta_k}$ ,  $\frac{\partial^4 D_i}{\partial m_i^4}$ ,  $\frac{\partial^4 D_i}{\partial y_i^3 \partial \theta_j}$ ,  $\frac{\partial^4 D_i}{\partial y_i^2 \partial \theta_j \partial \theta_k}$   
as this is done in SAI. (For  $\hat{p}$  via full Newton).

As for the zip model, we first define the deviance as -2l for model estimation.

w.r.t.  $y$  for  $y > 0$

$$\textcircled{1} \quad \frac{dL}{dy} = \frac{y}{e^y - 1}, \quad \textcircled{2} \quad \frac{d^2 L}{dy^2} = (1-e^y) \frac{dy}{dy} - \left( \frac{dy}{dy} \right)^2$$

exactly as for zip.

$$\textcircled{3} \quad \frac{d^3 L}{dy^3} = -e^y \frac{dy}{dy} + (1-e^y)^2 \frac{dy}{dy} - 3(1-e^y) \left( \frac{dy}{dy} \right)^2 + 2 \left( \frac{dy}{dy} \right)^3 \quad \text{and}$$

$$\textcircled{4} \quad \frac{d^4 L}{dy^4} = (3e^y - 4)e^y \frac{dy}{dy} + 4e^y \left( \frac{dy}{dy} \right)^2 + (1-e^y)^3 \frac{dy}{dy} - 7(1-e^y) \left( \frac{dy}{dy} \right)^2 + 12(1-e^y) \left( \frac{dy}{dy} \right)^3 - 6 \left( \frac{dy}{dy} \right)^4$$

See SAI of Hood et al. (2016) for dealing with these derivatives as  $y \rightarrow \pm\infty$

w.r.t.  $\gamma$  for  $y > 0$

$$\textcircled{5} \quad \frac{dy}{d\gamma} = \frac{dL}{d\gamma} = \frac{d}{d\gamma} \left( y - y \log(1+\alpha e^\gamma) - \log \left\{ (1+\alpha e^\gamma)^{\frac{1}{\alpha}} - 1 \right\} \right)$$

$$= y - \frac{y}{1+\alpha e^\gamma} - \frac{1-\alpha e^\gamma}{(1+\alpha e^\gamma)^{\frac{1}{\alpha}-1}}$$

$$= y - y \frac{e^\gamma}{1+\alpha e^\gamma} - \frac{e^\gamma (1+\alpha e^\gamma)^{\frac{1}{\alpha}-1}}{(1+\alpha e^\gamma)^{\frac{1}{\alpha}-1}}$$

$$= y - \frac{y \alpha e^x}{1 + \alpha e^x} - \left( \frac{e^x}{1 + \alpha e^x} \right) \left( \frac{(1 + \alpha e^x)^{\frac{1}{\alpha}}}{(1 + \alpha e^x)^{\frac{1}{\alpha}} - 1} \right)$$

Define  $\beta := \frac{e^x}{1 + \alpha e^x}$ ,  $\tau := \frac{(1 + \alpha e^x)^{\frac{1}{\alpha}}}{(1 + \alpha e^x)^{\frac{1}{\alpha}} - 1}$

$$\Rightarrow \frac{dy}{dx} = y - y \alpha \beta - \beta \tau$$

$$\textcircled{2} \quad \frac{d^2 y}{dx^2} = \beta \{ y \alpha^2 \beta - y \alpha + \alpha \beta \tau - \tau + \beta \tau^2 - \beta \tau^2 \}$$

Proof:  $\frac{d}{dx} \{ y - y \alpha \beta - \beta \tau \} = -y \alpha \frac{d\beta}{dx} - \frac{d\beta}{dx} \tau - \beta \frac{d\tau}{dx}$

But  $\frac{d\beta}{dx} = \frac{(1 + \alpha e^x) e^x - e^x \cdot \alpha e^x}{(1 + \alpha e^x)^2}$

$$= \frac{e^x}{1 + \alpha e^x} - \frac{\alpha e^{2x}}{(1 + \alpha e^x)^2} = \beta - \alpha \beta^2$$

and  $\frac{d\tau}{dx} = \frac{\left[ (1 + \alpha e^x)^{\frac{1}{\alpha}} - 1 \right] \left[ \alpha e^x \cdot \frac{1}{\alpha} \cdot (1 + \alpha e^x)^{\frac{1}{\alpha}-1} \right]}{\left[ (1 + \alpha e^x)^{\frac{1}{\alpha}} \right] \left[ \alpha e^x \cdot \frac{1}{\alpha} \cdot (1 + \alpha e^x)^{\frac{1}{\alpha}-1} \right]}$

$$= \frac{\left[ (1 + \alpha e^x)^{\frac{1}{\alpha}} - 1 \right]^2}{\left( (1 + \alpha e^x)^{\frac{1}{\alpha}} - 1 \right)^2}$$

$$= \frac{e^x (1 + \alpha e^x)^{\frac{1}{\alpha}}}{(1 + \alpha e^x) \left[ (1 + \alpha e^x)^{\frac{1}{\alpha}} - 1 \right]} - \frac{e^x (1 + \alpha e^x)^{\frac{1}{\alpha}}}{(1 + \alpha e^x) \left[ (1 + \alpha e^x)^{\frac{1}{\alpha}} - 1 \right]^2}$$

$$= \beta \tau - \beta \tau^2$$

$$\Rightarrow \frac{d^2 y}{dx^2} = -y \alpha (\beta - \alpha \beta^2) - \beta \tau + \alpha \beta^2 \tau - \beta \tau + \beta^2 \tau^2 - \beta \tau^2$$

$$= y \alpha^2 \beta^2 - y \alpha \beta + \alpha \beta^2 \tau - \beta \tau + \beta^2 \tau^2 - \beta \tau^2$$

$$= \beta \{ y \alpha^2 \beta - y \alpha + \alpha \beta \tau - \tau + \beta \tau^2 - \beta \tau^2 \}$$

□

We also need

$$\mathbb{E}\left[\frac{d^2Y}{d\delta^2}\right] = \mathbb{E}_Y \mathbb{E}\left[\frac{d^2Y}{d\delta^2} | Y\right]$$

$$= \mathbb{E}_Y \left\{ \mathbb{E}\left[\underbrace{\frac{d^2Y}{d\delta^2}}_{=0 \text{ for } y=0} | Y=0\right] \mathbb{P}(Y=0) + \mathbb{E}\left[\frac{d^2Y}{d\delta^2} | Y>0\right] \mathbb{P}(Y>0) \right\}$$

$$= \mathbb{E}_Y \left\{ \mathbb{E}\left[\frac{d^2Y}{d\delta^2} | Y>0\right] \underbrace{\mathbb{P}(Y>0)}_q \right\}$$

$$= \mathbb{E}_Y \left\{ q \left( y\alpha^2\beta^2 - y\alpha\beta + \alpha\beta^2\tau - \tau\beta + \beta^2\tau^2 - \beta^2\tau \right) \right\}$$

$$= q (\mathbb{E}[y]\alpha^2\beta^2 - \mathbb{E}[y]\alpha\beta + \alpha\beta^2\tau - \tau\beta + \beta^2\tau^2 - \beta^2\tau)$$

where  $\mathbb{E}[y] = q\tau e^\delta$ , as derived on page 6 .

$$\textcircled{3} \quad \frac{d^3L}{dt^3} = p \left\{ -8yx^3\beta^2 + 3yx^2\beta - 2x^2\beta^2z - yx + 3\alpha\beta z - 3\alpha\beta^2z^2 + 3\alpha\beta^2\tau - \tau + 3\beta\tau^2 - 3\beta\tau - 2\beta^2z^3 + 3\beta^2\tau^2 - \beta^2z^2 \right\}$$

Proof. Using a numerical linear algebra package, set  $\infty$ .  $\square$

$$\textcircled{4} \quad \frac{d^4L}{dt^4} = p \left\{ 6yx^4\beta^3 - 12yx^3\beta^2 + 6x^3\beta^3z + 7yx^2\beta - 12x^2\beta^2z + 11x^2\beta^3z^2 - 11x^2\beta^3\tau - yx + 7\alpha\beta\tau - 18\alpha\beta^2z^2 + 18\alpha\beta^2\tau + 12\alpha\beta^3z^3 - 18\alpha\beta^3\tau^2 + 6\alpha\beta^3z^4 - \tau + 7\beta\tau^2 - 7\beta\tau - 12\beta^2z^3 + 18\beta^2\tau^2 - 6\beta^2z + 6\beta^3\tau + 12\beta^3z^3 + 7\beta^3\tau^2 - \beta^3\tau \right\}$$

Proof.  $\infty$   $\square$

As with  $L^{22}$ , some care is required to ensure that the derivatives evaluate accurately without overflow even as wide a range of  $\tau$  and  $\kappa$  as possible. As  $\tau \rightarrow \infty$ ,  $\beta = \frac{1}{e^{-\tau} + \kappa} \rightarrow \frac{1}{\kappa}$  for fixed  $\kappa$ , while

$$\tau = \frac{1}{1 - (1 + \kappa e^\tau)^{-1/\kappa}} \rightarrow 1, \quad \text{since } 1 + \kappa e^\tau \rightarrow \infty \Rightarrow (1 + \kappa e^\tau)^{-1/\kappa} \rightarrow 0$$

whereas as  $\tau \rightarrow -\infty$ ,  $\beta \rightarrow \frac{1}{e^{-\tau}} \rightarrow 0$  for fixed  $\kappa$ , while  $e^\tau \rightarrow 0$   
 $\Rightarrow (1 + \kappa e^\tau)^{-1/\kappa} \rightarrow 1 + \frac{1}{\kappa e^\tau} = 1 + e^\tau \rightarrow 0$   $\tau = \frac{(1 + \kappa e^\tau)^{1/\kappa}}{(1 + \kappa e^\tau)^{1/\kappa} - 1}$   
first order Taylor expansion about  $\tau = \kappa e^\tau = 0$

$$\rightarrow \frac{1 + e^\tau}{1 + e^\tau - 1} = \frac{1 + e^\tau}{e^\tau}$$

$$= e^{-\tau} + 1 \rightarrow e^{-\tau}$$

\* How do we deal with products:  $\beta\tau, \beta\tau^2, \beta^2\tau$  etc. what does it converge to?

Since as  $\tau \rightarrow -\infty$ ,  $\beta \rightarrow \frac{1}{e^{-\tau}}$  and  $\tau \rightarrow e^{-\tau}$   
 $\Rightarrow \beta\tau \rightarrow 1 \Rightarrow (\beta\tau)^{\alpha} \rightarrow 1 + \alpha e^{-\tau}$   
 (alternatively),

$$\lim_{\tau \rightarrow -\infty} \tau \beta = \lim_{\tau \rightarrow -\infty} \frac{\beta}{1 - (1 + \kappa e^\tau)^{-1/\kappa}}$$

$$\begin{aligned}
 (1^{\text{st}} \text{ Hopital}) &= \lim_{r \rightarrow -\infty} \frac{\beta - \alpha \beta^2}{\gamma_k \alpha r^k (1 + \alpha r^\alpha)^{-\gamma_k - 1}} \\
 &= \lim_{r \rightarrow -\infty} \frac{\beta (1 - \alpha \beta)}{r^k (1 + \alpha r^\alpha)^{-\gamma_k - 1}} \\
 &\Rightarrow \lim_{r \rightarrow -\infty} \frac{e^r (1 - \alpha \beta)}{r^k (1 + \alpha r^\alpha)^{-\gamma_k - 1}} \\
 &= \lim_{r \rightarrow -\infty} \frac{(1 - \alpha \beta)}{(1 + \alpha r^\alpha)^{-\gamma_k - 1}} = 1
 \end{aligned}$$

also ;  $\beta^a/b \rightarrow 0$  if  $a > b$  as  $r \rightarrow -\infty$   
as  $r \rightarrow \infty$ ,  $\beta \rightarrow \alpha^{-1}$  and  $\alpha \rightarrow 1 \Rightarrow \beta \rightarrow \alpha^{-1}$

with these we get

$$\begin{aligned}
 \frac{\partial L}{\partial r} &\rightarrow y - 1 \text{ as } r \rightarrow -\infty, \quad \frac{\partial L}{\partial r} \rightarrow y - y - \frac{1}{\alpha} = -\frac{1}{\alpha} \text{ as } r \rightarrow \infty \\
 \frac{\partial^2 L}{\partial r^2} &\rightarrow 0 \text{ as } r \rightarrow -\infty, \quad \frac{\partial^2 L}{\partial r^2} \rightarrow y - y + \frac{3}{\alpha^2} - \frac{1}{\alpha} + \frac{1}{\alpha^2} - \frac{1}{\alpha^2} \\
 &= \frac{1}{\alpha} - \frac{1}{\alpha} + \frac{1}{\alpha^2} - \frac{1}{\alpha^2} = 0 \text{ as } r \rightarrow \infty \\
 \frac{\partial^3 L}{\partial r^3} &\rightarrow 0 \text{ as } r \rightarrow -\infty, \quad \frac{\partial^3 L}{\partial r^3} \rightarrow -2y + 3y - 2\frac{1}{\alpha} - y + \frac{3}{\alpha} \\
 &\quad - \frac{3}{\alpha^2} + \frac{3}{\alpha^2} - \frac{1}{\alpha} + \frac{3}{\alpha^2} \\
 &\quad - \frac{3}{\alpha^2} - \frac{2}{\alpha^3} \\
 &\quad + \frac{3}{\alpha^3} - \frac{1}{\alpha^3} \\
 &= \frac{1}{\alpha} - \frac{1}{\alpha} + \frac{3}{\alpha^2} - \frac{3}{\alpha^2} \\
 &\quad + 0 = 0 \text{ as } r \rightarrow \infty \\
 \frac{\partial^4 L}{\partial r^4} &\rightarrow 0 \text{ as } r \rightarrow -\infty, \quad \frac{\partial^4 L}{\partial r^4} \rightarrow 0 \text{ as } r \rightarrow \infty
 \end{aligned}$$

For extended GAsns in which  $\gamma$  is a fn of  $\sigma$  and extra parameters  
 e.g.,

$$\gamma = \theta_1 + (\nu + e^{\theta_2}) \sigma \quad (\text{as for the zip model in blood at al (2016)})$$

$$\frac{d\gamma}{d\theta_1} = 1, \quad \frac{d\gamma}{d\theta_2} = e^{\theta_2} \sigma, \quad \frac{d\gamma}{d\sigma} = \nu + e^{\theta_2}, \quad \frac{d^2\gamma}{d\sigma^2} = 0$$

$$\frac{d^2\gamma}{d\theta_1^2} = \frac{d^2\gamma}{d\theta_1 d\theta_2} = \frac{d^2\gamma}{d\theta_2 d\theta_1} = 0, \quad \frac{d^2\gamma}{d\theta_2^2} = e^{\theta_2} \sigma, \quad \frac{d^2\gamma}{d\sigma d\theta_2} = e^{\theta_2}$$

$$\frac{d^3\gamma}{d\sigma d\theta_1^2} = 0, \quad \frac{d^3\gamma}{d\sigma d\theta_2 d\theta_1} = 0, \quad \frac{d^3\gamma}{d\sigma d\theta_2^2} = \nu,$$

$$\frac{d^3\gamma}{d\sigma^2 d\theta_1} = \frac{d^3\gamma}{d\sigma^2 d\theta_2} = \frac{d^3\gamma}{d\sigma^3} = 0$$

$$\frac{d^4\gamma}{d\sigma^4} = \frac{d^4\gamma}{d\sigma^3 d\theta_1}, \quad \frac{d^4\gamma}{d\sigma^3 d\theta_2} = \frac{d^4\gamma}{d\sigma^2 d\theta_1^2} = \frac{d^4\gamma}{d\sigma^2 d\theta_2^2}$$

$$= \frac{d^4\gamma}{d\sigma^2 d\theta_1 d\theta_2} = 0$$

## Total derivatives.

I We focus on  $\theta_i$ , for  $i \in \{1, 2\}$ . Derivatives involving  $\theta_0$  are considered in section 2.

$$\begin{aligned} \frac{dy}{dr} &= \frac{\partial y}{\partial r} + \frac{\partial y}{\partial \eta} \cdot \frac{\partial \eta}{\partial r}, \quad \frac{d^2L}{dr^2} = \frac{\partial^2 L}{\partial r^2} + \frac{\partial^2 L}{\partial \eta \partial r} \cdot \frac{\partial \eta}{\partial r} \\ &\quad + \frac{\partial^2 L}{\partial \eta^2} \cdot \frac{\partial \eta}{\partial r} \overset{\text{cancel}}{=} 0 \\ &\quad + \frac{\partial^2 L}{\partial \eta^2} \cdot \left( \frac{\partial \eta}{\partial r} \right)^2 \\ &\quad + \frac{\partial^2 L}{\partial \eta^2} - \frac{\partial^2 \eta}{\partial r^2} \\ &= \frac{\partial^2 L}{\partial r^2} + \frac{\partial^2 L}{\partial \eta^2} \left( \frac{\partial \eta}{\partial r} \right)^2 \\ &\quad + \frac{\partial^2 L}{\partial \eta^2} \frac{\partial^2 \eta}{\partial r^2} \end{aligned}$$

$$\begin{aligned} \frac{dy}{d\theta_i} &= \frac{\partial y}{\partial \eta} \cdot \frac{\partial \eta}{d\theta_i}, \quad \frac{d^2L}{dr d\theta_i} = \frac{\partial^2 L}{\partial r \partial \eta} \cdot \frac{\partial \eta}{\partial \theta_i} + \frac{\partial^2 L}{\partial \eta^2} \cdot \frac{\partial \eta}{\partial \theta_i} + \frac{\partial^2 L}{\partial \eta^2} \frac{\partial \eta}{\partial r} \\ &\quad \underset{\approx 0}{\sim} \\ &= \frac{\partial^2 L}{\partial \eta^2} \cdot \frac{\partial \eta}{\partial \theta_i} \cdot \frac{\partial \eta}{\partial r} + \frac{\partial^2 L}{\partial \eta^2} \cdot \frac{\partial \eta}{\partial r} \end{aligned}$$

$$\begin{aligned} \frac{\partial^3 L}{\partial r^2 d\theta_i} &= \frac{\partial^3 L}{\partial \eta^3} \cdot \frac{\partial \eta}{\partial \theta_i} \cdot \left( \frac{\partial \eta}{\partial r} \right)^2 + \frac{\partial^2 L}{\partial \eta^2} \frac{\partial^2 \eta}{\partial r^2} \cdot \frac{\partial \eta}{\partial \theta_i} + \frac{\partial^2 L}{\partial \eta^2} \cdot \frac{\partial \eta}{\partial \theta_i} \cdot \frac{\partial^2 \eta}{\partial r^2} \\ &\quad + \frac{\partial^2 L}{\partial \eta^2} \cdot \frac{\partial^3 \eta}{\partial r^2 \partial \theta_i} \\ &= \frac{\partial^3 L}{\partial \eta^3} \frac{\partial \eta}{\partial \theta_i} \left( \frac{\partial \eta}{\partial r} \right)^2 + \frac{\partial^2 L}{\partial \eta^2} \left( \frac{\partial \eta}{\partial r} \cdot \frac{\partial \eta}{\partial \theta_i} + \frac{\partial \eta}{\partial \theta_i} \cdot \frac{\partial^2 \eta}{\partial r^2} \right) \\ &\quad + \frac{\partial^2 L}{\partial \eta^2} \cdot \frac{\partial^3 \eta}{\partial r^2 \partial \theta_i} \end{aligned}$$

$$\begin{aligned}
 \frac{\partial^3 L}{\partial r^3} &= \frac{\partial^3 L}{\partial \eta^3} + \frac{\partial^3 L}{\partial \eta^2} \cdot \frac{\partial \eta}{\partial r} \cdot \left( \frac{\partial \eta}{\partial r} \right)^2 + \frac{\partial^2 L}{\partial \eta^2} \left[ \frac{\partial^2 \eta}{\partial r^2} \cdot \frac{\partial^2 \eta}{\partial \eta^2} \right] \\
 &\quad + \frac{\partial^2 L}{\partial \eta^2} \cdot \frac{\partial^2 \eta}{\partial r^2} + \frac{\partial^2 L}{\partial \eta^2} \cdot \frac{\partial^3 \eta}{\partial r^3} \\
 &= \frac{\partial^3 L}{\partial \eta^3} + \frac{\partial^3 L}{\partial \eta^2} \left( \frac{\partial \eta}{\partial r} \right)^3 + 3 \frac{\partial^2 L}{\partial \eta^2} \frac{\partial^2 \eta}{\partial r^2} \frac{\partial \eta}{\partial r} + \frac{\partial^2 L}{\partial \eta^2} \cdot \frac{\partial^3 \eta}{\partial r^3}
 \end{aligned}$$

$$\frac{\partial^2 L}{\partial \eta_i \partial \eta_j} = \frac{\partial^2 L}{\partial \eta^2} \frac{\partial \eta}{\partial \eta_j} \frac{\partial \eta}{\partial \eta_i} + \frac{\partial^2 L}{\partial \eta^2} \cdot \frac{\partial^2 \eta}{\partial \eta_i \partial \eta_j}$$

$$\begin{aligned}
 \frac{\partial^3 L}{\partial r \partial \eta_i \partial \eta_j} &= \frac{\partial^3 L}{\partial \eta^3} \frac{\partial \eta}{\partial \eta_j} \frac{\partial \eta}{\partial \eta_i} \frac{\partial \eta}{\partial r} + \frac{\partial^2 L}{\partial \eta^2} \left[ \frac{\partial^2 \eta}{\partial \eta_i \partial \eta_j} \frac{\partial \eta}{\partial r} + \frac{\partial^2 \eta}{\partial \eta_i \partial r} \frac{\partial \eta}{\partial \eta_j} \right] \\
 &\quad + \frac{\partial^2 L}{\partial \eta^2} \frac{\partial \eta}{\partial \eta_j} \frac{\partial^2 \eta}{\partial \eta_i \partial r} + \frac{\partial^2 L}{\partial \eta^2} \frac{\partial^3 \eta}{\partial r \partial \eta_i \partial \eta_j} \\
 &= \frac{\partial^3 L}{\partial \eta^3} \frac{\partial \eta}{\partial \eta_i} \frac{\partial \eta}{\partial \eta_j} \frac{\partial \eta}{\partial r} + \frac{\partial^2 L}{\partial \eta^2} \left[ \frac{\partial^2 \eta}{\partial \eta_i \partial \eta_j} \frac{\partial \eta}{\partial r} + \frac{\partial^2 \eta}{\partial \eta_i \partial r} \frac{\partial \eta}{\partial \eta_j} \right] \\
 &\quad + \frac{\partial \eta}{\partial \eta_j} \frac{\partial^2 \eta}{\partial \eta_i \partial r} + \frac{\partial^2 L}{\partial \eta^2} \frac{\partial^3 \eta}{\partial r \partial \eta_i \partial \eta_j}
 \end{aligned}$$

$$\begin{aligned}
 \frac{\partial^4 L}{\partial r^2 \partial \eta_i \partial \eta_j} &= \frac{\partial^4 L}{\partial \eta^4} \frac{\partial \eta}{\partial \eta_j} \frac{\partial \eta}{\partial \eta_i} \left( \frac{\partial \eta}{\partial r} \right)^2 + \frac{\partial^3 L}{\partial \eta^3} \left[ \frac{\partial^2 \eta}{\partial \eta_i \partial \eta_j} \left( \frac{\partial \eta}{\partial r} \right)^2 + \frac{\partial^2 \eta}{\partial \eta_i \partial r} \frac{\partial \eta}{\partial \eta_j} \right] \\
 &\quad + \frac{\partial^3 L}{\partial \eta^3} \frac{\partial \eta}{\partial \eta_j} \left( 2 \frac{\partial^2 \eta}{\partial \eta_i \partial \eta_i} \frac{\partial \eta}{\partial r} + \frac{\partial^2 \eta}{\partial \eta_i \partial r} \cdot \frac{\partial \eta}{\partial \eta_i} \right) \\
 &\quad + \frac{\partial^2 L}{\partial \eta^2} \left( \frac{\partial^3 \eta}{\partial \eta_i \partial \eta_j \partial r} \frac{\partial \eta}{\partial r} + \frac{\partial^2 \eta}{\partial \eta_i \partial r} \frac{\partial^2 \eta}{\partial \eta_j \partial r} + \frac{\partial^3 \eta}{\partial \eta_i \partial \eta_j \partial r} \frac{\partial \eta}{\partial r} \right. \\
 &\quad \left. + \frac{\partial^2 \eta}{\partial \eta_i \partial r} \frac{\partial^2 \eta}{\partial \eta_j \partial r} \right) \\
 &\quad + \frac{\partial^2 L}{\partial \eta^2} \frac{\partial \eta}{\partial \eta_i} \frac{\partial^3 \eta}{\partial \eta^2 \partial \eta_i} + \frac{\partial^2 L}{\partial \eta^2} \frac{\partial^4 \eta}{\partial r^2 \partial \eta_i \partial \eta_j}
 \end{aligned}$$

$$= \frac{\partial^4 L}{\partial \eta^4} \frac{\partial^2 \eta}{\partial \theta_i} \frac{\partial^2 \eta}{\partial \theta_i} \left( \frac{\partial \eta}{\partial r} \right)^2$$

$$+ \frac{\partial^4 L}{\partial \eta^3} \left[ \frac{\partial^2 \eta}{\partial \theta_i \partial \theta_j} \left( \frac{\partial \eta}{\partial r} \right)^2 + 2 \frac{\partial^2 \eta}{\partial \theta_i} \frac{\partial^2 \eta}{\partial \theta_i} \frac{\partial^2 \eta}{\partial \theta_j} \right]$$

$$+ \frac{1}{2} \frac{\partial^2 \eta}{\partial \theta_j} \frac{\partial^2 \eta}{\partial \theta_i \partial \theta_i} \frac{\partial^2 \eta}{\partial r^2} + \frac{\partial^2 \eta}{\partial \theta_i} \frac{\partial^2 \eta}{\partial \theta_j} \frac{\partial^2 \eta}{\partial r^2}$$

$$+ \frac{\partial^4 L}{\partial \eta^2} \left[ \frac{2 \partial^3 \eta}{\partial \theta_i \partial \theta_i \partial \theta_j} \frac{\partial \eta}{\partial r} + \frac{2 \partial^2 \eta}{\partial \theta_i} \frac{\partial^2 \eta}{\partial \theta_i} + \frac{\partial^3 \eta}{\partial \theta_i \partial \theta_j} \frac{\partial \eta}{\partial r^2} \right]$$

$$+ \frac{\partial^2 \eta}{\partial r^2} \frac{\partial^2 \eta}{\partial \theta_i \partial \theta_j} + \frac{\partial^3 \eta}{\partial r^2 \partial \theta_i} \frac{\partial^2 \eta}{\partial \theta_j}$$

$$+ \frac{\partial L}{\partial \eta} \frac{\partial^4 \eta}{\partial r^2 \partial \theta_i \partial \theta_j}$$

$$\frac{\partial^4 L}{\partial \theta^3 \partial \theta_i} = \frac{\partial^4 L}{\partial \theta^3 \partial \eta} - \frac{\partial^2 \eta}{\partial \theta_i} + \frac{\partial^4 L}{\partial \eta^4} \frac{\partial \eta}{\partial \theta_i} \left( \frac{\partial \eta}{\partial r} \right)^3 + \frac{\partial^3 L}{\partial \eta^3} - 3 \left( \frac{\partial \eta}{\partial r} \right) \frac{\partial^2 \eta}{\partial \theta_i \partial \theta_i}$$

$\xrightarrow{=0}$

$$+ \frac{3 \partial^3 L}{\partial \eta^3} \frac{\partial^2 \eta}{\partial \theta_i} \frac{\partial^2 \eta}{\partial r} \frac{\partial^2 \eta}{\partial r^2} + 3 \frac{\partial^2 L}{\partial \eta^2} \left[ \frac{\partial \eta}{\partial r} \frac{\partial^2 \eta}{\partial \theta_i \partial \theta_i} \frac{\partial^2 \eta}{\partial r^2} \right.$$

$$\left. + \frac{\partial^2 \eta}{\partial r} \frac{\partial^2 \eta}{\partial \theta_i \partial \theta_i} \right] + \frac{\partial^2 L}{\partial \eta^2} \frac{\partial^3 \eta}{\partial \theta_i} \frac{\partial^3 \eta}{\partial r^3} + \frac{\partial^2 L}{\partial \eta^2} \frac{\partial^4 \eta}{\partial r^2 \partial \theta_i}$$

$$= \frac{\partial^4 L}{\partial \eta^4} \frac{\partial \eta}{\partial \theta_i} \left( \frac{\partial \eta}{\partial r} \right)^3 + 3 \frac{\partial^3 L}{\partial \eta^3} \left[ \left( \frac{\partial \eta}{\partial r} \right)^2 \frac{\partial^2 \eta}{\partial \theta_i \partial \theta_i} + \frac{\partial \eta}{\partial \theta_i} \frac{\partial \eta}{\partial r} \frac{\partial^3 \eta}{\partial r^2} \right]$$

$$+ \frac{\partial^2 L}{\partial \eta^2} \left[ \frac{\partial^2 \eta}{\partial \theta_i} \frac{\partial^2 \eta}{\partial \theta_i} \frac{\partial^2 \eta}{\partial r^2} + 3 \frac{\partial \eta}{\partial r} \frac{\partial^3 \eta}{\partial \theta_i \partial \theta_i} + \frac{\partial^3 \eta}{\partial r^3} \frac{\partial \eta}{\partial \theta_i} \right]$$

$$+ \frac{\partial L}{\partial \eta} \frac{\partial^4 \eta}{\partial r^2 \partial \theta_i \partial \theta_i}$$

$$\frac{\partial^4 L}{\partial \theta^4} = \frac{\partial^4 L}{\partial r^4} + \frac{\partial^4 L}{\partial \eta^4} \frac{\partial \eta}{\partial r} \left( \frac{\partial \eta}{\partial r} \right)^3 + \frac{\partial^2 L}{\partial \eta^3} \cdot 3 \left( \frac{\partial \eta}{\partial r} \right)^2 \frac{\partial^2 \eta}{\partial r^2}$$

$$+ 3 \frac{\partial^3 L}{\partial \eta^3} \cdot \frac{\partial \eta}{\partial r} \frac{\partial \eta}{\partial r} \frac{\partial^2 \eta}{\partial r^2} + 3 \frac{\partial^2 L}{\partial \eta^2} \left[ \frac{\partial \eta}{\partial r} \frac{\partial^2 \eta}{\partial r^2} \frac{\partial^2 \eta}{\partial r^2} + \right.$$

$$\left. \frac{\partial^2 \eta}{\partial r} \frac{\partial^2 \eta}{\partial r} \frac{\partial^3 \eta}{\partial r^3} \right] + \frac{\partial^2 L}{\partial \eta^2} \frac{\partial \eta}{\partial r} \frac{\partial^3 \eta}{\partial r^2} + \frac{\partial L}{\partial \eta} \frac{\partial^4 \eta}{\partial r^2 \partial r^4}$$

$$\begin{aligned}
 &= \frac{\partial^4 L}{\partial r^4} + \frac{\partial^4 L}{\partial y^4} \left( \frac{\partial y}{\partial r} \right)^4 + 6 \frac{\partial^3 L}{\partial y^3} \left( \frac{\partial y}{\partial r} \right)^2 \frac{\partial^2 L}{\partial r^2} \\
 &\quad + \frac{\partial^2 L}{\partial y^2} \left[ 3 \left( \frac{\partial^2 y}{\partial r^2} \right)^2 + 4 \frac{\partial y}{\partial r} \frac{\partial^3 y}{\partial r^3} \right] + \frac{\partial L}{\partial y} \frac{\partial^4 y}{\partial r^4}
 \end{aligned}$$

## II Derivatives involving $\theta_0$

Since  $x = \gamma_r$  and  $r \in R_{>0} \Rightarrow x \in R_{>0}$ . It is however easier to work with unrestricted parameter. Therefore, we define  $\alpha := e^{\theta_0}$  with  $\theta_0 \in \mathbb{R}$  unrestricted.

Recall that for  $y > 0$ ,

$$\begin{aligned}
 L^{2x} &= \log(1 - e^{-2x}) + y \log \alpha + yx - y \log(1 + \alpha e^x) - \log\{(1 + \alpha e^x)^k - 1\} \\
 &\quad + \log \Gamma(y + \frac{1}{\alpha}) - \log \Gamma(y+1) - \log \Gamma(\frac{y}{\alpha})
 \end{aligned}$$

$$\begin{aligned}
 (\alpha = e^{\theta_0}) &= \log(1 - e^{-2x}) + y \log e^{\theta_0} + yx - y \log(1 + e^{\theta_0} e^x) - \log\{(1 + e^{\theta_0} e^x)^k - 1\} \\
 &\quad + \log \Gamma(y + e^{\theta_0}) - \log \Gamma(y+1) - \log \Gamma(\frac{y}{e^{\theta_0}})
 \end{aligned}$$

Note that if  $x = (1 + e^{\theta_0} e^x)^{\frac{1}{e^{-\theta_0}}}$ , then  
 $\log x = e^{-\theta_0} \log(1 + e^{\theta_0} e^x)$

$$\begin{aligned}
 \frac{dy}{d\theta_0} &= \frac{e^{-\theta_0}}{1 + e^{\theta_0} e^x} \cdot \frac{e^{\theta_0} e^x}{e^{-\theta_0}} + \log(1 + e^{\theta_0} e^x) \cdot e^{-\theta_0} \cdot -1
 \end{aligned}$$

$$= \frac{e^x}{1 + e^{\theta_0} e^x} - e^{-\theta_0} \log(1 + e^{\theta_0} e^x)$$

$$\Rightarrow \frac{dy}{d\theta_0} = \left( 1 + e^{\theta_0} e^x \right)^{\frac{1}{e^{-\theta_0}}} \left\{ \beta - e^{\theta_0} \log(1 + e^{\theta_0} e^x) \right\}$$

also,  $\frac{d}{dz} \log \Gamma(z) =: \psi(z)$ , where  $\psi$  is the digamma fn.

Now dropping the  $2x$  superscript, we have,

$$\frac{dy}{d\theta_0} = \frac{0 + y/e^{\theta_0} - e^{\theta_0} + 0 - y}{1 + e^{\theta_0} e^x} \cdot \frac{e^{\theta_0} e^x}{e^{-\theta_0}} - \frac{1}{(1 + e^{\theta_0} e^x)^{e^{-\theta_0}} - 1}$$

$$\begin{aligned}
 & \left. \left( \frac{\partial}{\partial \theta_0} \right) e^{-\theta_0} \right\} \beta - e^{-\theta_0} \log(1 + e^{\theta_0} e^r) \\
 & - \varphi(y + e^{-\theta_0}) e^{-\theta_0} + \varphi(e^{-\theta_0}) e^{-\theta_0} \\
 & = y - y \beta e^{\theta_0} - \tau \left\{ \beta - e^{-\theta_0} \log(1 + e^{\theta_0} e^r) \right\} \\
 & - e^{-\theta_0} \varphi(y + e^{-\theta_0}) + e^{-\theta_0} \varphi(e^{-\theta_0})
 \end{aligned}$$

To compute  $\frac{d^2 l}{d\theta_0^2}$ , we need  $\frac{d\beta}{d\theta_0}$ , and  $\frac{dy}{d\theta_0}$ ,

$$\frac{d\beta}{d\theta_0} = \frac{d}{d\theta_0} \frac{\mu r}{1 + e^{\theta_0} e^r} = \frac{1 + e^{\theta_0} e^r \cdot 0 - e^r \cdot e^r e^{\theta_0}}{(1 + e^{\theta_0} e^r)^2}$$

$$= - \frac{e^{2r}}{(1 + e^{\theta_0} e^r)^2} e^{\theta_0} = - \beta^2 e^{\theta_0}$$

Let leave the rest to the computer; see [here](#);

$$\begin{aligned}
 \frac{d^2 l}{d\theta_0^2} &= -y \beta e^{\theta_0} + y \beta^2 e^{2\theta_0} + \tau^2 \left( e^{-\theta_0} \log(1 + e^{\theta_0} e^r) - \beta \right)^2 \\
 &\quad - \tau \left( e^{-\theta_0} \log(1 + e^{\theta_0} e^r) - \beta \right)^2 \\
 &\quad + \tau \left( \beta + \beta^2 e^{\theta_0} - e^{-\theta_0} \log(1 + e^{\theta_0} e^r) \right) \\
 &\quad + e^{-\theta_0} \varphi(y + e^{-\theta_0}) - e^{-\theta_0} \varphi(e^{-\theta_0}) + e^{-2\theta_0} \varphi^{(1)}(y + e^{-\theta_0}) \\
 &\quad - e^{-2\theta_0} \varphi^{(1)}(e^{-\theta_0})
 \end{aligned}$$

For  $\varphi^{(1)}$ , see  
Polygamma  
Fn on Wikipedia.

\* How do we deal with products  $\tau e^{-\theta_0} \log(1 + e^{\theta_0} e^r)$ , ...  
since as  $r \rightarrow -\infty$ ,  $\tau \rightarrow +\infty$  and  $\log(1 + e^{\theta_0} e^r) \rightarrow \log(1) = 0$   
we end up with the product  $+\infty \cdot 0$ , which is indeterminate.  
But we have hope if  $\tau \rightarrow +\infty$  slower than the terms of interact  
with  $\rightarrow 0$ , in which case the interaction  $\rightarrow 0$  as  $r \rightarrow -\infty$ .  
Taking  $\theta_0$  as fixed, we have

$$(i) \lim_{r \rightarrow -\infty} \tau \log(1 + e^{\theta_0} e^r) = \lim_{r \rightarrow -\infty} \frac{\log(1 + e^{\theta_0} e^r)}{1 - (1 + e^{\theta_0} e^r)^{-e^{-\theta_0}}}$$

$$\text{(L'Hopital)} = \lim_{r \rightarrow -\infty} \frac{e^{\theta_0} e^r}{(1 + e^{\theta_0} e^r)(0 + e^{-\theta_0} (1 + e^{\theta_0} e^r)^{-e^{-\theta_0}} \cdot e^{\theta_0} e^r)}$$

$$\begin{aligned}
 &= \lim_{r \rightarrow -\infty} \frac{e^{\theta_0 r}}{e^r (1 + e^{\theta_0 r})^{-e^{-\theta_0}}} \\
 &= \lim_{r \rightarrow -\infty} \frac{e^{\theta_0}}{(1 + e^{\theta_0 r})^{-e^{-\theta_0}}} = e^{\theta_0}
 \end{aligned}$$

$$\Rightarrow (c \log(1 + e^{\theta_0} e^r))^a \rightarrow e^{a\theta_0} \quad \forall a \in \mathbb{R}$$

also,  $c^a \log(1 + e^{\theta_0} e^r)^b \rightarrow 0 \quad \text{if } b > a \text{ as } r \rightarrow -\infty, a, b \in \mathbb{R}$

$$(ii) \lim_{r \rightarrow -\infty} c \left( e^{-\theta_0} \log(1 + e^{\theta_0} e^r) - \beta \right) \stackrel{(i)}{=} \frac{e^{-\theta_0} - e^{-\theta_0} - 1}{1 - 1} \xrightarrow{b \rightarrow 1, \text{ as } r \rightarrow -\infty} 0$$

$$\text{Define } K = e^{-\theta_0} \log(1 + e^{\theta_0} e^r) - \beta$$

$$\Rightarrow \lim_{r \rightarrow -\infty} cK = 0 \quad / \quad \Rightarrow \lim_{r \rightarrow -\infty} (ck)^a = 0 \quad \forall a \in \mathbb{R}$$

$$\Rightarrow \lim_{r \rightarrow -\infty} c^a K^b = 0 \quad \forall a, b \in \mathbb{R} \quad \text{if } b > a$$

$$\begin{aligned}
 (iii) \lim_{r \rightarrow -\infty} c \left( \beta + \beta^2 e^{\theta_0} - e^{-\theta_0} \log(1 + e^{\theta_0} e^r) \right) \\
 = 1 + 0 - e^{-\theta_0} e^{\theta_0} = 1 - 1 = 0
 \end{aligned}$$

for fixed  $\theta_0$

For  $r \rightarrow -\infty$ ,  $c \rightarrow 1$ ,  $\beta \rightarrow e^{-\theta_0}$ ,  $\log(1 + e^{\theta_0} e^r) \approx \log(e^{\theta_0} e^r)$   
since  $e^{\theta_0} e^r$  will dominate 1. and  $\log(e^{\theta_0} e^r) \rightarrow \theta_0 + r$ .

We'll use this even though we don't have indeterminacy since  
the fit implementation also uses it. See how  $\log(e^r - 1)$  is approximated  
as  $e^r$  as  $r \rightarrow \infty$  for the zip model likelihood here 😎.

With these, we get, as  $r \rightarrow -\infty$

$$\frac{dy}{d\theta_0} \rightarrow y - e^{-\theta_0} \varphi(y + e^{-\theta_0}) + e^{-\theta_0} \varphi(e^{-\theta_0})$$

$$\begin{aligned}
 \frac{d^2y}{d\theta_0^2} \rightarrow & e^{-\theta_0} \varphi(y + e^{-\theta_0}) - e^{-\theta_0} \varphi(e^{-\theta_0}) + e^{-2\theta_0} \varphi^{(1)}(y + e^{-\theta_0}) \\
 & - e^{-2\theta_0} \varphi^{(1)}(e^{-\theta_0})
 \end{aligned}$$

when  $r \rightarrow -\infty$

$$\frac{dV}{d\theta_0} \rightarrow y - y e^{-\theta_0} e^{\theta_0} - (-e^{-\theta_0} (\theta_0 + r) + e^{-\theta_0}) \\ - e^{-\theta_0} \varphi(y + e^{-\theta_0}) + e^{-\theta_0} \varphi(e^{-\theta_0})$$

$$= e^{-\theta_0} \{ \theta_0 + r - 1 - \varphi(y + e^{-\theta_0}) + \varphi(e^{-\theta_0}) \}$$

$$\frac{d^2 V}{d\theta_0^2} \rightarrow e^{-\theta_0} + e^{-2\theta_0} e^{\theta_0} - e^{-\theta_0} (\theta_0 + r) + e^{-\theta_0} \varphi(y + e^{-\theta_0}) \\ - e^{-\theta_0} \varphi(e^{-\theta_0}) + e^{-2\theta_0} \varphi^{(1)}(y + e^{-\theta_0}) - e^{-2\theta_0} \varphi^{(1)}(e^{-\theta_0})$$

$$= e^{-\theta_0} \{ 2 - \theta_0 - r + \varphi(y + e^{-\theta_0}) - \varphi(e^{-\theta_0}) \\ + e^{-\theta_0} \varphi^{(1)}(y + e^{-\theta_0}) - e^{-\theta_0} \varphi^{(1)}(e^{-\theta_0}) \}$$

$$\frac{d^2 V}{d\theta_0 d\theta_1} = \frac{d^2 V}{d\theta_0 d\theta_2} = 0$$

$$\frac{d^3 V}{d\theta_0 d\theta_1} = -y \beta e^{\theta_0} + y \beta^2 e^{2\theta_0} - \beta \tau^2 (e^{-\theta_0} \log(1 + e^{\theta_0} e^r) - \beta) \\ + \beta \tau (e^{-\theta_0} \log(1 + e^{\theta_0} e^r) - \beta) + e^{\theta_0} \beta^2 \tau$$

$$\frac{d^3 V}{d\theta_0 d\theta_2} = -y \beta e^{\theta_0} + y \beta^2 e^{2\theta_0} - 2y \beta^2 e^{1\theta_0} - \beta \tau^2 (e^{-\theta_0} \log(1 + e^{\theta_0} e^r) - \beta) \\ + \beta \tau (e^{-\theta_0} \log(1 + e^{\theta_0} e^r) - \beta) + \tau^2 \beta^2 \tau^2 (e^{-\theta_0} \log(1 + e^{\theta_0} e^r) - \beta) \\ - 3 \beta^2 \tau^2 (e^{-\theta_0} \log(1 + e^{\theta_0} e^r) - \beta) - \tau^2 \beta^2 \tau (e^{-\theta_0} \log(1 + e^{\theta_0} e^r) - \beta) \\ + \beta \tau^2 (e^{-\theta_0} \log(1 + e^{\theta_0} e^r) - \beta) + 2\tau^2 \beta^2 \tau - 2\tau^2 \beta^3 \tau^2 \\ - 4e^{2\theta_0} \beta^3 \tau + 4e^{\theta_0} \beta^3 \tau$$

$$\frac{d^3 V}{d\theta_0 d\theta_1 d\theta_2} = \frac{d^2 V}{d\theta_0 d\theta_1 d\theta_2} = 0$$

$$\frac{d^3 V}{d\theta_1 d\theta_2} = -y \beta e^{\theta_0} + y \beta^2 e^{2\theta_0} - 2y \beta^2 e^{1\theta_0} - 2\beta \tau^2 (e^{-\theta_0} \log(1 + e^{\theta_0} e^r) - \beta)^2 \\ + 3 \beta \tau^2 (e^{-\theta_0} \log(1 + e^{\theta_0} e^r) - \beta)^2$$

$$\begin{aligned}
& -\beta z^2 \left( -e^{-\theta_0} \log(1+e^{\theta_0} e^x) + \beta + \beta^2 e^{\theta_0} \right) \\
& - \beta z (e^{-\theta_0} \log(1+e^{\theta_0} e^x) - \beta)^2 \\
& + \beta z (-e^{-\theta_0} \log(1+e^{\theta_0} e^x) + \beta + \beta^2 e^{\theta_0}) \\
& + 2\beta^2 z^2 e^{\theta_0} \left( e^{-\theta_0} \log(1+e^{\theta_0} e^x) - \beta \right) \\
& - 2\beta^2 z e^{\theta_0} (e^{-\theta_0} \log(1+e^{\theta_0} e^x) - \beta) \\
& + \beta^2 z e^{\theta_0} - 2\beta^2 z e^{2\theta_0}
\end{aligned}$$

$$\frac{d^4 L}{dt^2 d\theta_0 d\theta_1} = \frac{d^2 L}{d\theta^2 d\theta_0 d\theta_2} = 0$$

$$\begin{aligned}
\frac{d^4 L}{d\theta^2 d\theta_0^2} &= -y p^2 e^{\theta_0} + 7y p^2 e^{2\theta_0} - 12y p^3 e^{3\theta_0} + 4y p^4 e^{4\theta_0} \\
&- 2\beta z^3 (e^{-\theta_0} \log(1+e^{\theta_0} e^x) - \beta)^2 + 3\beta z^2 (e^{-\theta_0} \log(1+e^{\theta_0} e^x) - \beta)^2 \\
&- \beta z^2 (-e^{-\theta_0} \log(1+e^{\theta_0} e^x) + \beta + \beta^2 e^{\theta_0}) \\
&- \beta z (e^{-\theta_0} \log(1+e^{\theta_0} e^x) - \beta)^2 + \beta z (-e^{-\theta_0} \log(1+e^{\theta_0} e^x) + \beta + \beta^2 e^{\theta_0}) \\
&+ 6\beta^2 z^4 (e^{-\theta_0} \log(1+e^{\theta_0} e^x) - \beta)^2 \\
&+ 2\beta^2 z^3 e^{\theta_0} (e^{-\theta_0} \log(1+e^{\theta_0} e^x) - \beta)^2 \\
&- 12\beta^2 z^3 (e^{-\theta_0} \log(1+e^{\theta_0} e^x) - \beta)^2 \\
&+ 2\beta^2 z^3 (-e^{-\theta_0} \log(1+e^{\theta_0} e^x) + \beta + \beta^2 e^{\theta_0}) \\
&- 3\beta^2 z^2 e^{\theta_0} (e^{-\theta_0} \log(1+e^{\theta_0} e^x) - \beta)^2 \\
&+ 7\beta^2 z^2 (e^{-\theta_0} \log(1+e^{\theta_0} e^x) - \beta)^2 \\
&+ 4\beta^2 z^2 e^{\theta_0} (e^{-\theta_0} \log(1+e^{\theta_0} e^x) - \beta) \\
&+ \beta^2 z^2 e^{\theta_0} (-e^{-\theta_0} \log(1+e^{\theta_0} e^x) + \beta + \beta^2 e^{\theta_0}) \\
&- 3\beta^2 z^2 (-e^{-\theta_0} \log(1+e^{\theta_0} e^x) + \beta + \beta^2 e^{\theta_0}) \\
&+ \beta^2 z e^{\theta_0} (e^{-\theta_0} \log(1+e^{\theta_0} e^x) - \beta)^2 \\
&- \beta^2 z (e^{-\theta_0} \log(1+e^{\theta_0} e^x) - \beta)^2 \\
&- 4\beta^2 z e^{\theta_0} (e^{-\theta_0} \log(1+e^{\theta_0} e^x) - \beta)
\end{aligned}$$

$$\begin{aligned}
& - \beta^2 e^{8x} (-e^{-8x} \log(1+e^{8x}e^x) + \beta + \beta^2 e^{8x}) \\
& + \beta^2 e^{-2} (-e^{-8x} \log(1+e^{8x}e^x) + \beta + \beta^2 e^{8x}) \\
& + 2\beta^2 e^{-2} - 8\beta^3 e^3 e^{8x} (e^{-8x} \log(1+e^{8x}e^x) - \beta) \\
& - 4\beta^2 e^2 e^{8x} (e^{-8x} \log(1+e^{8x}e^x) - \beta) \\
& + 12\beta^3 e^2 e^{8x} (e^{-8x} \log(1+e^{8x}e^x) - \beta) \\
& - 2\beta^5 e^2 e^{8x} + 4\beta^3 e^2 e^{8x} (e^{-8x} \log(1+e^{8x}e^x) - \beta) \\
& - 4\beta^3 e^2 e^{8x} (e^{-8x} \log(1+e^{8x}e^x) - \beta) \\
& - 8\beta^3 e^2 e^{8x} + 2\beta^3 e^2 e^{8x} + 6\beta^4 e^2 e^{8x} \\
& + 6\beta^4 e^2 e^{8x} - 6\beta^4 e^2 e^{8x}.
\end{aligned}$$

$$\begin{aligned}
\frac{d^4 y}{dr^4 d\theta_0} = & -y \beta^{8x} + 2y \beta^2 e^{8x} - 12y \beta^3 e^{8x} + 6y \beta^4 e^{8x} \\
& - \beta^2 (e^{-8x} \log(1+e^{8x}e^x) - \beta) + \beta e^{-8x} \log(1+e^{8x}e^x) - \beta \\
& + 6\beta^2 e^3 (e^{-8x} \log(1+e^{8x}e^x) - \beta) + 3\beta^2 e^2 e^{8x} (e^{-8x} \log(1+e^{8x}e^x) - \beta) \\
& - 9\beta^2 e^2 (e^{-8x} \log(1+e^{8x}e^x) - \beta) - 3\beta^2 e^2 e^{8x} (e^{-8x} \log(1+e^{8x}e^x) - \beta) \\
& + 5\beta^2 e^{-2} (e^{-8x} \log(1+e^{8x}e^x) - \beta) \\
& + 4\beta^2 e^2 e^{8x} - 6\beta^3 e^4 (e^{-8x} \log(1+e^{8x}e^x) - \beta) \\
& - 6\beta^2 e^3 e^{8x} (e^{-8x} \log(1+e^{8x}e^x) - \beta) \\
& + 12\beta^3 e^3 (e^{-8x} \log(1+e^{8x}e^x) - \beta) \\
& - 2\beta^3 e^2 e^{8x} (e^{-8x} \log(1+e^{8x}e^x) - \beta) \\
& + 9\beta^3 e^2 e^{8x} (e^{-8x} \log(1+e^{8x}e^x) - \beta) \\
& - 7\beta^3 e^2 (e^{-8x} \log(1+e^{8x}e^x) - \beta) \\
& - 9\beta^3 e^2 e^{8x} + 2\beta^3 e^2 e^{8x} (e^{-8x} \log(1+e^{8x}e^x) - \beta) \\
& - 3\beta^3 e^2 e^{8x} (e^{-8x} \log(1+e^{8x}e^x) - \beta)
\end{aligned}$$

$$+\beta^3 \tau (e^{-\theta_0} \log(1+e^{\theta_0} e^\tau) - \beta)$$

$$\begin{aligned}& -6\beta^3 e^{2\theta_0} + g\beta^3 e^{\theta_0} + 6\beta^4 e^{\theta_0} \\& + g\beta^4 e^2 e^{2\theta_0} - g\beta^4 e^2 e^{\theta_0} + 6\beta^3 e^3 e^{\theta_0} \\& - g\beta^4 e^2 e^{2\theta_0} + 3\beta^4 e^2 e^{\theta_0}.\end{aligned}$$

For us in 'predict' (se-fit)

$$\text{Recall } E[\tau] = q \tau e^r = q \frac{e^r}{1 - (1 + \kappa e^r)^{-\alpha}}, \quad r \sim ZTMB.$$

Let the ZTMB mean be  $\bar{\mu}$ ,

$$\begin{aligned} \bar{\mu} &= \frac{e^r}{1 - (1 + \kappa e^r)^{-\alpha}}, \quad d\bar{\mu}/dr = e^r \left[ \frac{1 + \kappa}{\alpha} \right] + \kappa e^r \\ &= e^r (\beta z - \beta z^2) + \kappa e^r \\ &= e^r \beta z - e^r \beta z^2 + \kappa e^r \end{aligned}$$

as  $r \rightarrow -\infty$

$$e^r \beta z \rightarrow \beta, \quad e^r \beta z^2 \rightarrow e^r z \quad (\text{since } \beta z \rightarrow 1)$$

$$\rightarrow 1 \quad (\text{as } z \rightarrow e^{-r})$$

$$\Rightarrow \bar{\mu} \rightarrow \beta - 1 + 1 = \beta$$

$$\text{as } r \rightarrow \infty, \quad \bar{\mu} = (e^r \beta z - e^r \beta z^2 + \kappa e^r)$$

$$\rightarrow e^r/\alpha - e^r/\alpha + e^r$$

$$= e^r$$

$$q = 1 - e^{-e^r}, \quad dq/dr = \frac{dq}{dy} \cdot \frac{dy}{dr}$$

$$\frac{dq}{dy} = e^{-e^r} \kappa z, \quad y = \theta_1 + (\theta_2 + e^{\theta_2}) z$$

$$\Rightarrow \frac{dy}{dz} = b + e^{\theta_2}$$

$$\Rightarrow \frac{dq}{dr} = e^{-e^r} \kappa z (b + e^{\theta_2}), \quad (\text{we don't do asymptotics with } y \text{ bc it is endogenous i.e. it depends on } r \text{ already})$$

$$\Rightarrow \frac{dE[\tau]}{dr} = \frac{dq}{dr} \cdot \bar{\mu} + q \cdot \frac{d\bar{\mu}}{dr}$$